DEVELOPMENT OF SUSTAINABLE TRAFFIC CONTROL PRINCIPLES FOR SELF-DRIVING VEHICLES: A PARADIGM SHIFT WITHIN THE FRAMEWORK OF SOCIAL JUSTICE

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ABSTRACT

Developments of commercial self-driving vehicle (SDV) technology has a potential for a paradigm shift in traffic control technology. Contrary to some previous research approaches, this research argues that, as any other technology, traffic control technology for SDVs should be developed having in mind improved quality of life through a sustainable developmental approach. Consequently, this research emphasizes upon the social perspective of sustainability, considering its neglect in the conventional control principles, and the importance of behavioral considerations for accurately predicting impacts upon economic or environmental factors. The premise is that traffic control technology can affect the distribution of advantages and disadvantages in a society, and thus it requires a framework of social justice.

The framework of social justice is inspired by John Rawls' Theory of Justice as fairness, and tries to protect the inviolability of each user in a system. Consequently, the control objective is the distribution of delay per individual, considering for example that the effect of delay is not the same if a person is traveling to a grocery store as opposed to traveling to a hospital. The notion of social justice is developed as a priority system, with end-user responsibility, where user is able to assign a specific Priority Level for each individual trip with SDV. Selected Priority Level is used to determine the right-of-way for each self-driving vehicle at an intersection. As a supporting mechanism to the priority system, there is a structure of non-monetary Priority Credits. Rules for using Priority Credits are determined using knowledge from social science research and through empirical evaluation using surveys, interviews, and web-based experiment. In the physical space, the intersection control principle is developed as hierarchical self-organization, utilizing communication, sensing, and in-vehicle technological capabilities. This distributed control approach should enable robustness against failure, and scalability for future expansion. The control mechanism has been modeled as an agent-based system, allowing evaluation of effects upon safety and user delay. In conclusion, by reaching across multiple disciplines, this development provides the promise and the challenge for evolving SDV control technology. Future efforts for SDV technology development should continue to rely upon transparent public involvement and understanding of human decision-making.

DEDICATIONS

One of the greatest inventors ever, Nikola Tesla, once said: "Let the future tell the truth, and evaluate each one according to his work and accomplishments. The present is theirs; the future, for which I have really worked, is mine." Consequently, this work is dedicated to all those individuals that, like Nikola Tesla, have struggled in the present to bring progress for the human kind in the future.

In addition, this work is dedicated to all those people whose life paths have crossed with mine. I sincerely thank you for all the influence you have made on me. Hopefully, this research effort will get us one step closer to a just society.

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1. INTRODUCTION

1.1 Research Background and Motivation

Einstein said, 'The problems we face cannot be solved by the same level of thinking that created them.' Throughout the world, engineers of the 21st century are facing significant challenges of modernizing the fundamental structure that supports human civilization [1]. The infrastructure of tomorrow needs to accommodate increased population, while giving proper attention to environmental and energy-use considerations. The vision for improving transportation systems, as one of the major infrastructures, would require design of the integrated, effective, and accessible systems.

One of the components of the civil infrastructure facing a challenge are traffic control systems. In the next several years, the community of traffic control engineers has a unique opportunity to develop radically different traffic control technology. This opportunity originates from the development of short-range vehicle-to-vehicle and vehicle-to-infrastructure communication [2]. This technology will enable transfer of periodic or activated messages that can inform the surrounding vehicles and infrastructure of e.g. speed, position, and direction of the vehicle [3]. Second area of development is in sensing devices installed in vehicles, which will enable real-time gathering of data about the vehicle and its environment, including geographical coordinates, speeds, directions, accelerations, obstacles, etc. [4]. Finally, vehicles today are having higher power reserves and can store large amounts of data, compared to a typical mobile computer [3, 5]. The combination of all these new technologies will give rise to capabilities for individual vehicles for navigating their environment and perform all safety-critical driving actions, without the need for a driver [6, 7]. Moreover, this technology will enable the formation of cooperative vehicle systems, where vehicles coordinate their movements with surrounding vehicles [8].

As a result, the emerging technology of self-driving vehicle (SDV) has potential for introducing a radical change in the fundamental premises of future transportation systems (e.g., these technologies can result in a safer, more efficient and more comfortable

driving experience [9] or mobility for people unable to drive [10]). In addition to safety and reduced need for infrastructure, self-driving vehicle technology can provide new models of vehicle ownership, productivity improvements, improved energy efficiency, and potential for new business models [11] Moreover, this technology has a significant export potential [12] and potential for return on investment [13].

However, not all the users are still sure about the benefits from SDV technology. In a recent survey of 2,000 drivers [14], 64% of participants said computers were not capable of the same quality of decision-making that human drivers exhibit. In addition, 75% of respondents said they can drive a car better than a computer could, and 75% said they would not trust a driverless car to take their children to school. Moreover, about 20% of drivers said they would buy a fully autonomous car if one were available. In addition to this survey, there have been interviews with focus groups from California, Illinois, and New Jersey [15]. These interviews also showed divided user opinions related to SDVs, with willingness to use SDV depending on the location the person is coming from and their gender. Finally, there are further concerns that electronics systems have become critical to the functioning of the modern automobile, and that these are presenting new human factors challenges for system design [16].

Besides promising numerous opportunities, the technology of self-driving vehicle will have a significant impact on the development of traffic control principles and technology. One of the important issues is the control of self-driving vehicles at intersections, as the critical points on any transportation network. Consequently, full self-driving automation can result in radically changed traffic control system, leading to the new generation of traffic control technology – traffic control 2.0 (C2).

In order to benefit from the significant potential of this emerging technology, the community of transportation engineers now has both an opportunity and an obligation to develop C2 with a long-term vision in mind. Considering that C2 technology is currently undergoing foundational development, this is the ideal point in time to broaden design activities to include wider impacts. The development of traffic control technology for 21st century will need to incorporate sustainability as an important underlying concept [17],

thus meeting the needs of the present generations, without compromising the ability of future generations to fulfill their own needs [2, 18-20]. Consequently, sustainable traffic control technology is neither irreversible nor does it result in situations that exclude certain system options merely because they were not supported at particular time. As a result, C2 should be able to achieve delicate balance between the needs of multiple segments of a population in current and future generations [21, 22]. This concept includes the idea of concern for essential needs of each individual and idea of removing limitations imposed by the state of technology and social organization. However, sustainability bases on "triple bottom line" development, with economic, environmental and social components, that cannot achieve a basic level if there is no simultaneous development of all three aspects [23-25]. Consequently, broadening design perspective for C2 would require inclusion of social sustainability components, which will lead to the necessary improvement of human health protection, social equity, inclusion, improved long-term quality of life [21, 26-29].

The community of transportation experts has already recognized the breadth of sustainability requirements for transportation systems. Strategic Plan [30] from Institute of Transportation Engineers points out that public should experience an improved quality of life through an economically, socially and environmentally sustainable transportation system. Consequently, technological decisions stop being only technical decisions, but instead they develop economic, social and environmental implications. After all, technology is there to solve problems and improve human life. Finally, it is important to emphasize that several other communities (e.g., car manufacturers, mobile service providers, etc.) are already undergoing significant development efforts for self-driving vehicle technology. However, although this recognizes the importance of self-driving vehicle technology, this is also a danger that C2 technology will be developed solely with economic purpose in mind (e.g., based on electronic toll collection).

Previous Research Efforts for Intersection Control of Self-Driving Vehicles

For almost a decade, there have been efforts for developing intersection control approaches for self-driving vehicles. The chronological development of control mechanisms for self-driving vehicles is presented in Table 3.

Table 1: Principles of operation for self-driving vehicle control at intersections

Authors / Year	Principle of operation
(Naumann, Rasche, & Tacken, 1998)	Right of way is assigned based on delay, number of vehicle in the queue, and approaching velocity.
(Dresner & Stone, 2004)	Reservation of space-time based on first-in first-out (FIFO) principle, according to the time of request for reservation.
(Dresner & Stone, 2006)	FIFO, but emergency vehicle receives right-of-way by clearing the lane for that vehicle.
(Raravi, Shingde, Ramamritham, & Bharadia, 2007)	Minimizing the maximum travel time to the intersection.
(Schepperle, Böhm, & Forster, 2007)	FIFO for initial reservation, but a vehicle can exchange time-slots with another vehicle if that other vehicle pays.
(Schepperle & Böhm, 2007)	Basic variant: auction for time-slot with the vehicle with the highest bid receiving the right-of-way. Variant with subsidies: The candidate with highest accumulated bid receives the right-of-way.
(M. Vasirani & Ossowski, 2008)	Driver agents must purchase the necessary reservations from the intersection manager agents. Intersection manager "sells" the right-of-way in attempt to maximize profit.
(VanMiddlesworth, Dresner, & Stone, 2008)	FIFO
(Regele, 2008)	Predefined right-of-way for certain movements over other movements through the intersection.
(M. Vasirani & Ossowski, 2009a)	Longest in the system: vehicle with the earliest arrival
Shortest in the system: vehicle with the latest arrival
Farthest to go: vehicle with the longest path to the destination
Nearest to source: vehicle closest to its origin
(Yan, Dridi, & El Moudni, 2009)	Minimizing the time a vehicle takes to cross the intersection.
(de La Fortelle, 2010)	FIFO
(Milanés, Pérez, Onieva, & González, 2010)	Subject vehicle yields to the vehicle on the right.
(Makarem & Gillet, 2011)	Heavier vehicles with higher effect of inertia during velocity adjustment are given an indirect priority.
(Alonso et al., 2011)	Resolving conflict based on the classification of the road (otherwise FIFO).
(Au, Shahidi, & Stone, 2011)	Vehicles receive the right-of-way depending on the time of their arrival or based on their experienced delay at the intersection.

(Ghaffarian, Fathy, & Soryani, 2012)	Maximize traffic throughput based on waiting delay or queue length.
(J. Lee & Park, 2012)	Gap adjustment mechanism for minimizing the total length of overlapping trajectories.
(Makarem, Pham, Dumont, & Gillet, 2012)	Priority determined by the distance to the intersection.
(Zohdy, Kamalanathsharma, & Rakha, 2012)	Minimization of total delay.
(Park & Lee, 2012)	Priority assigned to the lane with the longest queue, or if the vehicle reaches certain waiting period.
(Li, Chitturi, Zheng, Bill, & Noyce, 2013)	FIFO, but with priority reservation of vehicle in queue that is above certain length.
(Mladenovic & Abbas, 2013)	Priority queuing principle where each vehicle has assigned individual priority level (e.g., based on number of passengers).

In addition, some of these researchers recognized the need to relate vehicle routing and intersection control [31-34]. All these control principles were primarily compared with conventional control principles, always resulting in significant improvements. However, there have been limited number of research efforts that tried to compare these mechanisms [35].

Centralized control decisions

These research efforts for self-driving vehicles control have succeeded to progress away from conventional traffic-signal control parameters (i.e., split, cycle length, offset). However, although a great number of these research efforts has maintained C1 control mechanisms, with focus on centralized control mechanisms. Here, it is important to emphasize potential issues that centralized control decision can introduce:

- Centralized control has already proven to be sub-optimal for large transportation networks with many intersections [36].
- Centralized approach requires high computational requirements and increasing communication overhead [37].
- Centralized control approach lacks scalability and redundancy [37]..
- Considering the sheer size of transportation networks, investing in intersection controllers at each intersection can be an enormous investment.

- Centralized approach is not utilizing the computational capabilities future vehicles will have.

Operation based on queuing principles

Contrary to C1 principles, some research efforts have tried to introduce control mechanism based upon queuing principles (e.g., FIFO, adversarial queuing, priority queuing, etc.). However, this approach might introduce following issues:

- Theoretical queuing principles might not be efficient considering the increase in the number of coordinating intersections. Considering a case where there are n vehicles, but vehicle 1 has a conflict with all the other vehicles, while no other vehicles have conflicts with each other. If the vehicle 1 sends the request first, all the other n-1 vehicles will need to wait for that vehicle [38].

- FIFO queuing principle has been proven as less robust than traffic signal, with its performance being very sensitive to traffic demand. In the case of higher traffic volume, the correct arrival time at the intersection becomes harder to estimate and more sensitive to traffic variations, therefore many confirmed requests are withdrawn by the vehicles, thus reducing the intersection throughput [35].

Competition among the vehicle agents

Finally, several research efforts tried to introduce principles of economic market competition to the control mechanism for self-driving vehicle. This approach might have the following issues:

- Introducing competition among the agents might not always result in an optimal solution. For example, models might be very sensitive to assumptions on the auctioning order and actions' constraints [39, 40].

- Models might be very sensitive to assumptions on the auctioning order, constraints on actions, and people's beliefs and assuming that people ignore strategic behavior of other parties [39, 40].

- The auction-based system assumes that the travel budget of each drives is high enough, and that each driver bids and subsidizes their valuation per second of

reduced waiting time. Realistically, it can happen that the budget is too low and that a driver-assistance agent cannot afford to offer a price which corresponds to its true valuation [41]. The discrimination of "poor drivers" can happen in the initial time-slot acquisition phase [42].

- "Selling" the right to use the intersection space might be considered unfair, knowing that exploiting shifts in demand by raising prices is considered unfair [43]. In addition, aiming at profit maximization without fairness will lead to resistance of people [44], especially when there is singularity of supplier with service monopoly so the "customer" cannot avoid using the service.

1.2 Research Objectives

The goal of this research is to develop and evaluate an intersection control mechanism for self-driving vehicles, within the framework of social justice. The evaluation of the proposed control mechanism will be in comparison with state-of-the-art conventional traffic signal control. Evaluation will be based on the experienced delay for users, as total delay and individual delay, since the identified issue relates to the urgency associated with each user's trip, and the capability of the control framework to accommodate that information. Considering that the proposed mechanism will rely upon the end-user responsibility, the objective is also to evaluate the proposed framework from a standpoint of theoretical or empirical information on human decision-making within a framework of social justice. In addition, the design of the mechanism will be modified by user input. The scope of the research focuses on the application to isolated urban intersection, while considering some potential implications for network-wide operation. Consequently, this research needs to test the following hypothesis:

- An intersection control principle can be designed within the framework of social justice. This principle will succeed in protecting fundamental human rights better than a conventional intersection control principle.

The major research objectives of this dissertation are:

- To holistically investigate conventional traffic control principles, with main focus on traffic signal control.

- To establish a development approach that can include values into development of traffic control technology.

- To propose a framework of social justice, investigate the potential of conventional control to respond to questions of social justice, and propose an alternative control mechanism.

- To develop a model of the proposed control mechanism for isolated intersection.

- To use user input to evaluate and modify the proposed alternative control mechanism from the standpoint of end-user.

- To collect information on user decision-making, model this information, and evaluate the operation of the proposed mechanism at an isolated intersection.

1.3 Dissertation Contribution

Anticipated results from this dissertation are:

- Traffic control framework for SDVs, based on the principles of social justice.
- Information on user attitudes towards questions related to social justice considerations in intersection control.
- Information on user decision-making in relation to a proposed social justice framework.
- Information on the performance of credit system from simulating large-scale interactions.
- Information on the framework performance in relation to total and individual user delay.

1.4 Dissertation Organization

This dissertation consists of nine chapters. Chapter 1 presents an introduction, research objectives, contribution and organization of this dissertation. Chapter 2 provides a holistic assessment of conventional traffic control technology with a main focus on traffic signal control, and a relation to developmental approach for SDV technology. Chapter 3 provides a context for development of novel traffic control principles, with a focus on anthropocentric design. Chapter 4 presents a social justice framework, and evaluation of conventional and proposed control framework from a standpoint of social justice. Chapter 5 presents details on the self-organizing traffic control framework for SDVs. Chapter 6 present the modeling of proposed traffic control framework in an agent-based simulation environment. Chapter 7 presents the user opinions related to the proposed control framework collected from surveys and interviews, and consequent modifications to control framework. Chapter 8 presents development of web-based experiment for collection of user decision-making, and modeling this decision-making for operative evaluation of the proposed framework. Chapter 9 presents engineering significance of this dissertation, summary of findings, conclusions, and recommendations for further research. After references, there is a series of Appendices. An overview of dissertation elements is presented on the following Figure 1.
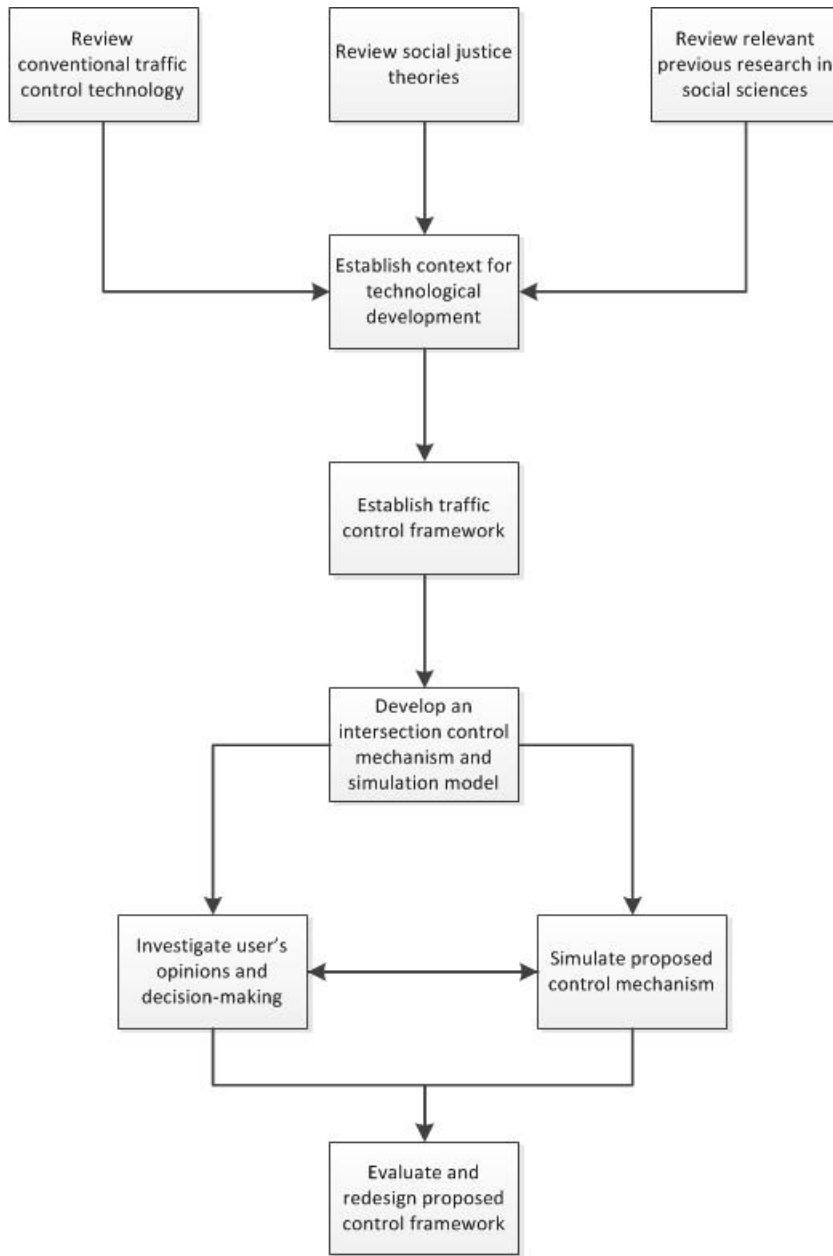
Figure 1: Dissertation elements

2. HOLISTIC ASSESSMENT OF CONVENTIONAL TRAFFIC-CONTROL TECHNOLOGY IN RELATION TO IMPLICATIONS FOR DEVELOPMENTAL CHALLENGES OF SELF-DRIVING VEHICLE CONTROL TECHNOLOGY

Abstract

Emerging technology for self-driving automation of vehicles has an enormous potential for changing the principles and technology for traffic control. Due to its importance, the foundational development of traffic-control technology for self-driving vehicles should be sustainable, in order to fulfill the needs of present and not constraint the needs of future generations. This survey paper first presents a holistic assessment of conventional traffic control technology. This assessment provides a detailed overview of evolving technological development, originating from interaction between industry, government, and research communities. In addition, we present operational principles and outcomes of conventional control, with pointers to the important design premises. Moreover, we present state-of-the-research efforts for development of intersection control principles for self-driving vehicles. Finally, we present conclusions and implications for further research that can positively influence the development of traffic-control technology for self-driving vehicles. The paper concludes with several areas for future research, with an emphasis on expanded anthropocentric design perspective and comparative evaluation of different operational principles. Presented future research directions should enable the development of sustainable long-term vision for self-driving vehicles control technology.

2.1 Introduction

Throughout the world, engineers of the 21st century are facing significant challenges of modernizing the fundamental structure that supports human civilization [1]. One of the components of the civil infrastructure facing a challenge is traffic signal control systems. In the next several years, the community of traffic control engineers has a unique opportunity to develop radically different traffic control technology. This opportunity originates from the development of short-range vehicle-to-vehicle and vehicle-to-infrastructure communication [2]. This technology will enable transfer of periodic or activated messages that can inform the surrounding vehicles and infrastructure of e.g. speed, position, and direction of the vehicle [3]. In addition to inter-vehicle communication, vehicles today are having higher power reserves and can store large amounts of data, compared to a typical mobile computer [3]. With these technological tendencies, it is becoming even more clear that vehicles of the future will start resembling to personal computers [5]. Finally, the development of sensing technology that will enable vehicle's detection of the surrounding environment will combine to result in significant distributive computational and sensing power integrated via wireless communications [6]. The combination of all these new technologies will give rise to capabilities for individual vehicles for navigating their environment and perform all safety-critical driving actions, without the need for a driver [7]. Besides improving energy efficiency of transportation systems, this technology has a significant export potential [12]. Consequently, this full self-driving automation can result in radically changed traffic control system, leading to the new generation of traffic control technology – traffic control 2.0 (C2).

In order to benefit from the significant potential of these technologies, the community of transportation engineers now has both an opportunity and an obligation to develop C2 with a long-term vision in mind. Considering that C2 technology is currently undergoing foundational development, this is the ideal point in time to broaden design activities to include wider impacts. The development of traffic control technology for 21st century will need to incorporate sustainability as an important underlying concept [17], thus meeting the needs of the present generations, without compromising the ability of future

generations to fulfill their own needs [2, 18]. Consequently, sustainable traffic control technology is neither irreversible nor does it result in situations that exclude certain system options merely because they were not supported at particular time. As a result, C2 should be able to achieve delicate balance between the needs of multiple segments of a population in current and future generations [21, 22].

This survey paper aims to indicate directions for future development of traffic control technology, influenced by the development of technologies in other engineering fields. In order to develop a long-term vision for C2 we need to understand the principles of conventional traffic control (C1) operation, with the resulting advantages and disadvantages. Understanding of foundational premises hinges on the investigation of the resulting historical development of traffic-control equipment, practice, and theory. First, this paper presents origins and development of C1 technology. Second, we present operational principles and outcomes of C1. In-depth perspective on C1 concludes by pointing out the important design premises, and their evaluation of applicability for C2. Finally, we present state-of-the-research and implications for further research that can positively influence the development of C2 technology. The focus of this review is specifically on traffic signal control. Although the authors recognize that the area of traffic control consists of many elements, and there can be many parallels, the scope of this paper is focused on traffic signal control considering the depth of analysis presented.

2.2 Origins and Development of C1

In order to develop a better vision for the future traffic-control systems, this section will present in-depth understanding of foundational vision for system design and its relation to the development of technology. However, as any technological change, the development of traffic control technology was driven by historical experience of actors, their perceptions of benefits, and resulting impacts. Because of this, understanding the resulting technology requires a historical perspective and analysis of the development performed by the three parties concerned in traffic signal control systems:

1. Governmental agencies (e.g., state or city Departments of Transportation);

2. Companies (e.g., organizations providing traffic control-related services or products);

3. Academic institutions (e.g., universities or transportation research institutes).

The overlap of these three sides is presented in Figure 2, marked as .gov, .com, and .edu, respectively. In C1, .gov is directly responsible for the operation of traffic signal control systems nationwide and related legislation. In addition, .com is responsible for developing equipment and implementing techniques for traffic signal control. Finally, .edu is responsible for the research and development in the area of traffic control theory. All the three parties have a common goal: to affect positively the performance of signal control systems through their effects on safety, efficiency, and environment. Specifically speaking, this is achieved through the development of technology. Here, we consider technology in its most wide meaning, including devices, theory, practical applications, etc., including all the elements that contribute positively to a society, which cannot be found independently in nature. Consequently, the efforts of the three sides need to be synergetic in order to achieve the global optimum of their common goal. However, this synergy and goal overlap is often not, if ever, achieved in reality. The focus of this part of the paper is to synthesize the developments among these three sides, and establish a relation between technology development and C1 operational principles.
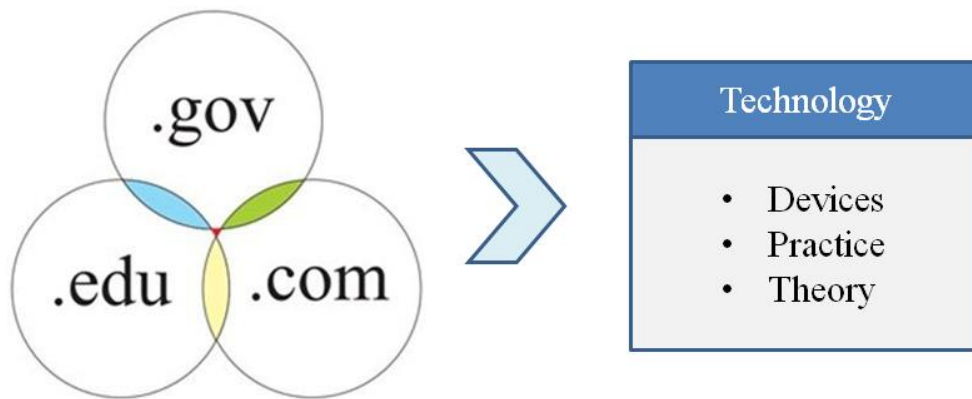
Figure 2: Overlap among stakeholders interested in development of traffic control technology and their impact on technology development

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The need for intersection control and initial efforts

Contrary to the popular belief, the need for the control of user movements through the intersection existed long before the introduction of motor vehicles. The congestion and safety issues, accompanied with the use of traffic control devices and access control were present even on the ancient Roman roads [45]. However, in the recent centuries, the intersections were becoming critical network points, especially in the dense urban environments. One of the examples of the solutions for introducing order into movements at intersection was an ordinance proclamation from New York City [46] issued in 1791, stating: "Ladies and Gentlemen will order their Coachmen to take up and set down with their Horse Heads to the East River, to avoid confusion". This was one of the first examples of traffic management for intersections using one-way street concept.

In the late 19th century, and due to the development of economy, there have been several main factors contributing to the safety and efficiency issues at intersections:

1. *Increase in urban population* – For example, more than half of the total urban population of United States was concentrated in the six largest cities New York, Philadelphia, Baltimore, Boston, New Orleans, and Charleston [47, 48].

2. *Increase in the number of trips* – For example, in 1913, New York was experiencing peak hours twice a day, as the traffic on the Fifth Avenue was growing twice the rate of city's population [49].

3. *Diversity of users* – For example, with walking already being the primary way of urban travel, there was a wider introduction of electric street railway in 1890s [50] and large-scale manufacturing of vehicles with internal combustion engine, which began in Detroit in 1901 [51].

With the increase in population, in number of trips, and with the introduction of motor vehicles into already pedestrian-congested city areas, network conditions continued to deteriorate further. The primary problem was traffic safety, considering the effects of vehicle-pedestrian crashes. First car accidents were reported in 1896, in London and New York [51]. Due to the deterioration of users' safety, city governments recognized the need for traffic control on the intersections. Traffic control became primarily the

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responsibility of the police [51], with the task to avoid the simultaneous coincidence of users in the same space [46]. Initially, the police officers were using hand signals, while later they started using revolving stanchions or large umbrellas with the words 'STOP' and 'GO' turning 90 degrees to alternate traffic flow [52].

The early development of traffic signal control equipment

Considering that intersection control was a responsibility of police officers, in order to improve their operation and safety, railway engineer John Peake Right [53, 54] invented the first illuminated traffic signal. Considering that signal lights were deployed at railroads as early as 1857 [45], this might be the origin of Right's idea. The first traffic signal was installed on December 10, 1868, outside of the British Houses of Parliament in London, at the intersection of George Street and Bridge Street [45, 55]. This manually operated semaphore [56, 57] had green and red lenses illuminated by gas for night operation [52]. The signal was primarily used for enabling pedestrian to cross the street by stopping the vehicles [51]. The official proclamation accompanying this device [45], issued by the London Police Commissioner, was "By the signal "caution", all the persons in charge of vehicles and horses are warned to pass over the crossing with care and due regard to the safety of the font passengers. The signal "stop" will only be displayed when it is necessary that vehicles and horses shall be actually stopped on each side of the crossing, to allow the passage of persons on foot; notice thus being given to all persons in charge of vehicles and horses to stop clear of the crossing". This is how the original engineering solution for the issue of intersection flows control was established on the principle of separating conflicting flows of users. This principle was materialized in a traffic signal device, visible and understandable for all the users.

Although Europe was the place of the first traffic signal, due to the increase in urban population and number of motor vehicles, the early developments of traffic control devices were primarily happening in the United States. The sequence of events is presented in Table 2. These developments completed the foundations of the modern traffic signal parameters, i.e., split, cycle length, and offset, and established a basis for the following decades of fixed-time traffic signal control.

Table 2: Event sequence in development of first traffic control equipment

Year / Place	Event
1909	First patents for traffic control devices in the United States.
1912 / Salt Lake City, Utah	Lester Wire designed a two-color traffic signal that used electric illumination.
1914 / Cleveland, Ohio	American Traffic Signal Company installed first electric two-color signals. The traffic signal faced two main street directions, with police officers controlling side street traffic and manually changing the lights.
1917	William Caglieri comes up with the idea that signals should automatically change colors at set intervals. The reason for the automation was to reduce manual labor, operator's error, and protect operator's safety and health. The timing mechanism operated as a clock, using a weight suspended from a cord that was rolled onto a drum, and had to be wound on a regular basis.
1918 / Salt Lake City, Utah	Charles Reading helped Lester Wire to link six traffic lights, to provide coordination for traffic travelling at 30 km/h.
1918 / Detroit, Michigan	William Potts added a third yellow color to the signal, as a caution interval, warning drivers that the signal is changing.
1920 / Detroit, Michigan	William Potts designed the first four-way three-color traffic control device. The device was a rectangular box, having three stacked chambers with each chamber having a single light bulb. Because a single light bulb lit the four lenses in each compartment of this signal, the green and red lenses were alternating between top and bottom positions.

Sources: [45, 46, 49, 51, 52, 58, 59]

Further development of traffic signal equipment

After the early development and implementations in the US, Western Europe widely adopted traffic signals several years later. Paris installed its first red and two-way only light in 1922, with Berlin and London following in 1924 and 1931, respectively [49]. However, the development continued primarily in the United States, but without any significant standardization. The market contained a wide variety of traffic regulating devices, ranging from improvements to simple semaphore devices to tall apparatuses that covered entire intersections. Most of these devices relied on cables and pulleys or underground crank mechanisms used by traffic police from the corners of intersections. Only few of these devices had automatic capabilities. In 1923, a railway signal company Crouse-Hinds stationed in Houston, developed the first automatic variable timing switch using induction disc that could vary the cycle length and split [45, 49]. In the late 1920s and early 1930s, a significant impact on traffic signal control technology development originated from the interest of big engineering companies into traffic signal equipment. These companies with large engineering teams established a niche for a serious market manufacturing signals and traffic signal controllers [53]. One such example was when General Electric bought the patent from G. A. Morgan, one of the inventors of traffic regulating devices. By the 1940s, there were several large companies manufacturing traffic signal equipment.

As the automation of traffic signal control developed further, the key element for the operation of traffic signals became traffic signal controller [58]. Until the 1970s, a vast majority of signals operated using electromechanical controllers. These controllers ranged from simple factory cut sets of cams that were turned by small synchronous motors to the more complex and precise ratchet cam controllers that, in some cases, had multiple control rings. The basic concept of operation was related to rotation of the camshaft mechanism. This mechanism was rotating cams and dials, used to activate load switches at fixed points in time [60]. The circulatory timing dials were the main mechanical elements ensuring the repetitiveness of fixed-time signal intervals [61], dividing the green time of the cycle between a limited number of stages that had a fixed sequence [62]. The mechanical elements of electromechanical controllers were the

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physical representation of the four main parameters of traffic signal control: cycle length, split, offset, and phase sequence.

Initial development of detection equipment

In order to automate further the labor in traffic signal control, some inventors were working on developing detection equipment. Charles Adler, Jr. [63] was the first to invent the acoustic detector operation for a traffic signal. His design was based on the microphone mounted on a pole at an intersection, which could detect a vehicle's horn honk or engine rumbling. Sonic vibrations would activate the mechanism that shifts the electrical circuits and change the light. In 1928 a horn-actuated signal was installed near Baltimore, Maryland [55]. About the same time, Henry Haugh developed a pressure detector. The detector was designed to send electrical impulses to the signal controller when two metal strips touch under vehicles pressure. By 1934, loop detectors, as an emerging technology started to be widely used [51], and replaced most of the other detector technology.

The development of microprocessor-based equipment

Mid-1960s introduced computer technology in traffic signal control. For example, computerized traffic control was introduced in Toronto, Canada and San Jose, California, [46]. The 1970s introduced microprocessor-based traffic signal controllers, that almost completely replaces electromechanical controllers [60]. These controllers base on the solid-state technology, with increased capabilities in actuated control. Controller is able to recognize larger number of different input from the detection system and to calculate control actions in real-time [60]. Originally, microprocessor-based controllers were relying on a multitude of nested and interrelated "if…then" rules for state transition [53]. However, although based on microprocessor technology with high computational capabilities, they kept the concept of the camshaft assembly by storing of timing plans based on cycle, split, and offset in the random access memory [61]. In addition, a major limitation is that controllers only have access to the data measured in few fixed positions [8].

Recent development in United States, under coordination between Institute of Transportation Engineers, National Electrical Manufacturers Association, and American Society of State and Highway Transportation Officials was primarily directed toward establishing standards for the industrial-based traffic controller [54, 59]. The latest controller standards gave the opportunity for third-party vendors to develop their own signal control software based on the standardized hardware structure and operating system. This has allowed increased flexibility in the development of market controller software. Market-driven competition used this flexibility to develop a multitude of signal control software [64]. In addition, modern traffic controller in United States has in average over 200 programmable parameters, including many sophisticated and advanced features [64, 65].

Besides variety in controller standardization in the North America, there are many different principles of controller architecture throughout the world. The levels of standardization for design and operations vary significantly across world regions, with some regions (e.g. Eastern Europe, South America, Middle East, China, India, etc.) simultaneously applying several different standards. For example, controller architecture defined by German standards supports freely programmable controllers – similar to Programmable Logic Controllers [66]. A typical programming of European controllers bases upon stage sequencing logic. The essential difference among North American and European interval-based controllers is that North American controller software has all the possible operational options already developed in separate submenus. On the other hand, European controllers do not have such established programming structure. The principles of European controller operation, as many other standards, were developed under the influence of specific traffic environments. However, all of those controllers throughout the world, still focus on utilizing split, cycle length, offset, and phase sequence as the fundamental control parameters.

Resulting development of signal control practice

The development of signal control practice followed the foundational inventions of devices and their operational parameters. The first traffic "experts" were usually amateur

enthusiasts [49]. In 1903, William Eno was the first to have a consulting practice, spreading the education on the traffic phenomenon, one-way systems, and uniform driving regulations. In 1924, Burton Marsh was appointed by the City of Pittsburgh as the world's first traffic engineer [51]. However, a community of practitioners was strengthened with the foundation of the Institute of Traffic Engineers in 1931 [49], and with the first codification of traffic engineering practice in 1932 [51]. The development of technology was accompanied with the development of the regulative system. In 1901, the International Law Association established a committee for traffic regulations [51]. One of the recommendations of this committee was giving the right of way to the vehicle on the driver's curbside at the intersection. In addition, there were other regulation, such as a requirement from drivers to show turning directions by hand, which was proclaimed in Berlin in 1902 [51].

Nowadays, signal control engineers have to set up traffic signals to serve many types of users, reach balance between competing demands, and accommodate agency's operations and maintenance capabilities [67]. The current practice in the US groups phases into a continuous loop while separating the crossing or conflicting traffic movements with clearance intervals [56]. Timing plans are still defined in terms of cycle length, split, and offset – just as decades ago. The expertise of the traffic engineer is still a key factor for determining the implementation of particular optimal control strategy [68]. In general, traffic engineers perform signal optimization using some of the market available software (e.g., Sychro, PASSER, Transyt 7F, LinSig, Maxband, etc.) [69]. These timing plans, based on split, cycle length, and offset as parameters are then delivered to the traffic signal field technician for input into the traffic signal controllers. However, although controllers operate on similar, they also have a range of other parameters that are not optimized.

In the current state-of-the-practice, there are five levels of traffic signal control systems currently available:

1. *Isolated operation* - Intersection controller is not coordinated with any other intersection controllers, can operate without a cycle length, and its parameters are

primarily defined to establish safe operation (e.g., dilemma zone protection, pedestrian detection, etc.).

2. *Time base coordination* – Intersection controllers at this level are not interconnected and achieve time base coordination by relating cycle times and offsets to a common time standard [70].

3. *Time-of-day and manual control of timing plans* – At this level, intersection controllers are interconnected for coordinating time-of-day selection of timing plans or allowing the selection of timing plans by an operator.

4. *Traffic-responsive control* – These strategies are based on the system detectors that select a plan from a timing plan library, according to the current traffic conditions. These systems can be closed-loop or centrally controlled.

5. *Adaptive traffic control* – Intersections operating under adaptive control are controlled by upstream and downstream detectors, and have algorithms that perform small/rapid timing adjustments on a cycle-by-cycle basis.

Adaptive Traffic Control Systems (ATCS) are the last generation of C1 systems [71]. Basic premise behind their operation is capturing of current traffic demand data for optimization of traffic signal timing [72, 73]. They are usually implemented for coordinated network traffic-signal systems. ATCS use advanced optimization and modeling algorithms, and are effective in dealing with changes in traffic conditions, with special events, reducing spillback on the freeway, etc. Although most of these systems started as research projects of academic community, today most of them are delivered as complete software products that sometimes require vendor-specific hardware. In addition, considering they are delivered as complete software solutions, they are usually able to store large amounts of real-time performance measurements, create numerous reports, and visualize network conditions.

Resulting development of signal control theory

The actual theory of traffic signal control was historically lagging behind the development of the traffic signal equipment and practice. The theory development

originated from the observation of the practical problems and related ad hoc engineering solutions based on experience. Although the original vision of the development of C1 was to improve the safety at intersections through the orderly movement of traffic [58], the increase in traffic demand lead to the conclusion that their operation can result in improvement or degradation of efficiency. Most of the related research about traffic-control theory based on finding an optimal control strategy is trying to balance several conflicting goals [36].

The application of scientific methods in determining signal timing started after World War II [51]. By the 1950s, scientists from many other sciences were starting to become interested in finding the solutions for traffic problems [46]. Primarily, this was a work of application of queuing theory and operations research, from the emerging discipline of industrial engineering [49]. Consequently, the first papers on traffic theory were published in the Operations Research journal. Figure 3 shows an example of word frequency in the literature for such terms as "industrial engineer", "traffic engineer", "traffic control", "traffic signal", "traffic controller", and "cycle length", obtained from Google Books Ngram Viewer [74]. The sample shows annual percentage of these terms in literature published between 1900 and 2005. From this figure, one can conclude that the term "industrial engineer" had been used in literature some 10 years before terms such as "traffic control" or "traffic engineer". However, it is interesting to see from the same figure that the term "traffic control" had a peak frequency at year 1945. Moreover, it is interesting to see how the term "traffic engineer" was used more frequently than the term "industrial engineer" around 1945. Consequently, this graphical example of word frequency for some terms related to traffic-control demonstrates a close connection between industrial engineers and traffic control.
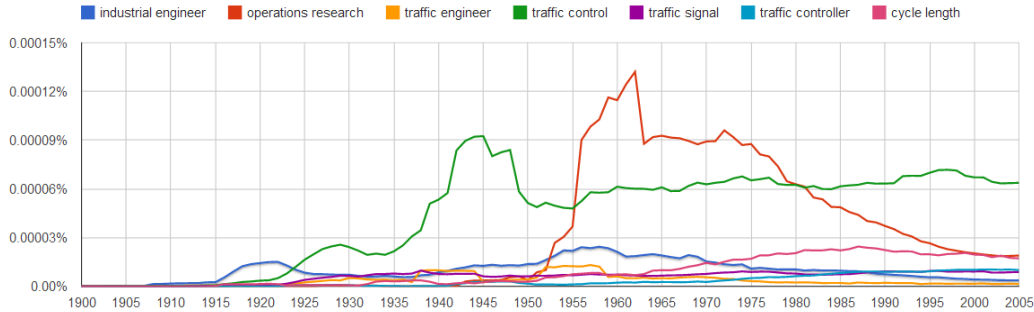
Figure 3: Word frequency for terms related to traffic signal control in literature from 1900 to 2005

Some of the early contributions to traffic theory were those of Reuschel (1950), Pipes (1953), Lightill and Whitham (1955) [46]. After these initial developments, a defining foundations for fixed time operation of traffic signals at isolated intersection was the work of Webster [75] in 1958, who introduced and defined the terms effective green, lost time, cycle length, and delay as an important optimization factor. These theoretical developments initiated in 1950s have established over 50 years of research efforts for improvement of traffic control systems in two main areas – efficiency and safety. Developments ranged from traffic control for oversaturated conditions, control for special vehicles and different users (e.g., pedestrians, transit vehicles, emergency vehicles, etc.), environmentally sustainable traffic control, improving driver's response to signal indications (e.g., dilemma zone), etc. Here, we would like to emphasize on two research areas, which have progressed away the furthest in comparison to general C1 control mechanisms.

Environmentally sustainable traffic control

The research community has already recognized that current timing plans are still determined with the objective to minimize negative operational effects in terms of efficiency [56]. However, the research community has developed some initial efforts for establishing environmentally sustainable traffic control [60, 76-81]. These research initiatives have made significant progress by recognizing that minimizing vehicular delay and stops, as the conventional approach to traffic control, does not achieve optimally sustainable equilibrium. These research efforts focused on minimizing negative environmental effects of traffic control (e.g., CO_2 emissions).

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Theoretical advances based upon artificial intelligence techniques

In addition to the efforts to introduce environmental sustainability in C1, communities of computer science and industrial systems engineers have tried to develop novel control approaches using artificial intelligence techniques [82-86]. Additional research in this area focused on using evolutionary game theory and reinforcement learning for modeling of intersection control [87-92]. In this research, traffic controllers at intersections are considered as individually motivated agents, taking into consideration their own local, but also global network goals. However, all these efforts maintained the focus on C1 parameters (split/cycle/offset).

2.3 Operational Principles and Outcomes of C1 Devices, Practice, and Theory

Resulting effects

From the analysis in the previous section, one can see how traffic signal control technology has originated and evolved, influenced by prevailing circumstances. We have seen in the historical overview how the reasons for existence of traffic control technology evolved in time. Under those circumstances, C1 has evolved, in the interaction between .gov, .com, and .edu. The clear advantage of C1 was the orderly movement of traffic. However, the engineering solution that provides foundation for modern traffic control was not envisioned to scale-up as the system progressed through development of technology and techniques. The current practice and directions for theoretical development are becoming increasingly constrained due to the foundational definitions. Modern traffic signal control systems are becoming increasingly complex and yet can rarely achieve optimum for all the users. One example of these current issues is the "2012 Signal Report Card" by National Transportation Operations Coalition[63] which assigned an overall grade of D+ to traffic signal infrastructure and operations across United States. This report is pointing out to many specific problems that estimated 311,000 signals in United States have. The negative results [93, 94] that modern traffic signals are creating can be categorized as:

- Excessive user delay and stops,

- Disobedience of signal indications,

- Increase use of less adequate routes,

- Reduction of intersection capacity,

- Increase in congestion,

- Increase in the frequency of crashes,

- Reduction of gaps.

Gaps in the development between devices, practice, and theory in C1

It is observable that in the course of time there was lack of complete overlap and coordination between the .com, .gov, and .edu. This frequently unsynchronized development of equipment, practice, and theoretical methods has resulted in the following developmental gaps in:

Devices:

- The developments of microprocessor-based technology was never properly accompanied with the development of traffic signal control theory [61]. The conventional parameters, i.e., split/cycle length/offset, are still constraining the development of traffic signal control theory.

- Because of the multitude of controller capabilities, and variety of agency standards for controllers [60] it is difficult to predict their operation under different traffic conditions [95]. In addition, there are no detailed procedures for making field adjustments since controller manuals usually describe what the controller feature is doing, but they do not describe when, where, or most importantly, how to effectively use a specific programmable feature [65].

- Signal timing parameters from optimization software are not directly convertible into controller timing parameters [96], and this input relies upon extensive expertise of the technician/engineer [55, 69].

- Existing dominant loop detection equipment is based on 1950s technology, with limited classification capabilities [97].

Practice and theory:

- C1 always has constant lost (intergreen) times that are introduced for safety reasons, but always increase the overall intersection delay.

- Centralized control approach, which is dominant in C1, has proven to be sub-optimal for large transportation networks with many intersections [98]. Although the optimal control problem can be formulated for any traffic signal network, its real-time solution and implementation is extremely difficult to accomplish. In addition to the size of the problem for urban networks, there are many unpredictable and hard-to-measure disturbances in the traffic flow.

- In general, all approaches belonging to the same phase will have the same green period even though the traffic requirements of the approaches may be different [68].

- C1 extensively utilizes the concepts of the main and minor road, assuming all the vehicles on the approach are having the same priority of the trip [99].

- There are unclear guidelines for division of traffic networks, for establishing the type of signal control, for selection of timing plans and their deployment periods, and for use of detector data [70].

- Widely implemented fixed-time strategies are based on the historical rather than real-time data [46]. In reality, demand and turning movements change every day, especially due to special events or incidents.

- Optimizing for total delay that is frequently used in theory and practice is only an approximation of what society really wants from traffic signal control [99].

- The expertise of the traffic engineer is still the key factor for determining the implementation of particular optimal control strategy [67-69]. This results in current control approaches that are usually responsive and concerned with local optimums.

- ATCS are usually vendor-specific and delivered in the manner of "a black box", due to the proprietary in-built modeling and optimization algorithms [72, 73]. Despite having advanced capabilities, ATCS:

  - Require human supervision;

  - Lack benefits for networks with predictable or oversaturated conditions;

  - Have no special consideration for pedestrian or bike operation, have long initial setup time;

  - Accompanying controller equipment and communication interfaces are frequently tied to one vendor;

  - Have steep learning curve because of difficulties to explain the operation;

  - Lack support after installation;

  - Have high installation requirements for detector and communication equipment;

  - Have higher maintenance and operational costs for maintaining system in the optimal performance.

General principles of C1

As a consequence of presented evolution, C1 today relies upon the following principles:

1. Separation of aggregated conflicting traffic flows using signal indications.

2. Determining optimality by primarily focusing on aggregate efficiency effects.

3. Centralized architecture that relies upon externalized human supervision and local sensing.

These principles have their aforementioned advantages and disadvantages, in relation to the complete development of devices, practice, and theory. The next paper section will present some recent development in traffic control technology that are both similar and different than these C1 principles.

2.4 Research Efforts for Intersection Control of Self-driving Vehicles

Considering the development of self-driving vehicle technology, a part of the current trend in research focuses on control of self-driving vehicles. The chronological development of control mechanisms for self-driving vehicles is presented in Table 3.

Table 3: Principles of operation for self-driving vehicle control at intersections

Authors / Year	Principle of operation
[100]	Right of way is assigned based on delay, number of vehicle in the queue, and approaching velocity.
[101]	Reservation of space-time based on first-in first-out (FIFO) principle, according to the time of request for reservation.
[102]	FIFO, but emergency vehicle receives right-of-way by clearing the lane for that vehicle.
[103]	Minimizing the maximum travel time to the intersection.
[104]	FIFO for initial reservation, but a vehicle can exchange time-slots with another vehicle if that other vehicle pays.
[105]	Basic variant: auction for time-slot with the vehicle with the highest bid receiving the right-of-way. Variant with subsidies: The candidate with highest accumulated bid receives the right-of-way.
[31]	Driver agents must purchase the necessary reservations from the intersection manager agents. Intersection manager "sells" the right-of-way in attempt to maximize profit.
[106]	FIFO
[107]	Predefined right-of-way for certain movements over other movements through the intersection.
[35]	Longest in the system: vehicle with the earliest arrival Shortest in the system: vehicle with the latest arrival Farthest to go: vehicle with the longest path to the destination Nearest to source: vehicle closest to its origin
[108]	Minimizing the time a vehicle takes to cross the intersection.
[109]	FIFO
[110]	Subject vehicle yields to the vehicle on the right.
[111]	Heavier vehicles with higher effect of inertia during velocity adjustment are given an indirect priority.
[112]	Resolving conflict based on the classification of the road (otherwise FIFO).
[113]	Maximize traffic throughput based on waiting delay or queue length.
[114]	Gap adjustment mechanism for minimizing the total length of overlapping trajectories.
[115]	Priority determined by the distance to the intersection.
[116]	Minimization of total delay.
[117]	Priority assigned to the lane with the longest queue, or if the vehicle reaches certain waiting period.
[118]	FIFO, but with priority reservation of vehicle in queue that is above certain length.
[119]	Priority queuing principle where each vehicle has assigned individual priority level (e.g., based on number of passengers).

In addition, some of these researchers recognized the need to relate vehicle routing and intersection control [31-34]. All these control principles were primarily compared with conventional control principles, always resulting in significant improvements. However,

there have been limited number of research efforts that tried to compare these mechanisms [35].

Centralized control decisions

These research efforts for self-driving vehicles control have succeeded to progress away from conventional traffic-signal control parameters. However, although a great number of these research efforts has maintained C1 control mechanisms, with focus on centralized control mechanisms. Here, it is important to emphasize potential issues that centralized control decision can introduce:

- Centralized control has already proven to be sub-optimal for large transportation networks with many intersections [36].

- Centralized approach requires high computational requirements and increasing communication overhead [37].

- Centralized control approach lacks scalability and redundancy [37]..

- Considering the sheer size of transportation networks, investing in intersection controllers at each intersection can be an enormous investment.

- Centralized approach is not utilizing the computational capabilities future vehicles will have.

Operation based on queuing principles

Contrary to C1 principles, some research efforts have tried to introduce control mechanism based upon queuing principles (e.g., FIFO, adversarial queuing, priority queuing, etc.). However, this approach might introduce following issues:

- Theoretical queuing principles might not be efficient considering the increase in the number of coordinating intersections. Considering a case where there are n vehicles, but vehicle 1 has a conflict with all the other vehicles, while no other vehicles have conflicts with each other. If the vehicle 1 sends the request first, all the other n-1 vehicles will need to wait for that vehicle [38].

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- FIFO queuing principle has been proven as less robust than traffic signal, with its performance being very sensitive to traffic demand. In the case of higher traffic volume, the correct arrival time at the intersection becomes harder to estimate and more sensitive to traffic variations, therefore many confirmed requests are withdrawn by the vehicles, thus reducing the intersection throughput [35].

Competition among the vehicle agents

Finally, several research efforts tried to introduce principles of economic market competition to the control mechanism for self-driving vehicle. This approach might have the following issues:

- Introducing competition among the agents might not always result in an optimal solution. For example, models might be very sensitive to assumptions on the auctioning order and actions' constraints [39, 40].

- Models might be very sensitive to assumptions on the auctioning order, constraints on actions, and people's beliefs and assuming that people ignore strategic behavior of other parties [39, 40].

- The auction-based system assumes that the travel budget of each drives is high enough, and that each driver bids and subsidizes their valuation per second of reduced waiting time. Realistically, it can happen that the budget is too low and that a driver-assistance agent cannot afford to offer a price which corresponds to its true valuation [41]. The discrimination of "poor drivers" can happen in the initial time-slot acquisition phase [42].

- "Selling" the right to use the intersection space might be considered unfair, knowing that exploiting shifts in demand by raising prices is considered unfair [43]. In addition, aiming at profit maximization without fairness will lead to resistance of people [44], especially when there is singularity of supplier with service monopoly so the "customer" cannot avoid using the service.

2.5 Conclusion and Implications for Further Research

We have started this review by identifying the need to understand the dynamical nature of technological development and the way current technological vision for conventional traffic control evolved and became embedded. In the historical perspective, we have seen that the C1 systems are the result of the converging effects of the three main stakeholders: the industry, the research community, and the practitioner community. The original development of traffic signal control equipment, practice, and theory was based on the engineering solution for the emerging problem of intersection control at the beginning of 20th century. Traffic signal, in its form known to us today, has prevailed as the main control device, providing uniform information to all users under all conditions. In addition, split, cycle length, offset, and phase sequence are still the main control parameters our community is trying to improve upon. Although proving beneficial for decades to come, the foundational premises of this solution are showing gaps in the development between .com, .gov, and .edu. One of the greater issues is that the development of theory was superimposed on the already existing device and practice development. Consequently, it is more and more evident that the foundational premises are gradually reaching the limit of their progressive capacity for theoretical development. It is becoming more and more evident that there needs to be an expansion in the original traffic control perspective established more than a century ago.

The current technological developments in computer, communication, and sensing technology happening in other engineering fields could enable a full scale deployment of self-driving vehicles. Consequently, our community has a unique opportunity for perspective expansion and a chance to reinvent some of the basic operational premises of traffic control systems. Considering undergoing foundational development of self-driving vehicle technology, now is the time to shape its long-term vision, considering that already developed technology is hard to change. The community of transportation experts has already recognized the breadth of sustainability requirements for transportation systems. Institute of Transportation Engineers Strategic Plan [30] points out that public should experience an improved quality of life through an economically, socially and environmentally sustainable transportation system. Consequently, technological decisions

stop being only technical decisions, but instead they develop economic, social and environmental implications. After all, technology is there to solve problems and improve human life. Finally, it is important to emphasize that several other communities (e.g., car manufacturers, mobile service providers, etc.) have already recognized the importance of self-driving vehicle technology. However, this introduces a danger that C2 technology will be developed solely with economic purpose. Some authors, e.g., [8], have already pointed out to some of the challenges and open issues. However, although we re-emphasize some of those challenges, we also present additional challenges derived from the overview presented here.

Testing different operational principles for C2

C2 technology has the potential to satisfy higher development requirements, and we as a community should not overlook this opportunity. On the contrary, we should have a flexible perspective, and focus on a broad range of dimensions when developing C2. Otherwise, we might constrain future development of C2 technology. Considering the status of C1 and the current research of C2, one can conclude that previous approaches are primarily focused on increasing mobility. We as a research community should especially be careful of blindly accepting principles of C1 operation as a legacy, without questioning these principles in-depth. In order to justify future C2 technology, the advantages to be gained must clearly outweigh the disadvantages. In order to accomplish this, we need to:

- Establish a common procedure and platform for evaluating a broad range of operational principles.

- Investigate potential for the approach where control actions will be the responsibility of individual self-driving vehicles, without centralized control. Examples are already there, with recent developments in decentralized control frameworks and use of model-predictive control approach [37, 120].

- Investigate potential for varying different control approaches for different traffic situations or network routes.

- Investigate potential for platoon formation [8].

- Investigate robustness of different system mechanisms to handle nonrecurring events and issues of scalability [8].

Inclusion of social sustainability and impact on public perception

If we take a perspective that issues of efficiency are related to economic parameters (e.g., minimizing delay), and that the need for environmental sustainability of traffic control systems has already been recognized, current vision for C2 technology still requires fulfilling social concerns and objectives, as a part of sustainable vision [19]. Consequently, broadening design perspective for C2 would require inclusion of social sustainability components, which will lead to the necessary improvement of human health protection, social equity, inclusion, improved long-term quality of life [26-28] [21, 29]. This requires an expanded perspective for long-term technological development. The radar graph on the left-hand side of Figure 4 shows three main objectives present in C1, while the radar graph on the right shows recommendation for the expanded design perspective. The important point related to inclusion of social parameters in design is that it can potentially result in a greater user interest for investment in large-scale deployment of C2 technology. By emphasizing that C2 technology is designed with considerations of social impact, the public perception of this technology can be positively influenced. Finally, presented perspective expansion will need further efforts related to the development of sustainability parameters for future traffic control.
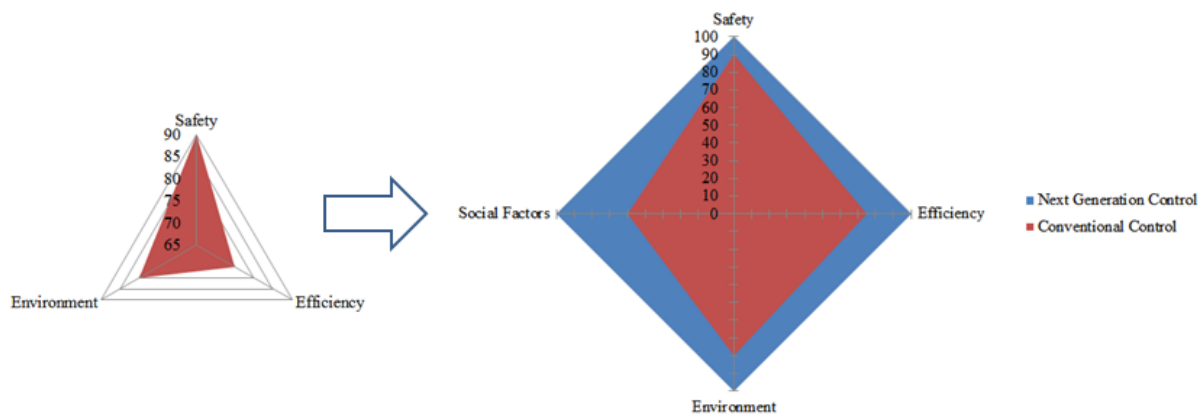
Figure 4: Comparison of goals and their fulfillment for conventional and next generation control

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Engaging relevant society's constituencies in decision-making about technology's impacts

Considering the importance of this technology, although engineers have an important role, the input for its design cannot be obtained only from engineers. Issues can easily arise if all the perspectives on the issues are not taken into consideration. In the case the design vision for C2 technology does not include wide range of experts and users, we will limit possibilities for technological development, and consequently a range for positive impacts. Consequently, there is a need for following:

- Obtain the input from other groups of experts besides engineers. Potentially, input can be obtained from economists, sociologists, ethicists, etc.

- Obtain the input from a large number of potential users with different demographic characteristics. This should provide information that can be incorporated into technology design to satisfy current needs, but also consider technological flexibility for future modifications.

Active shaping of vision

Finally, all further research efforts should not just advance knowledge, but also influence policies and ultimately alter prevailing patterns of activities and reduce travel demand while enhancing accessibility. Consequently, this is a call to our community for developing a long-term vision, which should go beyond reducing immediate negative effects of C1. In order to have a better C2 technology for a better society, we need active seeking and shaping of vision. Now is a crucial point in time to start asking ourselves as a community more "what" instead of solely "how" questions. Some of those "what" questions are:

- What are the intentions of C2 technology?
- What vision of life will this technology have?
- What will be short-term and long-term effects on human behavior?
- What will be specific social, economic, and environmental effects?

3. DEVELOPMENT OF SOCIALLY SUSTAINABLE TRAFFIC-CONTROL PRINCIPLES FOR SELF-DRIVING VEHICLES: THE ETHICS OF ANTHROPOCENTRIC DESIGN[1]

Abstract

Converging effect of communication, sensing, and in-vehicle computing technology has ensured potential to develop large-scale deployment of self-driving vehicles. Considering the potential impact of this technology, the approach for development cannot overlook needs regarding sustainability and social considerations. This paper argues that control technology for self-driving vehicles has both direct and indirect effect on fundamental human rights, and that the anthropocentric design perspective is a necessary ethical approach. Furthermore, we present current perspectives on operational principles, and relevant theoretical and empirical social implications. We conclude that there is potential for development of traffic-control principles for self-driving vehicles on the basis of mutually-advantageous cooperative production. Finally, we present several important areas for further investigation.

3.1 Introduction

Development of communication, sensing, and in-vehicle computing technology in the last two decades has enabled the development of self-driving vehicle technology [6]. Considering the converging effect of all three technologies, self-driving vehicles will be able to "perform all safety-critical driving functions and monitor roadway conditions for an entire trip" [121]. In operating a self-driving vehicle, the user will only be expected to provide destination or navigation input, and not to take over the control of the vehicle at any point during the trip. Expected positive result of this emerging technology is to improve traffic safety, by exempting the human from the task of driving [16]. In addition to potential decrease in crashes, there should be improvements to mobility for people unable to drive, improvements in fuel economy, and decrease in environmental effects from vehicular traffic [122]. However, this technology will not only lead to benefits in transportation, but it will also provide benefits to the society in general. For example, there may be reduced need for new infrastructure, productivity improvements, potential for new business models [11], and return on investment [13].

Considering the aforementioned radical technological change coming with self-driving vehicles, traffic control technology will be subject to evolution. This will potentially result in a new generation of traffic control technology – traffic control 2.0 (C2). Our argument will focus primarily on traffic control technology (devices and principles) for self-driving vehicles. The perspective we have is that operating principles directly relate to the desired functionality that should be achieved with technology. On the other side, devices should follow the development of operational principles, as their materialization. Considering these points, the argument presented here will primarily focus on operational principles for intersection control, as an important traffic control case.

3.2 The Approach for Development of Technology

A general approach to control technology for self-driving vehicle should aim at improving quality of life, through contribution to the common good of man and through nonmaleficence [123]. Considering this goal of technology, the principles of sustainability should be foundation for development approach. Sustainable development

would allow for satisfying our current needs, without constraints to fulfilling future generations' needs [124]. However, it is important here to emphasize the complexity of envisioning a sustainable technology, since notion of sustainability does not solely include environmental considerations, as often thought of. Sustainability also includes economic and social considerations, and without this holistic approach (Figure 5), sustainable development is elusive [24].

In addition to the considerations of sustainable development, we need to take into account that, despite being a technical phenomenon, technology is also a social phenomenon. Technology connects humans and their reality [125], it enables relationships between humans and the surrounding world, and it is both a terminus and creator of context for human experience [126]. Consequently, technology is not a value-neutral tool but a force that is conditioning human agency [127]. Moreover, technology is restructuring the patterns of human relationships, relationships between means and ends, body and mind, individual and community, etc. Finally, technology mediates the relation between the technology user and the consequences of her action, influences her perceptions, possibilities and assessment of the good life, etc. [128].
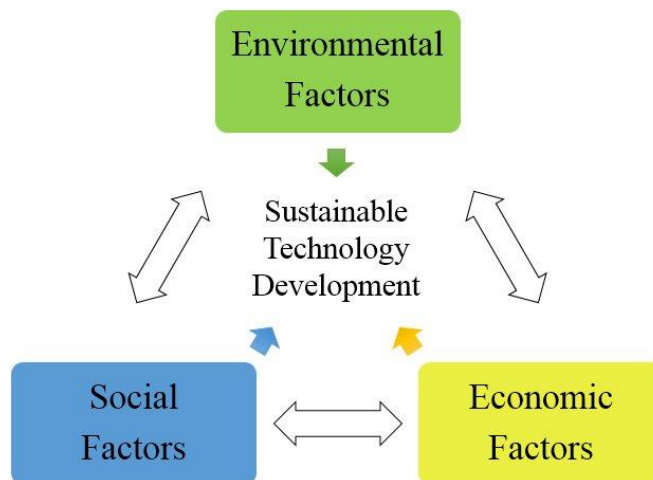
Figure 5: Sustainable technology development

Considering that technology evokes and fundamentally influences user's behavior, technology does not simply withholds some operational principles (e.g., safety, efficiency, ease of use), but it also promotes social, moral, and political values.

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Consequently, development of technology cannot include only developing some instrumental functionality, but needs to include the considerations of human actions and behavior [129, 130].

Considering the holistic perspective of sustainable development, and the perspective of technology as socio-technical phenomenon, responsibility of technology designers is going beyond technical questions. Balancing all three aspects of sustainability highly depends on the social component. Not taking into consideration behavioral considerations during the development of this technology, we will be unable to accurately predict its impact on economic and environmental impacts. Sustainable design needs to include social considerations, as another design constraint, alongside technical, economic, or environmental constraints [131].

One additional consideration is that self-driving vehicle technology is currently undergoing its foundational development, there should be a high emphasis on developing a long-term vision. This is especially important since aiming at immediate efficiencies might introduce issues of long-term risks. Moreover, as technology matures and becomes widely present, it tends to have higher social impact [132].

As a result, social responsibility for technology designers is to include relevant social concerns into their design vision [133]. Overlooking the importance of social effects would not just conflict with an approach of sustainable technological development, but would be an unethical act in itself [129, 134, 135]. This is the reason why we believe that anthropocentric approach needs to be an origin of technological development.

3.3 Critical Relations to Fundamental Human Rights

Having in mind the need for social considerations while developing technology, emerging technology of self-driving vehicle can have many undesired consequences. For example, considering the capabilities of self-driving vehicles in collecting, storing, and transmitting user-sensitive information, there will surely be user privacy concerns. However, our line of argument will try to go in a different direction than any existing

research. In order to establish a new relation between the principles of intersection operation and social concerns, we need to start by understanding traffic as a phenomenon.

1. *Traffic is a phenomenon with underlying social needs.* Traffic is a result of demand for transport of people and goods. Demand for travel from point A to point B occurs as a consequence of spatial and temporal dislocation of content. Behind all the vehicles and drivers, there are specific trip purposes that each individual needs to fulfill in specific time. People go to different places, planning to arrive at specific times, with a demand for fulfilling given purposes at the destination.

2. *Traffic involves large-scale and long-term human interactions.* The interactions in traffic include a large number of users that have dynamic character. In addition, the need for mobility and access is something that an individual has throughout a lifespan. That need changes in the nature, but rarely ceases to exist.

3. *Traffic includes strong interdependence among users.* This is especially evident at intersections. Intersections are critical points on the network, because they are trying to accommodate trips on the network in a limited space-time. The limitation originates from a physical constraint that objects, in this case users, cannot and should not occur at the same point in the intersection at the same time. Consequently, there is limited availability of dedicated time to cross through the intersection. Users are highly dependent on each other, since their positive or negative behavior affects the behavior of other users, affects the system, and as a feedback loop, each individual user too.

The underlying social needs, large-scale and long-term interactions, with interdependencies are all interrelated. It is an essential problem of differences in simultaneous users' needs. At a certain point in time, in usual traffic conditions, some people are going to a vacation destination, while some people are driving to the hospital in an emergency. Essentially, considering the sum of all these needs and their consequences, traffic becomes something that economists would recognize as system similar to a non-zero sum game [136].

We will consider these points from a standpoint of intersection's operational principle. The primary role of any intersection traffic-control principle is to prevent the occurrence of two vehicles at the same place and the same time. Prevention of simultaneous occurrence of users is performed by determining which user can enter the intersection space at every time point. This restriction can be justified by one central goal of traffic control: to protect the life and limb of roadway users. In fulfilling this goal, traffic control respects the human right to life, one of the fundamental human rights recognized by the United Nations [137].

However, as a consequence of any such operational principle, there is a delay for some of the intersection's users. This delay is a part of the extended travel time from point A to point B. This means that, in order to fully protect the fundamental right to life, there is an imposed control over another fundamental human right – the right to freedom of movement. In addition, considering that intersections are a public space and a public investment, the activity of intersection control technology is a public service. Consequently, intersections and their technology should be pure public goods [138], providing non-excludable and non-rival benefits to all people. This relates operation of traffic control technology to the human right to equal access to public service, as another fundamental human right recognized by United Nations [137].

However, the relations between traffic control principles and fundamental human rights are even more delicate than just explained. As a consequence of restricting the right to freedom of movement and the right to equal access to public service, there is an indirect effect on the fulfillment of other fundamental human rights: right to life, right to work, right to leisure, right to standard of living adequate for health, and right to education. For example, a person waiting excessively at an intersection on his way to the hospital might die. A person waiting excessively at an intersection might be late for an important job interview, leaving his family without income. On the contrary, the operation of traffic control system does not affect some other rights (e.g., the right to property and right to peaceful assembly).

As a result, the question of operating principle at the intersection, through its effect on distribution of delay among users, results in various effects on fulfillment of universal human rights, and places even higher emphasis upon the underlying social relations.

3.4 Current Perspectives on C2 Operating Principles

Knowing the importance of the relation between fundamental human rights and operating mechanism for an intersection, we will briefly analyze the current operating principles developed for controlling self-driving vehicles at intersections. These principles are grouped as follows:

1. Conventional control principles (e.g., predefined right-of-way for certain movements over other movements through the intersection [110, 112, 139], minimizing the time a vehicle takes to cross the intersection [140], maximizing traffic throughput based on waiting delay or queue length [141], or minimizing total delay [142]);

2. Queuing principles (e.g., first-in, first-out [101], adversarial queuing [35], or priority queuing [119]);

3. Economic principles (e.g., auction for time-slot [105], purchasing the time-slot from intersection manager that tries to maximize "profit" [31]).

These principles might have technical drawbacks, especially for a large-scale network implementation, where issues of scalability and redundancy are important. However, we have focused on those issues elsewhere. The point that we want to make is that these principles focus solely on technical details, not taking into consideration actual social relations. First, the fixation of a control principle on a predefined "static" rule that uses the approaching link or predefines order of service bluntly neglects individuals' needs for crossing the intersection. Similarly, determination of optimality by minimizing aggregate negative effects neglects the individual user needs. A very good example is a person waiting on the "minor" intersection approach, on his way to the emergency room, while all the people on the "main" approaches are, for example, going shopping. This situation might happen if the operational principle aims at minimizing total delay. Such principle

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does not recognize the discrepancy in individual's needs, and cannot accommodate them. These current principles do not have a mechanism to obtain or include the information on specific trip purpose and desired arrival time of each individual, and include that information in the decisions. Control decisions are externalized, and, consequently, imprecise.

Another critical point is that operational principles are developed without consideration of relations between technology and human behavior. This is especially important in the operational principles that neglect human altruistic behavior or do not limit the pursuit of self-interest. In addition, "selling" the right to use the intersection space might be considered unfair, knowing that exploiting shifts in demand by raising prices is considered unfair [43]. In addition, aiming at profit maximization without fairness will lead to resistance by people [44], especially when there is singularity of supplier with service monopoly so the "customer" cannot avoid using the service.

3.5 Theoretical Implications from Social Science Research

Considering that the previous control approaches are primarily starting from a technical standpoint, perception of technological functionality and design might be restricted with these traditional views. Bearing in mind that technology need to be developed to take into consideration human behavior, this section turns towards the findings from social science research. These points will be grouped and discussed to direct towards a potential approach when developing intersection control principles for self-driving vehicle technology.

As the first point, development of C2 technology should take into account human tendency to cooperate and divide labor, especially at a group level. In general, in every social system, people belong to one of the three groups: reciprocal types, free-riders, or pure cooperators. Reciprocal types are people who contribute to the public good as a positive function of their beliefs about others' contributions, and they usually constitute the majority in the system (around 65%). On the opposite, there are only around 20% of free-riders that by default do not try to cooperate, and around 15% pure cooperators, that

by default always try to cooperate [20, 143-145]. Consequently, the structure of the system, can nudge people towards cooperation or non-cooperation.

It has been proven that people cooperate even with non-relatives, and often in situations of extremely high risk [146]. Cooperation has evolved primarily based on the principles of reciprocity [147], but people are willing to cooperate even in the case of indirect reciprocity [148]. In addition, development of C2 should rely upon the notion that people do not always follow strict self-interest hypothesis. People do care about the outcome other people in the system receive [149]. It is not true that people at all times pursue their material self-interest and do not care about the social goals, per se, because their utility diminishes from disadvantageous inequality [145]. It is important to emphasize that people do cooperate if they perceive that other people cooperate as well, especially in the long-term relations [20]. In addition, social consideration in interaction increases as the payoff from the cooperation and the degree of the common interest increase [150, 151]. Moreover, if individuals have the opportunity to affect the relative payoffs, they take into consideration equity outcomes, even in the presence of competition [145]. Finally, considering the size of cooperation groups, there is no explicit negative effect on the cooperation as the group size increases. The relation might be positive or negative, depending on the way in which individual and group payoffs are affected or how the communication is performed [152].

However, C2 cannot solely rely upon people's intrinsic willingness to cooperate and not being strictly self-interested. It is important to remember that cooperative acts are vulnerable to exploitation by selfish partners [146]. The problems may arise due to the time delay inherent in reciprocity, or when an individual does not (equally) contribute to the creation or maintenance of a shareable benefit or good. When public good is free for overusing, individuals or groups will usually overuse it. This problem is known as the "tragedy of the commons" [153]. Furthermore, operational principle of C2 should avoid the assurance problem [154]. This problem exists when individuals are better off if they follow the same minimal standard, but are second best off if, in the case when there are defectors, they join the defectors rather than continue to follow the standards. On the opposite, individuals are worst off if there are defectors but they do not join them.

Without the external incentive (e.g. reputation, punishment, etc.) this cooperation might not be stable.

As an important point, C2 should incorporate the opportunity to build reputation in time [148]. The previous research shows that individuals respond differently in instances of anonymity versus instances where reputation building is possible [20, 155]. After a certain time, each individual begins to perceive herself as dependent on the others, and realizes that exploiting the others is hopeless. The notion of the future contact in the long term system results in the sense of dependence on the other's good will, which consequently leads to the goal of achieving mutual cooperation in the present [148, 156]. On the opposite, refusing to help the others in the system changes one's social status [20]. In addition to building reputation, C2 necessitates a structure that will prevent too many defectors from receiving the benefits of long-term cooperation. Individuals should/ought to realize the undesirable consequences of free riding through the established sanctioning system [157-159] and social pressure [160]. Moreover, development requires that people are willing to provide a sanctioning system, as a part of the public good [20]. Moreover, humans often care strongly about fairness and they are prepared to punish others who deviate from a fair principle, even at a personal cost [161] in order to maintain stable cooperation [145]. A good example is altruistic punishment, when individuals punish free riders that negatively deviate from the cooperation standard [20, 162].

3.6 Empirical Implications

Besides considering theoretical implications, public opinions are important to investigate, since they can significantly influence the direction and pace of technology development. This is consequently important for the development of self-driving vehicle technology, which is already facing some negative preconceptions. For example, one previous survey [14] has shown that 75% of respondents think they can drive a car better than a computer could, and the same percentage answered they would not trust a driverless car to take their children to school.

To supplement traditional technology development approaches, we have investigated public concerns related to social aspects of traffic control technology for self-driving

vehicles. Survey included 239 responses, the majority from United States. There were 56% male, and 44% female respondents, born in the range from 1933 to 1993. In one question, respondents were asked to describe their understanding of the term "better intersection control technology". The responses focused on "smarter" devices that adjust to the current traffic situation, technology that is efficient, economical, fuel-efficient, safer, causing less pollution and noise, or broad improvement suggestions (e.g., roundabouts). Respondents also mentioned the need for better education and understanding of human behavior, better rules and better enforcement, as well as technology that includes moral factors (e.g., providing fairness and general satisfaction).

These results show us that existing traffic control technology shapes respondents' perceptions about improved technology, since they most frequently refer to the examples from conventional technology. Conventional principles restrict the awareness of the needs for some of the users. However, people have expressed consideration for a "common good", and consideration for fairness, in a sense that no one should wait very long time at an intersection. In general, respondents have stated the opinion that whatever the "better technology" may be, it is not currently implemented.

In the next question, respondents were asked to estimate the impact of traffic control technology on their needs, grouped according to Maslow's hierarchy of needs [163]. Majority of respondents (58%) have identified the relation to the need for safety (e.g., security of body, security of employment, security of resources, security of health, security of property). However, 15% and 14% of respondents identified relation to esteem (e.g., self-esteem, confidence, respect for others, respect from others, etc.) and self-actualization (e.g., morality, creativity, problem solving, lack of prejudice, etc.), respectively. In the following questions, when presented with specific choices, respondents recognized the effect of traffic control technology on safety, travel time, environment, but also on human emotions and land use implications.

However, when respondents were presented with a question on relation between human rights and traffic control, they recognized the effect on human rights (especially right to life and right to work) and commented on relation between human rights and overall

quality of life. Finally, when asked for what trip purpose they would accept waiting at the intersection, considering that the traffic was set up to benefit all the users, only 8% of respondents answered they would accept waiting while going to the hospital, and only 14% of respondents answered the delay would be acceptable while going to a job interview. Conclusively, respondents have shown that the relative importance of the delay depends on the trip purpose.

In final questions, when asked if they would support paying for the right-of-way at intersection, only 3% of respondents answered positively. However, majority of people (62%) would be willing to pay higher price for a self-driving vehicle technology that will protect human rights (e.g., by ensuring an individual receives the right-of-way in urgent situations). A point to underline is that majority of people (77%) thought that it would be beneficial to publicly decide on the mechanism for assigning the right-of-way at intersections. Finally, majority of people (66%) would provide support (political, financial, and social) for including social considerations into the development of control technology for self-driving vehicles.

3.7 Paradigm Shift through Anthropocentric Design

Besides the sole broadening and diversification of social appraisal of technology by amplifying social impact, we need to consider designing technology in such a way that the responsibility of the end user is enhanced instead of limited. Considering theoretical and empirical implications, C2 can rely on human's tendency to cooperate, divide labor, and not be self-interested, in addition to a modifiable structure with communication, reputation-building, and sanctioning system. All these points can establish a structure that enables long-term and large-scale cooperation, while enhancing the end-user responsibility. Consequently, traffic, as a socio-physical phenomenon, will be to the mutual advantage of individual users.

In this structure, users will restrict their liberty in the ways necessary to yield advantages to users in need, while having the identical right to similar acquiescence on the part of those who benefited from their submission. Today, person A gives the right-of-way to person B since person B is having an emergency, while tomorrow person B gives the

right-of-way to person A, in the opposite case. From this perspective, a regulative framework with a contractually defined structure will impose an ordering of conflicting claims. Moreover, parties are not to gain from the cooperative labors of others without doing their fair share.

Undertaking this paradigm shift would develop traffic control as a fair system of social cooperation, where parties gain in the long term. The premise here is that the gain to the person who needs help far outweighs the loss of those required for helping him/her. In addition, assuming that the chances of being the beneficiary are not much smaller than those of being the one who must give aid, especially during an individual's lifespan, the principle is clearly in the interest of all the parties. Furthermore, the premise is that the publicly known principles of fairness are enough to bind those who take advantage of it – not just to accept it, but also to maintain it. The mutually-acknowledged and publicly-known interests would be enforceable as self-imposed by all the parties. There is a prima facie duty of fair play if the parties accept to act in accordance with the principles while knowingly accepting their benefits. This duty, as a feedback loop, would support the structure by rewarding the members for contributing to the common good. In addition, through the increase in understanding, the people will appreciate the mutual benefits of establishing fair social cooperation. The assumption is that the parties would recognize there is no need to violate the rules to protect personal interests, and they are able to recognize one another's good faith and desire for justice. Finally, this would reduce the wish to advance personal interests unfairly to the disadvantage of others. The resulting paradigm shift will try to achieve technological development so that traffic becomes a *large-scale, long-term, social phenomenon with a high degree of cooperative automation, functioning as a system for mutually-advantageous cooperative production.*

3.8 Recommendations for Further Investigations

From the previous sections, we recognize a need for perspective shift in the approach to self-driving vehicle technology design. This sections will present some of the recommendations for further investigations for development of self-driving vehicle technology.

Expanded design horizon

As an important point to highlight is not narrowing down the design horizon for the self-driving vehicle technology. This primarily includes attempting to take into consideration a complete range of relevant impacts, by determining what are concomitant cultural or social losses of new technology [164]. As a result, there is a need for a proactive approach to technology development in relation to values. An example of one of the similar approaches is identified as Value Sensitive Design [165-167]. The focus of this design approach is on deliberately incorporating moral values into technological design, while meeting traditional design criteria. The augmented list of technical criteria would go beyond conventional considerations, to include values that people consider important to life. Morally better designs would come through iterative conceptual, empirical, and technical investigations [166]. Finally, some of the essential questions that this iterative design approach would need to answer are as follows:

1. What are the intentions of self-driving vehicle technology design?
2. What social values will this technology promote?
3. What vision of life will this technology support?
4. What will be the short-term and long-term effects on human behavior?

Expanded decision-making constituencies

Having in mind the potential impacts of this technology, although engineers have an important role in the design, decision power should not be concentrated solely in a small group of experts, especially if they are influenced exclusively by corporate interests. There is a need to engage all relevant societal constituencies in decision-making about technology development. Allowing for decision space where individuals can decide what is the good life for them, could result in redesign that supports democratic self-management for future development [165, 166]. Providing space for reflective vision and critical conversations would provide essential understanding of the relevant values and their function in lives of people and groups. On the contrary, in cases when the design vision of C2 technology does not include wide range of users, there is the danger of

limiting possibilities for technological development, and consequently limiting a range of positive impacts.

Development of social justice framework

Knowing that the operation of the traffic control system relates to some of the fundamental human rights, this technology consequently relates to the distribution of advantages and disadvantages originating from those rights. Hence, this becomes an issue of social justice - a structure or framework for distribution of advantages and disadvantages in a society, which includes certain rules for distinguishing what is just and what is not [168]. Fairness is already considered as an important social value in designing technology [169]. However, the discussion on the social justice framework needs to become an integral part of the self-driving vehicle technology development. Conclusively, the design perspective requires ethical reflections, as some of the engineering fields have already recognized [170-174], along with similar consideration for transportation planning practices [175, 176].

Evaluation of technological development trajectories

It is inevitable that this revolutionary technology will result in countless novel opportunities, for which well though ethical policies might not be developed [132]. Consequently, there is a need to project and assess all the possible variations in development through constructive technology assessment [177]. In order to develop different development trajectories, there is a potential in using Ethical Delphi [178], crowdsourcing [179], and agent-based modelling techniques [180] to obtain large-scale and long-term interactions in different development trajectories.

3.9 Conclusion

Since the introduction of internal combustion engine and microprocessor technology, transportation has not faced a potential technological impact of this scale. Self-driving vehicle technology is bound to revolutionize transportation, and probably our societies as well. In our research approach, we have tried to aim beyond resolving immediate negative effects, but to take into consideration the long-term impact on society that this

technology might have. First, this is specifically related to the notion of common humanity, through our cross-generation responsibility for sustainable development of technology. Moreover, the standpoint for technological development considers that technology is a socio-technical phenomenon. Consequently, decisions related to design of technology cease to be solely technical decisions, but they tend to have direct social implications. We cannot lack the conscious reflections on the morals in technology, because it shapes the context of humans as moral agents and consequently it shapes humans themselves.

On the contrary, current development approaches do not place human into the center of attention. Focusing solely on technical details, there is a danger of "tunnel vision" in design of technology. These approaches neglect the features of traffic as a phenomenon, and they do not consider relations to human behavior and attitudes. Moreover, the very fact of missing references on relations between social impact and traffic control technology supports the notion that the mindset of the current generation of traffic engineers was never directed towards investigating social effects of technology under their purview.

In order to develop an expanded vision, we consider that the ethical approach requires anthropocentric perspective. We start from considerations of human needs, represented as fundamental human rights, in a relationship to operating principles for intersections. Human rights are selected as the most fundamental in hierarchy of values, and common to all humanity. In addition, theoretical and empirical investigations have determined the potential for technological development with social considerations included. This developmental approach also has potential for positive influence on public perception of the technology itself. Finally, our starting point for development is envisioning traffic as large-scale, long-term, social phenomenon with a high degree of cooperative automation, functioning as a system for mutually-advantageous cooperative production.

However, this vision leaves several points to highlight in the further development. First, there is a need for a framework of justice incorporated into technological design, which will guide the distribution of benefits and burdens from the new technology. Second, we

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highlight the Value Sensitive Design, as a formidable force which can help us in reflecting on ethical aspects in advance of technological development. Further investigations require the need for constructive technology assessment, which would involve discussions between different interest groups, interdisciplinary approach, and agent-based modelling. Hopefully, this research will be a useful addendum to a more comprehensive inquiry of relation between humans and self-driving vehicle technology.

4. ENGINEERING SOCIAL JUSTICE IN TRAFFIC CONTROL 2.0?

Abstract

This paper is focusing on the approach for designing traffic control systems so that they instantiate just social relations. First, this paper will start by examining if the question of social justice applies to traffic control technology. Second, the paper will explain the need to raise the point of justice in traffic control technology now. Paper than continues by introducing one of the leading frameworks for social justice. This framework is used as a model to develop a series of general desiderata and constraints on evaluating justice of traffic control systems. Furthermore, paper will consider if the conventional control satisfies the established perspective of social justice. For this argument, this paper will also present the core principles of conventional traffic control. Finally, paper outlines a vision of justice for C2, and shows how ethical design desiderata and constraints could be implemented in a next-generation traffic control system, with enabled end-user responsibility.

4.1 Introduction

The combination of increasing transportation demand and changing travel patterns will present increasingly daunting challenges for development of traffic control technology. Perhaps the most obvious challenge is *sustainability*: how to serve current needs and interests without compromising the ability of future generations to fulfil their needs [18, 181]. A less obvious challenge is to design traffic control systems so that they instantiate just social relations. This paper will focus on that neglected challenge.

First, we will start this paper by examining if the question of social justice applies to traffic control technology. Second, we will explain the need to raise the point of justice in traffic control technology now. We continue by introducing one of the leading frameworks for social justice. This framework will be used as a model to develop a series of general desiderata and constraints on evaluating justice of traffic control systems. Furthermore, we will consider if the conventional control satisfies the established perspective of social justice. For this argument, we will also present the core principles of conventional traffic control. In addition, we outline a vision of justice for C2, and will show how ethical design desiderata and constraints could be implemented in a next-generation traffic control system.

The main question – how should we engineer social justice into the new system – is of great importance, and is something that cannot be answered in this paper solely. However, the intention of this paper is to initiate a discussion on this question by providing a certain perspective for technological development framework.

4.2 The Need for Considerations of Social Justice in Traffic Control

As a general approach, development of traffic control technology should aim at improving quality of life, through contribution to the common good of man and through nonmaleficence [123]. During technology development, engineers should make an effort to serve the public interest, with regard for safety, health, and public welfare, while actively preventing conditions that are threatening to life, limb, or property [182-184]. In

addition, engineers should improve the understanding of technology, its appropriate application, and potential consequences [185]. From these standpoints, the question of justice in traffic control can easily appear trivial or too abstract. We are not required to give way on the road to those of higher status. Moreover, someone waiting in a traffic queue is likely to feel annoyed rather than morally indignant. After all, no one is malevolently inflicting the traffic jam on someone else. However, this appearance is misleading.

In order to understand the perspective of social justice and traffic control, we need to understand the objectives of traffic control. In this argumentation, we will focus primarily on traffic control of intersections. The perspective we have is that operating principles directly relate to the desired functionality that should be achieved with technology. On the other side, devices should follow the development of operational principles, as their materialization. Considering these points, the argument presented here will primarily focus on operational principles and outcomes of intersection control. In addition, our consideration for technological development will include devices, practice, theory, and accompanying rule of law.

The purpose of traffic control device, with accompanying principles for its use, is to promote highway safety and efficiency by providing for the orderly movement of all road users [186]. Some of these devices have static principles, as a four-way stop sign, which always operates using the combination of first-come first-serve and right-hand side (or left-hand side) rules. On the contrary, traffic signals allow or forbid the movement of the user at a specific intersection point at specific point in time [99]. The red signal indication restricts your movement as long as it is active and the green signal is not. Accordingly, all the intersection control technology operate through an accompanying rule of law. However, what makes the difference on the control objective is the operating principle(s) for traffic control at an intersection.

The primary objective of any intersection traffic-control principle is to prevent collisions between intersection users. Prevention of simultaneous occurrence of users is performed by determining which user can enter the intersection space at every time point. This

restriction can be justified by one central goal of traffic control: to protect the life and limb of roadway users. In fulfilling this goal, traffic control respects the human right to life, one of the fundamental human rights recognized by the United Nations' Universal Declaration of Human Rights [137].

However, as a consequence of any intersection operational principle, there is a delay for some of the intersection's users – upon simultaneous arrival, some users have to wait for other users to cross the intersection. At this point, it is important to emphasize social dimension of traffic as phenomenon. Traffic, as evidently physical phenomenon, is a manifestation of simultaneous social needs. At a certain point in time, in usual traffic conditions, some people are going to a vacation destination, while some people are driving to the hospital in an emergency. Traffic also includes large-scale and long-term interactions and interdependencies among users. We participate in traffic as users throughout our lifetime and we depend on the other users in traffic (e.g., our place in the queue is determined by other users too). Therefore, controlling traffic becomes a question of balancing simultaneous users' needs. As a result, the question of operating principle at the intersection, through its effect on distribution of delay among users, results in various effects on fulfillment of universal human rights, and places even higher emphasis upon the underlying social relations.

The delay introduced by traffic control is a part of the extended travel time between two points in space. This means that, in order to fully protect the fundamental right to life, there is an imposed control over another fundamental human right – the right to freedom of movement. The effect of traffic control systems on the right to free movement has already been identified [49]. In addition, considering that intersections are a public space and a public investment, the activity of intersection control technology is a public service. Consequently, intersections and their technology should be pure public goods [138], providing non-excludable and non-rival benefits to all people. A good example of failure to protect this right is a non-functional detector that does not send a signal if someone is waiting at the intersection's approach. That person does not have equal access to the intersection as users on other approaches. This relates operation of traffic control

technology to the human right to equal access to public service, as another fundamental human right recognized by United Nations [137].

However, the relations between traffic control principles and fundamental human rights are even more delicate than just explained. As a consequence of restricting the right to freedom of movement and the right to equal access to public service, there is an indirect effect on the fulfillment of other fundamental human rights: for example, right to life, right to work, right to leisure, right to standard of living adequate for health, and right to education. For example, a person waiting excessively at an intersection on his way to the hospital might die. A person waiting excessively at an intersection might be late for an important job interview, leaving his family without income.

Considering that these rights are universal and fundamental for every human being, as prerequisite for carrying out life's plans, it becomes an imperative for traffic control technology not to promote unjust distribution of restrictions to these rights. When we are considering alternative traffic control technologies that all protect user safety to a high degree, ethical considerations related to other fundamental human rights become highly significant. This leads us to a question – what rights, to what extent, and in what situations should be restricted or protected. Therefore, traffic control technology needs to take into consideration questions of social justice, as a structure or framework for distribution of advantages and disadvantages in a society, including certain rules for distinguishing what is just and what is not. However, besides recognizing the need to consider social justice as an integral part of traffic control system, the next section will present why we should specifically emphasize this focus at the present moment.

4.3 The Immediate Need to Consider Questions of Social Justice in Relation to Traffic Control Technology

Considering that traffic control technology relates to questions of social justice, the next important question is why it would be beneficial to discuss justice of traffic control systems at the present moment. First, developing technology raises the prospect of radically revolutionized traffic control. Vehicles of the very near future will include

powerful computers [5, 187] and will be able to sense their surrounding environment [6]. Further, communication between vehicles (V2V) and between vehicles and infrastructure (V2I) will be enabled by implementation of Wireless Local Area Networks [3, 188]. All these technologies provide enormous opportunities for sophisticated traffic control utilizing rich real-time information. The converging effect of these technologies will enable wide-scale deployment of self-driving vehicles. This will enable enormous development in traffic control technology, thus replacing conventional control (C1) with a new generation – traffic control 2.0 (C2). In addition, this will introduce a radical change in the agent responsible for the driving, where vehicle takes over all the driving tasks from human. This intended change of agents is the driving force for developing converging effect of technology for vehicle communication, computing, and sensing. The reason is a potential to absolutely secure the right to life by removing the major cause of traffic accidents – human error [121].

Considering that C2 is currently under foundational development, the danger arises that, in the absence of an ethical framework, novel traffic control design might be shaped by private interests, to the detriment of human rights and the common good. Not taking into consideration the effects on social justice might result in unjust distribution of the potential benefits of new technology. In addition, developing traffic control technology might suffer from 'design inertia' – maintaining design assumptions that are tailored to earlier technology. Many engineering fields have already recognized the importance of ethics and social justice in designing various new technologies [170-174, 189]. For the reasons just stated, we should be sensitive to considerations of justice now, during the foundational development of new traffic control technology. The next section will present the perspective and desiderata for traffic control technology within one perspective of social justice.

4.4 Ethical Design Perspective and Desiderata for Evaluating Traffic Control Technology

In order to provide a framework for evaluation of justice in C1 system, and to discuss the foundational vision for C2, this section will outline some important points related to the

ethical framework for technological development. First, we will introduce one account of social justice. Second, we will present the relation between the operation of traffic control system and fundamental human rights, within the established social justice framework. Finally, we present desiderata introduced for evaluation of C1 and development of foundational principles for C2.

Although philosophers have developed many accounts of justice, we will focus on one of the most influential contemporary approaches: Rawls' Theory of Justice as fairness. This theory will be used as a framework for the development of traffic control technology[2]. Theory of justice as fairness is developed by philosopher John Rawls [203, 204] and is partially based on the social contract theory and partially on Kantian perspective on

[2] Despite the fact that this paper focuses on Rawlsian perspective, there are many other theoretical options. Thinking about questions of social justice originate at least from the time of Plato (427-347 BC), who emphasized the ideals of justice as essential virtue of the state rulers in his work "The Republic" [190] Plato and S. Halliwell, *The Republic* Aris and Phillips, 1988. Here, Plato has introduced the idea that justice is the result of a "well ordered" soul that would never do harm to anybody. Plato's student, Aristotle, in his work "The Nichomachean Ethics" [191] Aristotle and M. Ostwald, *Nicomachean ethics*: Bobbs-Merrill Indianapolis, IN, 1962. emphasized character over the set of rules. He argued in support of an educated individual that could apply just decisions in different cases, considering that different forms of justice are applicable for different cases. Aristotle relates justice to telos or the purpose of the social practice in question. A more specific point that Aristotle also presents is refraining from gaining some advantage for oneself by seizing what belongs to another. In the 18th century, Immanuel Kant, one of the greatest thinkers in the sphere of justice, based his perspective on justice on the concepts of universality, ultimate moral duty, and inviolability of every individual [192] I. Kant, A. W. Wood, and J. B. Schneewind, *Groundwork for the Metaphysics of Morals*: Yale Univ Press, 2002.. Kant considered that moral principles are general and universal, and they are the object of the individual's rational choice.

An important alternative theory to the Theory of Justice as fairness is utilitarianism. The main idea of utilitarianism is that the highest principle of morality is to maximize happiness for the greatest number of people, as the overall balance of pleasure over pain [193] J. Bentham, *An introduction to the principles of morals and legislation*: The Clarendon Press, 1879.. Utilitarian authors judged justice solely on the outcome of the actions, since justice is achieved if in any situation the greatest number of people achieve greatest happiness. Utilitarianism includes the concept of social cooperation, which aims to maximize happiness, but does not deal with the distribution of this sum among individuals. From the utilitarian perspective, justice is a matter of efficiency, aimed at promoting general welfare. A somewhat evolved view of utilitarianism came from John Stuart Mill [194] J. S. Mill, *Utilitarianism*: Wiley Online Library, 1863., who emphasized the principle of individual liberty. Mill assumed that people are reasonably good at pursuing their own benefit, so they should be left with the liberty of action. Therefore, the structure that protects liberty will maximize happiness.

Recent developments in the years after the introduction of Rawls' idea include other authors that have provided additional perspectives on social justice. Libertarian philosopher Robert Nozick [195] R. Nozick, *Anarchy, state, and utopia* vol. 5038: Basic Books, 1974. emphasizes the justice in initial possession and justice in transfer. In addition, Walzer [196] M. Walzer, *Spheres of justice: A defense of pluralism and equality*: Basic Books, 1983. recognizes that principles of justice are pluralistic in their form – different social goods are to be distributed for different reasons, in accordance with different procedures, and by different agents. He also emphasizes the idea that goods needs to be equally and widely shared (no monopoly principle), and that the distribution should be autonomous (no dominance principle). Dworkin considers that no human should have less than equal share of the common resources just in order that others may have more of what he lacks [197] R. Dworkin, "Why liberals should care about equality," *A Matter of Principle,* pp. 205-213, 1985.. Cohen [198] G. A. Cohen, "Where the action is: on the site of distributive justice," *Philosophy & public affairs,* vol. 26, pp. 3-30, 1997. thinks that justice requires promotion of an ethos friendly to equality, in addition to a legally coercive structure. This structure would need to prevent people from doing things by imposing barriers and deter people from doing things by ensuring that certain forms of unfermented behavior carry a penalty. Comparative allotment should be according to moral judgment Anderson [199] E. S. Anderson, "What is the Point of Equality?," *Ethics,* vol. 109, pp. 287-337, 1999. Sen, and Nussbaum [200] M. Nussbaum, "Frontiers of justice. Disability, nationality, species membership," 2007. emphasized the idea that people are entitled to different amounts of resources, simply because of their differences in the internal capacities and social situations that enable them to convert resources into capabilities for functioning [201] H. Brighouse, *Justice*. Malden, MA: Polity Press, 2004, [202] W. Kuklys and I. Robeyns, "Sen's capability approach to welfare economics," *Amartya Sen's Capability Approach,* pp. 9-30, 2005..

justice. The idea of social contract is that all the members of a society are sovereign individuals that are bound to share that sovereignty through obligations to each other [201]. Kantian principles argue that every person has inviolability that even welfare as a whole cannot override, thus denying the greatest outcome-based perspective that utilitarianism has [203]. Theory of justice as fairness is developed around a premise that principle of global efficiency cannot serve alone as a conception of justice [205]. The framework was arranged to maximize the benefits of the least advantaged in the complete scheme of equality shared by all, and based on the following two principles [204]:

1. Each person is to have an equal right to the most extensive total system of equal basic liberties compatible with the similar system of liberty for all.
2. Social and economic inequalities are to be arranged so that they are both:
   a) Attached to offices and positions open to all under conditions of fair equality of opportunity.
   b) To the greatest benefit of the least advantaged, consistent with the just savings principle;

The first principle has higher priority than the second principle, putting as the most important fact that every single individual has an inviolable set of basic rights and liberties. This principle supports the rights to judge the justice of institutions and policies, and to pursue individual conception of good, as free citizen. The second Rawls' principle relates to equality, and it consists of two parts, where first part is prior to the second part. The first part aims for fair equality of opportunity for obtaining social or economic benefits by allowing a fair chance for attaining social positions through their openness in the formal sense. For example, this means liberal equality, where everyone has an equal opportunity of education regardless of family income. The second part, based on the difference principle, focuses on the regulation of social and economic inequalities by accepting them only if they are to the greatest benefit of the least-advantaged members of

society. This is similar to the maximin principle, where the system should try to maximize the absolute minimum of the least-advantaged members of society[3].

Taking Theory of justice as fairness as a development framework, we can specify what are the rights needed to be secured by traffic control technology, according to the first Rawls' principle. As the most important point, C2 technology needs to secure primarily the right to life. Second, C2 should aim to fulfill the right to equal access of public service and the right to the freedom of movement, considering their indirect effect on fulfilment of other human rights. Following the first part of the second Rawls' principle, related to the equality of opportunity, it is important to emphasize that traffic control technology should respect the idea that all humans are born free and equal in dignity and rights. Accordingly, the fulfilment of abovementioned rights shall not relate to discrimination or social sorting based on any externally defined criteria, such as sex, race, color, ethic or social origin, generic features, language, religion or belief, political or any other opinion, property, birth, disability, age, sexual orientation, position in society, financial capabilities, or other status. Furthermore, no distinction shall be made on the basis of the political, jurisdictional or international status of the country or territory to which a person belongs, whether it be independent, trust, non-self-governing or under any other limitation of sovereignty. However, traffic control cannot completely avoid restricting freedom of movement, since this restriction is introduced to protect the right to life. This is the reason we should aim to maximize the benefit to the least advantaged users, or inverse, minimize restriction of their freedom of movement.

From the guiding principles presented above, this is an initial list of the technical desiderata developed:

1. The system needs to secure user safety by conforming to absolute safety constraints for different types of users[4]. This point relates to the fundamental right

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[3] For Rawls, the two principles constrain the choice of the basic structure of society, and are not to be applied case-by case [204] J. Rawls, *A theory of justice*: Belknap Press, 1999. Consequently, it is not clear that Rawls would count traffic control as part of the basic structure of society. However, our argument is offering a plausible *adaptation* of the Rawlsian principles to a concrete issue in engineering ethics.

to life and security, since the safety of any user cannot be violated by intentional design.

2. The system cannot reject access request to any current or potential user based on any externally defined criteria. Here we also emphasize that system should not include monetary exchange since individual's financial capability can be a limiting factor for the right to equal access.

3. The system needs to be able to accommodate all types of current or future vehicles and users and their movement needs. This point relates to the fundamental right to equal access for all system's users, especially considering the potential long-term operation of C2.

4. The system should be able to distinguish least advantaged users and minimize the restrictions on their fundamental human rights.

These are the guiding framework and ethical design desiderata for evaluating the justice of conventional control, and discussing the vision of future traffic control. At this point in our argument, we need to answer an important question – what is the consideration of social justice in conventional traffic control? In order to answer this question, we need to understand the core premises of conventional traffic control, which we will attempt in the next section.

4.5 Evaluation of Conventional Traffic Control from a Standpoint of Social Justice

In order to understand conventional traffic control, this section will explain the historical context in which modern traffic control technology was formulated, and consequent development of this technology. In addition, we will explain key operating principles,

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[4] Here, we are aware that technology can fail and consequently endanger human life. Moreover, imposed control delay for crossing the intersection has inherent, although indirect, effect on human life. However, as an evaluation and design premise, it would be unacceptable to consider the development of technology by planning for endangering the right to life.

and resulting control effects. These points will be used to evaluate the resulting effects upon social justice.

Before there was traffic control, there was traffic. Contrary to the popular belief, the need for the control of user movements through the intersection existed long before the introduction of motor vehicles [51, 206]. The congestion and safety issues, accompanied with the use of traffic control devices and access control were present even on the ancient Roman roads [45]. However, in the late 19th century, the increase in urban population [47, 48], the economic development with increasing number of users and trips [50, 206], and manufacturing of internal combustion engine vehicles [49, 51] lead to deterioration of users' safety at intersections. Besides the need to avoid collisions, traffic control devices were developed having in mind human as the acting agent responsible for driving tasks. This is the reason why they were developed to command attention, convey a clear and simple meaning, command respect, and give adequate time for response [186]. Moreover, traffic control devices were developed to reduce labor and increase safety for police officers that were initially responsible for controlling traffic at critical intersections [46, 51]. The emphasis on automated operation was later on influenced by other developmental factors (e.g., the emergence of microprocessor technology).

In addition to introducing static control rules present on most of the intersections even today (e.g., using stop sign or yield sign), one of the significant developments was the invention of illuminated traffic signal [45, 57]. This initial engineering solution for the issue of intersection control introduced separation of conflicting flows using fixed periods of displayed green/red lights to improve the safety of users. Introduction of traffic signal results in higher restriction than any other traffic control device, since traffic signal actively prohibits or allows crossing of intersection during specific time intervals [94].

Later developments in traffic signal control technology maintained original operating principle, using discrete time intervals when specific flow movements at an intersection are allowed. Further attempts to improve automated operation of traffic signal introduced cyclical repetition of time intervals for allowed movement from different intersection's approaches and coordination of operation between nearby intersections. Although the

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original traffic lights were developed for guaranteeing the safe crossing of conflicting flows of vehicles and pedestrians, the increase in traffic demand resulted in degradation of the intersections operational capability (e.g., delay). This has introduced a problem of optimal signal control system/strategy [36]. The search for this optimal strategy focused on minimizing the aggregate negative effects, such as delay (traveller utility), travel time and travel time reliability (traveller utility), stops (traveller utility), crashes (safety), fuel consumption (out of pocket cost), and emissions (environment) [70, 188].

However, the foundational constraints introduced by original traffic signal invention, make it extremely difficult for real-time solution to be implemented on traffic signal network [36]. Even the advanced traffic control technology, such as adaptive traffic control systems require human supervision during operation and do not guarantee benefits [73, 207]. Finally, even today, conventional control widely utilizes the concepts of the major and minor road, where larger amount of green time is dedicated to major approach [68, 99]. Furthermore, since vehicles on the same approach receive the same green period, this design approach assumes that all the users' trips on the same approach are of the same importance.

From this developmental perspective, we can see that the original perspective for traffic control was envisioned as a set of engineering solutions to an emerging issue of controlling traffic flow through intersections. As a consequence, the evolution of traffic control systems was constrained by the foundational premises. The result is:

1. Focus on influencing the human as the main agent of the driving process;
2. Using static rules or time-based separation of aggregated conflicting traffic flows using signal indications;
3. Determining control optimality based on aggregate effects;
4. Externalized control.

We can evaluate further the structure of the social justice system established by C1, through the Rawlsian perspective, and use this information for development of C2.

First, the fixation of a control principle on a predefined "static" rule that uses the approaching link or predefines order of service completely neglects individuals' needs for

crossing the intersection. In addition, although conventional control does sometimes distinguish between different types of users (e.g., emergency vehicle), there is no distinction between all the users or their specific needs. In C1, individual users receiving or losing benefits do not have direct and real-time input to the control process. Consequently, C1 cannot detect the least-advantaged user, does not protect the inviolability of the individual user, and does not apply different control principle to identical vehicles that have different destinations/trip purposes. To some extent, C1 behaves similar to an aristocratic justice system, where most of the time, a person from a lower rank (e.g., user "minor" intersection approach) has to yield to the person of higher rank (e.g., user approaching "main" approach). A good example is a person waiting on the "minor" intersection approach on his way to the emergency room, while several users on the "main" approach are, for example, going shopping.

C1 reflects an inadequate theory of social justice and is therefore objectionable. Justice in C1 originates from higher-order and externalized decision. The restriction of freedom of movement in conventional control is justified through the focus on aggregate effects and attempt to achieve "optimal" operation from a global standpoint. This in turn results in relying upon aggregate measurement function that is a sum of satisfactions of user's desires or effects. This assumption is assigning weight to each individual's utility function based on the benefit to the system. Resulting inequalities among individuals are justified on the ground that total disadvantages of those in one position are outweighed by the greater advantages of those in another position. This directly violates the fundamental right to equal access, again, in addition to restricting the freedom of movement as a necessary part of a control system. Finally, users are not prevented from violating the traffic signal rules, and the principles of operation sometimes even force users to violate the rules (e.g., running the red light when in emergency). This also allows for large scale user usurpation of the system that can lead to system failure. We see this situation frequently in undeveloped countries, when large number of people does not respect the signal indications so traffic signals do not have any function any more.

From the technical standpoint, the attempt of conventional control to maximize the system benefits has continuously failed since conventional control rarely achieves desired

global optimum because introduced optimization constraints/assumptions cannot be incorporated into control solution in real-time on a large-scale [36]. As a consequence of its operational principles, conventional traffic signals result in several negative effects (e.g., excessive user delay and stops, disobedience of signal indications, increase in use of less adequate routes, reduction of intersection capacity, increase in congestion, etc.) [93]. From this we can see that C1 does not eliminate negative impact on all three fundamental human rights in question. Here, we would like to emphasize that the most critical point of C1 is the failure to fully protect the fundamental right to life, since it results in increased frequency of crashes. Moreover, under the failed promise of protecting the right to life, C1 frequently violates right to equal access and right to the freedom of movement.

From all the points made in this section, C1 does not live up to a framework of justice envisioned by Rawls. Furthermore, it allows for usurpation from central control or user, while failing to maximize the expected benefits of the whole system. This concludes that C1, and its current vision, does not have a framework of justice that can fully protect fundamental human rights from Rawlsian perspective. In order to discuss some potential alternatives, next section will present a vision for C2, which includes a framework of Rawlsian justice.

4.6 A Vision for Next-Generation Traffic Control

From the analysis presented in the previous section, C1 fails to fully protect fundamental human rights. The reason are foundational conventional control principles that cannot completely protect fundamental human rights for the growing population. One of the key issues of C1 is externalized decision-making and neglect for actual user input that originates from observing traffic as solely physical phenomenon, without taking into consideration its social dimensions. Consequently, C1 principles do not recognize the discrepancy in individual's needs, and cannot accommodate them. These current principles do not have a mechanism to obtain or include the information on specific trip purpose and desired arrival time of each individual, and include that information in the decisions. Evidently, we need to develop a next-generation traffic control technology

based upon improved C1 principles, while utilizing the capabilities of in-vehicle computing, sensing, and vehicle-to-vehicle communication technologies.

Similar to conventional control, C2 should try to protect user's safety and maximize the user's benefits. In addition to preventing vehicle conflicts and avoiding putting people in danger of vehicle-to-vehicle collision, C2 will also need to protect the right to life and security in the indirect way. For example, if the user is driving another person that is having a heart attack, that vehicle should receive the right-of-way before, for example, another vehicle with the user that is going to work. The framework for introducing social justice into C2 would be based upon the framework developed by Rawls.

To develop the first technical principle, we need to be aware that traffic as a system has a large number of agents and dynamic character. This results in unpredictable and hard-to-measure disturbances, which are consequently hard to control. If we are to develop C2 by maintaining centralized control principle as in C1, we would need to have perfect information and high intelligence [208-210]. However, reality is different. Large quantity of decentralized information is hard to aggregate for automated decision-making. Contrary to the centralized, externalized conventional control, C2 should operate on the principle of decentralization. The principle of decentralization has been envisioned to have a form of hierarchical and cooperative self-organization. Self-organization is where control is transferred to the individual end-users, while enabling their control responsibility. This enables a dynamical, adaptive, and decentralized control principle based upon the relationships between the behavior of the individual agents (the microscopic level) and the resulting sophisticated structure and functionality of the overall system (the macroscopic level), where elements acquire and maintain structure without external control [211-215]. Self-organization is applicable to traffic control, since new technology can provide capability to develop it as an open system that continuously exchange information with the environment, and as a complex system that has numerous and changing elements [216]. The adaptive nature of self-organized systems results in the robustness against failure and scalability for future expansion. In addition, considering the complexity of physical manifestation that traffic as a phenomenon has, there is a need to consider macro conditions of the network. This requires introduction of hierarchical

cooperation, where vehicle agents cooperate on different network levels (e.g., intersection vs. network). As a result, introducing a hierarchical system of rules that enables cooperation is assumed to maximize the benefits from self-organization and prevent system failure.

For developing a second principle, we need to introduce several premises. First, considering that users are present in traffic throughout their lifetime, they are expected to gain by accumulating benefits in the long term. In addition, we need to assume that C2 agents will have roughly similar interests - the need to cross through the intersection. However, their needs are different. Some people are driving to a vacation, while some people are driving to the hospital in an emergency. Therefore, some need to cross the intersection before others. In order to distinguish between individuals, and protect their inviolability, C2 should use a priority principle for operation. Along with priority principle, end-user responsibility is enhanced by allowing user input and control decision-making. The key ethical principle behind priority principle is that *those who want to share justice will receive justice*. Determination of resource share will be allotted to by a *functional rule*. The priority system would allow fulfillment of every user's request *according to their strength*. Priority system should impose an ordering of conflicting claims, as a regulative framework, arranged to maximize the benefit of the least advantaged in the overall system. No request in C2 should be denied fulfillment unless a rational reason (rule) for this exists.

Although they might appear, inequalities in a C2 do not automatically represent undesirable situation. The idea is that individuals may impose a sacrifice on themselves now for the sake of greater advantage later, due to the firm long-term social agreement between the parties. In addition, these inequalities should result in the greatest benefit of the least advantaged agents and in the benefit of the whole system, since agents will cooperate under the principles of fair equality of opportunity to apply for their time to cross through the intersection.

The complete system of self-organized cooperation under priority principle should allow control decisions to be made by each individual agent at any point in time. C2 should

thus result in a fair and impartial agreement of distributed agents. The complete system is established on a contractually defined structure with publicly known principles of fairness. In this structure, users will restrict their liberty in the ways necessary to yield advantages to users in need, while having the identical right to similar acquiescence on the part of those who benefited from their submission. For example, today, person A gives the right-of-way to person B, since person B is having an emergency, while tomorrow person B gives the right-of-way to person A, in the opposite case. From this perspective, parties are not to gain from the cooperative labors of others without doing their fair share.

As a result, C2 would develop as a fair system of social cooperation, where parties gain in the long term. The premise here is that the gain to the person who needs help far outweighs the loss of those required for helping her. In addition, assuming that the chances of being the beneficiary are not much smaller than chances of being the one who aids, the principle is clearly in the interest of all the parties. Furthermore, the premise is that the publicly known principles of fairness are enough to bind those who take advantage of it – not just to accept it, but also to maintain it. The mutually acknowledged and publicly known interests would be enforceable as self-imposed by all parties. There is a *prima facie* duty of fair play if the parties accept to act in accordance with the principles while knowingly accepting their benefits. This duty, as a feedback loop, would support the structure by rewarding the members for contributing to the common good. In addition, through the increase in understanding, the people will appreciate the mutual benefits of establishing a fair social cooperation. The assumption is that the parties would recognize that there is no need to violate the rules to protect personal interests, for they are able to recognize other's good faith and desire for justice. Finally, this would reduce the wish to advance personal interests unfairly to the disadvantage of others.

In addition to fundamental rights, C2 will need to secure the stability of just institutions and their ability to endure over time [205]. In order to achieve stable operation over time, C2 needs to have framework for securing liberties and rights agreed upon by agents to constitute the structure of the system. As a result, the system would be protected from usurpation, as the attempt of any system element to endanger the inviolability of any user,

contrary to the established rules. This includes protection from central control and user usurpation. This premise further emphasizes that access to transportation systems need to be equally and widely shared, with the autonomous distribution. In addition, C2 needs to avoid situations such as a prisoner's dilemma, where the optimal user outcomes are obtained by those who cheat on the agreement, while the others keep their part of the bargain [217]. This could essentially result in a globally sub-optimal outcome where each user can expect to be cheated by another. This requires inevitable consideration of the role of user in traffic of the future.

C2 should base on the premise of enhancing the end-user responsibility, and is envisioned to emphasize the long-term and large-scale cooperation for the mutual advantage of individual users. C2 design should including behavioral considerations that can establish a just structure that enables long-term and large-scale cooperation. Consequently, C2 should use human tendency to cooperate, especially at a group level [146]. Social science research tells us that people cooperate:

- When there is direct [147] and indirect reciprocity [148];
- Because they care about the outcome other people in the system receive or because of greater social goals [145, 149];
- If they perceive that other people cooperate [20];
- If the payoff from the cooperation and the degree of the common interest increase [150, 151];
- If the structure can be modified by the agreement among members [20, 218];
- If there is more and better communication among members [20, 152];
- If there is an opportunity to build reputation [20, 148, 155];
- If there is a sanctioning system [20, 143-146, 153, 154, 157, 158, 219].

Taking into consideration the intention to have cooperative self-organization with priority principle, we will now present an example of control framework, thus furthering discussion for the vision of C2.

4.7 Next-generation Control Framework

This section will describe the framework of control mechanism in C2. The control mechanism is primarily developed for resolving conflicts at intersection, but it has potential to be expanded to any vehicle-to-vehicle interaction (e.g., lane change, platoon formation, etc.). The framework is established under the assumption of completely operational inter-vehicle and inter-infrastructure communications, in addition to in-vehicle processing and sensing power. Besides the existence of distributive computing power via wireless communications, the framework has the capability to accommodate both current and future vehicle technology, which will potentially include driverless vehicles. As a general point, C2 needs to have reasonable, justifiable, and comprehensible principles that could be applied consistently and intelligently across implementation cases. C2 should have the just state of actions that satisfy and secure individual's interests that would be satisfied and secured if all the agents had intelligently applied the principles in order to determine their actions.

In order to ensure the fundamental principles and vision presented in the section before, the framework will include two main components:

1. Cooperative, hierarchically-distributed, self-organization among the vehicles.
2. A priority system enabling selection of priority levels by the user for each vehicle trip in the network, based on the supporting structure of non-monetary credits.

Hierarchically-Distributed Self-Organization

The system will be based on the individual application for crossing time through the intersection and individual control commands. Individual vehicles, without the influence of external controller, will perform computation of parameters, under uniform rules. Network user can potentially be slowed down or stopped (assuming acceptable deceleration distance) according to the assignment of the right-of-way. The process of vehicle cooperation can be separated into three levels. Hierarchically the lowest, but the most important procedure will be happening at the intersection. First, intersection level procedure will focus on ensuring the safety of conflicting directions through the

intersection. Furthermore, this procedure will focus on assigning the right-of-way for specific vehicles and platoons, according to their time of arrival and Individual Priority Index (IPI). IPI is the numerical representation of individual trip priority for each vehicle. The second cooperation level is the link level, where vehicles can create platoons, based on their IPI value and routes. This cooperation would be arranged through vehicle leaders at the beginning of the platoon. Each vehicle, while entering the network will be emitting a call to join a platoon with similar IPI value and appropriate route. Hierarchically the highest level would be network wide cooperation. At this level, network level cooperation, central control and individual agents will be used to disseminate information on global network events. The role of the central control would be limited to information only, and should avoid any central control usurpation. Individual users can support cooperative communication and computation for each of these levels.

Adjusted approaching trajectories that protect the environment

Considering that proposed framework would include the reduction of approaching vehicle's velocity based on its IPI for adjusting the arrival time at the intersection, this speed adjustment that vehicle performs should be optimized for environmental effects. Resulting vehicle's approaching trajectory needs to have optimized acceleration/deceleration rates and speed values to minimize all the negative effects from vehicle's emissions.

Priority System

The mechanism for assigning the right-of-way will be based upon the priorities selected by each user approaching the intersection. The priority of each vehicle will be numerically represented as IPI. IPI is consisting of two main elements: Base Priority Index (BPI) and External Factors Index (EFI). In-vehicle calculation of IPI would be performed according to universally known and uniform rules.

Base Priority Index

BPI is developed on the premises of agreement and selective sacrifice to create a system of cooperative production. The BPI will be developed on the system of virtual Priority

Levels (PL) and Priority Credits (₡), according to the idea that "those who share justice, will receive justice". In the core of the ₡ system, each user will need to determine intrinsically the absolute priority that they consider their trip has. The details of the priority credit system will be explained in the following section.

Each person choosing the priority level will have the choice of "opportunity benefit". In cases when you drive regularly on a "normal/everyday priority level" and behave properly in the system of cooperative production, you have the "opportunity benefit" to choose the higher priority level if/when needed. If a need for urgency or faster crossing through the intersection exists, then the user has the choice to apply higher priority level and receive earlier the right-of-way. For example, one person would assign "very high priority" one day, due to the emergency that trip has (e.g., trip to the hospital). The other person for the same day would assign "low priority" since the trip has leisure as a purpose. In the case when these two vehicles approach the same intersection at approximately similar amount of time, the vehicle with "very high priority" would be the first one to receive right-of-way, relative to the vehicle with "low priority". The users in this situation might have respectively inverse roles, and would achieve the identical result. This is an underlying agreement between vehicles in a system of cooperative production – person A will yield to person B today when person B needs right-of-way, under agreement that person B will yield to person A tomorrow, when person A needs right-of-way.

The PLs will be defined on the ordinal scale from where each user will select their respective PL. The initial suggestion is that this ordinal scale should have 10 levels (Figure 6). The approach is similar to the 9-point Saaty's scale based on linguistic variables for evaluating criteria used in Analytic Hierarchy Process ranking [220]. However, the actual number of PLs needs to be decided after extensive consideration of user input and social science evidence.

| 1. Extremely unimportant | 2. Very unimportant | 3. Unimportant | 4. Slightly unimportant | 5. Neutral | 6. Slightly important | 7. Important | 8. Very important | 9. Extremely important | 10. Emergency |

Figure 6: Representation of Priority Levels

External Factor Index

EFI is the second factor of IPI, and it will consider the surrounding conditions and provide additional information for calculating the IPI (vehicle dynamic characteristics, intersection geometry, queue formation, etc.). For example, if the two vehicles have the same calculated BPI value, but one vehicle (e.g. a truck) is approaching the intersection from the approach that is downhill, compared with the other vehicle (e.g. passenger vehicle) coming from the level approach, considering their breaking capabilities and road slope, truck should receive the right-of-way first.

Priority Credits

The system for distribution and management of $\mathbb{C}$ is set up following the fundamental principles of next-generation control. Special emphasis was put on protection from user's usurpation, and for enabling responsibility of each user in the cooperative system. In addition, the system needs to be stable, preventing that users remain completely without $\mathbb{C}$ and thus lose their mobility. Moreover, the system needs externality-limitation, where users with frequent trips do not routinely ran out of credits and exacerbate pollution or logistics expenses. Besides the following points presented, the final framework should be developed based on participatory design and behavioral implications.

- Initial assignment of Priority Credits

All the drivers would receive the same initial amount of regular $\mathbb{C}$. This equalization in the initial distribution should lead to equalization of opportunities for welfare (Hausman and McPherson 1996).

- Transfer of Priority Credits

A just system requires equality in transfer. Although spending/gaining of $\mathbb{C}$ will be implemented only through transfer and solely in the responsibility of the driver agent, the mechanism for spending or gaining $\mathbb{C}$ will have uniform rules for all. A mechanism for spending and gaining $\mathbb{C}$ will depend on the PL selection and interaction with other agents on the network. In order to avoid induced demand, there will be a guaranteed $\mathbb{C}$ spending

for every day/trip the vehicle interacted with other users on the network. The idea is that transfer of $\mathbb{C}$ will depend on the proportional difference between agent's PL.

- Dynamic Priority Credit Ceiling

Dynamic $\mathbb{C}$ celling would be another feature of the mechanism that would allow the increase in the initial value of $\mathbb{C}$ assigned. The $\mathbb{C}$ celling would be a maximum number of $\mathbb{C}$ that individual user can have. Dynamic $\mathbb{C}$ celling would support reputation building, since the increase in the celling would happen in the case the driver had no records of abuse of the system. However, this credit celling would have preset maximum value, so people cannot overuse the system and "collect" $\mathbb{C}$ in non-peak hours so they can use them in peak-hour traffic.

- Daily Priority Credit Limit

There is a need for a limit to the number of credits that user can accumulate in a day. This need is primarily there to prevent user usurpation through induced SDV use for aggregating $\mathbb{C}$.

- Emergency Priority Credits

Emergency Priority Credits (E$\mathbb{C}$) are intended to be used in emergency situations, and are separate from $\mathbb{C}$. The initial assignment of E$\mathbb{C}$ would be different among individuals. People with disabilities or special medical conditions should be assigned higher initial number of E$\mathbb{C}$, considering that these credits are used for emergency situations, which are more likely to happen to these people [221]. However, in order to protect against user usurpation, there should be a system for pre- and post-activation verification with penalties for misuse.

Matching to the Technical Desiderata

The complete structure presented above, consisting of a system for cooperative self-organization and a priority system, has been developed having in mind previously presented vision, based on fundamental rights, protection from usurpation, and upon a Rawlsian principles. As a final point in argument for proposed C2 framework, we present a matching between technical desiderata and features of the proposed C2 framework.

1. The system will secure absolute user safety by removing the driving task from erroneous human, and introduce control of vehicle dynamics based on the driving situation.

2. The system will not reject request from any user since access will be allowed to anyone. Consequently, all the principles described here can relate to all the users (e.g., pedestrians, bicyclists, public transportation vehicles, etc.). In addition, the system will not include any monetary exchange during operation, since priority credits are non-monetary and cannot be bought but only earned and spend in interaction with other vehicles.

3. The system is flexible to accommodate all types of current or future vehicles and users and their movement needs. This relates further to openness towards democratic participatory development of Priority System parameters.

4. The system is able to distinguish least advantaged users and is trying to fully protect their fundamental human rights.

4.8 Conclusion

Considering new technological tendencies in the communication, sensing, and in-vehicle computing fields that can enable significant development of traffic control technology, the responsibility is on transportation engineers to develop long-term vision for evolution of traffic control technology. The long-term vision for the C2 control systems, that this paper is trying to initiate a discussion on, will need to achieve a careful balance between the needs of multiple segments of population in the current and future generations [21, 22]. This paper starts with a point that the question of justice applies to the traffic control technology, since traffic control technology can affect a just distribution of advantages and disadvantages by restricting fundamental rights.

The paper then proceeds by presenting a framework for social justice developed by John Rawls, which will be used for evaluation of conventional control and developing vision for C2. Design desiderata are presented, including primarily right to life, and secondary right to equal access to public service and right to the freedom of movement. In addition, a list of technical desiderata are developed.

Historical overview shows us that traffic control technology started developing at the end of 19th century, as an engineering solution to the problem of conflicting flows of users at intersections. Therefore, this technology did not have a long-term vision included in the foundational development. This technological development at the end of 19th and in first part of the 20th century have established conventional traffic control principles as static rules and separation of aggregated conflicting traffic flows using a traffic signal, determining optimality based on minimizing aggregate negative effects, and externalized centralization. Although proving beneficial for several decades, the foundational premises of this solution are currently showing many gaps. These foundational premises have potentially reached their progressive capacity and have ultimately failed to maximize user's benefits. However, for our argument here, it is more important to emphasize that they have failed to protect user's fundamental rights.

This paper has tried to provide one vision and foundational framework for the next-generation traffic control that includes considerations for social justice. The long-term vision for the next-generation traffic control systems presented here is based upon the premise of mutually-advantageous social cooperation with a priority system, which will guarantee fundamental rights to all the users, but primarily to the least advantaged. Using the distributed but connected computing power, next-generation traffic control should protect right to life, and respect the right to freedom of movement and access, thus achieving justice as fairness.

Although moral values are considered as a constraint on technological development [222], in this case ethics is used a source of technological development by enhancing the end-user's responsibility. With the shift of the external control component to the user and consequent increase in user's responsibility, there is a potential for user usurpation. The system is suggested to establish a mechanism for preventing user usurpation in the system of long-term cooperation with payoff, reputation building, and sanctioning system.

One of the limitations is that this paper does not focus on the issues of privacy, as an important issue in this type of system that relies highly on communication and processing

of personal information. In addition, this paper only briefly touches upon the important issue of environmental sustainability. Furthermore, this paper does not delve into details regarding the specifics of the technology developed based on the proposed principles (e.g., technology for pedestrians using the intersections) or the questions of feasibility and robustness of the proposed framework. Both of these last issues will require a technical investigation.

By reaching across multiple dimensions, this research is trying to initiate a discussion for the evolving traffic control framework. With the presented perspective shift on traffic control, this paper is trying to initiate a discussion about the parameters and control principles that include social dimensions. In the case of traffic control technology, technical decisions are rarely only technical decisions, but instead they tend to have direct social implications. Finally, this is just one attempt for investigating the issue of social justice in relation to traffic control technology development. And social justice is just one value that we might care about in technology development. However, one thing is sure - when we actually start including values in traffic control technology, this will truly be next-generation technology. However, this effort might require from us to investigate some, probably more fundamental, relations in our society. Until then, a long path of questions lies in front of us.

5. SELF-ORGANIZING CONTROL FRAMEWORK FOR DRIVERLESS VEHICLES[5]

Abstract

Development of in-vehicle computer and sensing technology, along with short-range vehicle-to-vehicle communication has provided technological potential for large-scale deployment of autonomous vehicles. The issue of intersection control for these future driverless vehicles is one of the emerging research issues. Contrary to some of the previous research approaches, this paper is proposing a paradigm shift based upon self-organizing and cooperative control framework. Distributed vehicle intelligence has been used to calculate each vehicle's approaching velocity. The control mechanism has been developed in an agent-based environment. Self-organizing agent's trajectory adjustment bases upon a proposed priority principle. Testing of the system has proved its safety, user comfort, and efficiency functional requirements. Several recommendations for further research are presented.

5.1 Introduction

Intelligent autonomous vehicles are an emerging technology that will radically change the fundamental premises of future transportation systems. The development of in-vehicle computer technology, vehicle sensors, and short-range vehicle-to-vehicle and vehicle-to-infrastructure communication has provided a unique technological opportunity for development of the autonomous vehicle [6]. Vehicles today already have higher power reserves, can have more than 20 built-in microprocessors [223], and can store large amounts of data [3]. With these technological tendencies, the vehicles of the future will have computational power comparable to personal computers [5]. In addition, there is a continuous development of inter-networking technologies as an implementation of Wireless Local Area Networks (WLAN) in vehicles [188]. This technology enables communication between vehicles (V2V), and between vehicles and infrastructure (V2I), both referred to as V2X. These devices enable transfer of periodic or activated messages, that can inform the surrounding vehicles and infrastructure of e.g., speed, position, and direction of the vehicle [3].

The new computing, sensing, and communication technologies in the future vehicles will introduce significant benefits and expand the paradigm of traffic safety [224, 225]. In addition to the continuous developments in the area of safety features for driverless vehicles, the community of transportation engineers has a unique opportunity to reinvent the traffic control principles. This opportunity is especially significant considering that potentially all the vehicles will be completely autonomous in the next couple of decades.

This paper is focusing on presenting a distributed agent-based framework for self-organizing and cooperative control of driverless vehicles. The intention is to propose a next-generation control framework for intersection control of driverless vehicles. Second section of the paper provides detailed overview of the state-of-the-art research and development. Third section presents the control mechanism developed in agent-based environment. Later paper sections present findings from system testing and conclusions.

5.2 Previous Research

For almost a decade, the communities of computer science and industrial systems engineers have tried to develop novel approaches for intersection control. The first research approach for autonomous vehicle control was established in 2004 with the development of the reservation system [101]. This system bases on the interaction between vehicle and intersection manager agent through message exchange. The vehicle agents calculate time of the arrival at the intersection and then informs the intersection. This advanced "call" by the vehicle is supposed to reserve the *n* x *n* grid of the intersection. The intersection manager simulates the crossing of the intersection by the agent vehicle, thus determining the occupied grid tiles in each simulation step. The intersection manager reserves the tiles only if there are no required tile occupied by another vehicle from a previous reservation. The same core group of researchers improved the original model in the recent years and expanded it to stop controlled intersections and network control [106, 226]. The reservation system primarily bases upon first-in first-out queuing principle.

Another approach for intersection control mechanism focused on implementing economic principles. One research group focused on developing intersection control mechanism as an auction-based system [227]. This initial time-slot auction is valuation-aware, basing on the valuation $v_j(t)$ each driver agent is willing to pay if he waits t seconds less. Each driver's valuation is different, and each driver has a budget b_j. Another group of researchers proposed the development of intersection control model as economic market [228], where the right-of-way is "sold".

Among some of the most recent developments, there is a proposed system of decentralized control, which maintained the first-in first-out operating principle [115]. In addition, another recent research approach focused on controlling the approach speed of driverless vehicles under the goal of minimizing total delay of users [229]. The potential drawbacks of the control principles introduced in the previous research are threefold:

- *Centralization of the control decision.* Majority of the previous control approaches require the existence of intersection or central controller that will determine the right-

of-way for individual vehicles. The centralized control approach has already proven as sub-optimal for large transportation networks with many intersections [98]. In addition, considering the share size of transportation networks, investing in intersection controllers at each intersection can be an enormous investment. Finally, centralized approach is not utilizing the computational capabilities future vehicles will have.

- *First-in first-out operating principle*. An example for drawback of this principle is considering a case where there are n vehicles, but vehicle 1 has a conflict with all the other vehicles, while no other vehicles have conflicts with each other. If the vehicle 1 sends the request first, all the other n-1 vehicles will need to wait for that vehicle simply because of arrival time [38].

- *Competition among the vehicle agents.* Introducing competition among the agents might not always result in an optimal solution. For example, models might be very sensitive to assumptions on the auctioning order and actions' constraints [39, 40]. In addition, the auction-based system assumes that the travel budget of each drives is high enough, and that each driver bids and subsidizes his valuation per second of reduced waiting time. Realistically, it can happen that the budget is low and that a driver-assistance agent cannot afford to offer a price which corresponds to its true valuation [42].

5.3 Agent-Based Distributed Control Mechanism

The research presented here is trying to eliminate the need for centralized controller, and propose a mechanism for distributed intelligence with cooperative communication and computation performed by individual vehicles. Self-organizing control has a potential for higher computational efficiency, robustness against failure, scalability for expansion, and smaller communication capacity requirements. The framework for this next-generation control bases upon the assumption of computational intelligence in vehicles, envisioning vehicles as independent agents. Based on that, vehicle agents will be able to perform domain-oriented reasoning and adapt their own actions to changing environments [230].

The control framework is envisioned to be decomposed over many task-oriented and independent agents [231]. In addition, the framework is envisioned to have three cooperation layers: Network, Route, and Intersection. These are not control layers, since all the computation is performed in-vehicle. These layers are primarily used for cooperative inter-vehicle communication, where vehicles exchange information on their environment. At the highest hierarchical level, the central information point will disseminate information on global network events. Individual vehicles will use this information to plan routes. At the route level, depending on the selected route, vehicles will be joining cooperative platoons. This will be coordinated with vehicle leaders at the beginning of the platoon.

The most important procedure is at the intersection level, and this paper will primarily focus on describing this part of the framework. At the intersection level, vehicle agents or their respective cooperative platoons will focus on determining the right-of-way at the intersection. The self-organizing in-vehicle computation bases upon the information sensed or communicated from surrounding vehicles. The rules for assigning right-of-way will be according to their time of arrival and cooperative rules, while ensuring the safety of conflicting directions through the intersection.

Approaching trajectory adjustment

Each vehicle agent performs a continuous calculation of its approaching velocity. This continuous calculation allows for sudden changes in the vehicle's environment. The rule for resolving conflicting vehicles bases upon the Priority Level (PL) that each vehicle agent has. This PL can be determined based on vehicle occupancy, vehicle type (e.g., emergency vehicle), vehicle's dynamic characteristics (e.g., vehicle's breaking capabilities), or constraining intersection characteristics (e.g., approach grade, queuing capacity). The detailed rules for calculating PL will be presented elsewhere, considering that the focus of this paper is on presenting the distributed control framework. However, it is important to emphasize here that these rules will be uniform across all the vehicles of the same type.

PL values for individual vehicle agents are used for conflict resolution upon simultaneous arrival. This principle allows for taking into consideration the actual user characteristics, besides just serving the vehicle that arrived first. In addition, this principle can clearly distinguish vehicles with higher priority, such as emergency or public transportation vehicles. Furthermore, PL principle can allow for development of cooperative platoons of vehicles with similar characteristics on the route level.

PL principle is derived from the priority queuing principles [232]. The assumption of the model is there are N priority classes, with class 1 having the highest priority. Under this queuing discipline, a user is selected for service if it is the member of the highest priority class. However, the users within a class are selected on a first-in first-out basis. The interarrival times of users of each class and users of different classes are mutually independent, and identically (Poisson) distributed random variables.

In priority queues, the priority assignment for each class is in the increasing order of $c_i\mu_i$, with c_i being the cost of a user of priority class i, and μ_i the respective service rate. Thus, the highest priority is assigned to the user class with the highest value of $c_i\mu_i$. This PL function takes into consideration the user or vehicle characteristics mentioned above (e.g., number of occupants, emergency of the trip, etc.). However, contrary to the queuing theory approach, vehicles cannot be assigned back to queue, so the proposed model is expanded to take into consideration vehicle's approaching trajectory to the intersection. Each vehicle agent can calculate its own PL and obtain PL from the other vehicles, and thus determine the order in which vehicles should receive the right-of-way through intersection. Stepping further from the reservation first-in first-out principle, the concept of in-vehicle computation based on PL can accommodate for different user, vehicle, or intersection characteristics.

Each vehicle agent is performing a continuous calculation of its own desired velocity, to accommodate for incidents or different vehicle dynamics. This calculation is performed in-vehicle, every 1/10 of a second, based on the subject vehicle's parameters and based on the parameters communicated from the surrounding vehicles. Each vehicle agent can calculate conflicting vehicle trajectories, since it receives information from surrounding

vehicles. In addition, the vehicle has predefined information on the intersection's geometry, and consequently on conflicting areas. Conflict determination is performed based on the estimated time of arrival and estimated time of departure from the conflict zone. The underlying principle is that the rear end of vehicle with higher Pl has to leave conflict area before the vehicle with lower PL can enter the conflict area. This requires that the respective entrance and exit times (in absolute values) for conflicting vehicles need to be equal. Consequently, the adjusted velocity of the vehicle with lower PL is:

$$V_i = V_j * \frac{EnterDis_i}{ExitDis_j}$$

where:

V_i – approaching velocity of the subject vehicle

V_j – approaching velocity of the conflicting vehicle

$EnterDis_i$ – distance to entering conflict zone for the subject vehicle

$ExitDis_j$ – distance to exiting conflict zone for the conflicting vehicle

Vehicle with the highest PL will always maintain its original desired velocity, while the vehicles with the lower PL will reduce their approaching velocity accordingly (by decreasing). Vehicles are not allowed to have approaching velocity higher than the set up speed limit, that is determined based on the safety constraints of the intersection geometry. The control principle is presented on the Figure 7. This figure shows vehicle agents 1 and 3 approaching the intersection with reduced desired and real velocities. Both vehicle agents had to reduce the speed comparing to vehicle 4, which has cleared the intersection. Vehicle 4 maintained its desired velocity of 50 km/h, and crossed through the intersection in the previous time steps. The assigned right-of-way for vehicle 4 over vehicle 3, and for vehicle 3 over vehicle 1 bases upon the PL of each agent. Vehicle 1 (in blue) had a smaller PL value than vehicle 2 (in green), and this is the reason its desired speed was highly reduced. However, both vehicle agents 1 and 3 had to reduce respectively their velocity compared to vehicle agent 4.
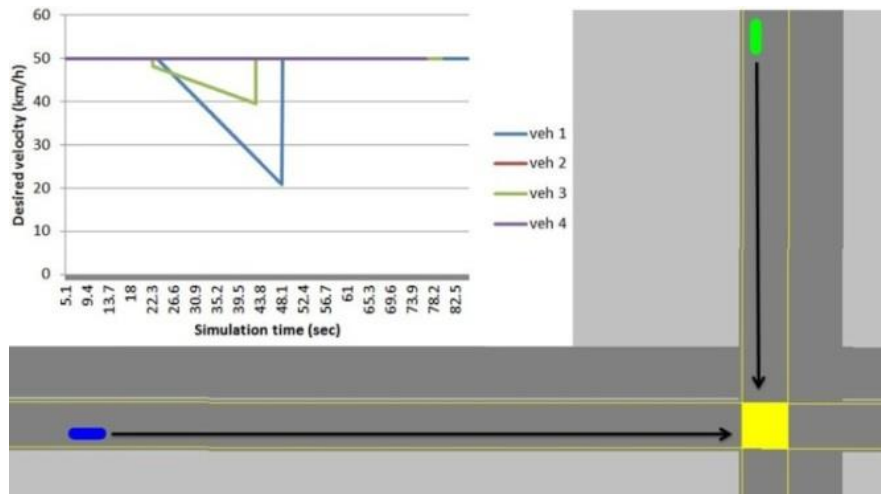
Figure 7: Reduction of agents' desired velocities based on their PL

The pseudo-code for the continuous in-vehicle computation is as following:

IF communication has been established with other vehicle agents AND WHILE agent is approaching intersection

   CALCULATE the arrival and exit time from conflict areas with other vehicle agents

     CALCULATE conflict based on arrival time AND exit time overlap

            IF conflict exists

       CALCULATE AND COMPARE Priority Levels of vehicle agents and determine individual right-of-way

          CALCULATE new desired velocity

Proposed agent-based control framework is modeled in VISSIM traffic simulation environment. The control algorithm has been implemented using application programming interface (API) [233]. The API programming has enabled a development of a fully connected environment, with each vehicle agent having identical computational capabilities, as if equipped by on-board computer. The self-organizing control logic in each vehicle agent is developed using external driver model dynamic link library (DLL). During each simulation step (10 Hz), VISSIM calls DLL code for each driver agent. VISSIM passes the current state of the vehicle agent and its surrounding agents to the DLL. Each vehicle agent DLL computes its new parameters. These new parameters are

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then sent back to VISSIM in the next simulation step for each individual agent. The information communicated and computed by vehicle agents includes the real and desired velocity, GPS coordinates, simulation time (GPS clock time), route, and Priority Level parameters. Based on these parameters for subject agent and information from the other surrounding vehicles and intersection, the DLL computes desired velocity for the subject vehicle's next time step. This calculation is performed for all the vehicle agents in the communication range around the intersection (200 m).

The control algorithm implemented in each agent bases primarily on using desired velocity as a VISSIM control variable. This variable is different from the actual agent's velocity. The desired velocity represents agent's calculated velocity, calculated based upon the right-of-way assignment for each agent. The actual agent's velocity depends upon the acceptable acceleration/deceleration rates, and fluctuations of the vehicle's engine control mechanism.

5.4 System Testing

In order to test the proposed control framework, the testing requirements were defined as:

- The system needs to secure absolute user safety
- The in-vehicle system needs to be able to operate away from the intersection proximity and allow for acceptable acceleration/deceleration of users
- The system needs to result in the greater efficiency benefits than the conventional traffic control system

The proposed control framework has been tested at an isolated intersection. The testing intersection consisted of the four single lane approaches. The approach speed limit was 50 km/h. The testing considered simultaneous vehicle arrival on each approach, with passenger vehicles. Testing was performed over 1000 simulation runs, for validity reasons. PL for each vehicle was generated randomly, using uniform distribution.

Safety Analysis

As the most important principle for any intersection control mechanism is its safety, the proposed system was developed including safety buffers in spatial and temporal calculations performed in-vehicle. To test the safety of these calculations and the

resulting vehicle trajectories, research team performed a conflict analysis using Surrogate Safety Assessment Model (SSAM) [234]. The automated conflict analysis used VISSIM-generated trajectory files for each simulation run.

The analysis focused on the frequency and character of narrowly averted vehicle-to-vehicle collisions. The parameters used included the maximum time-to-collision (TTC), maximum post-encroachment time (PET), and conflict angles. TTC is the minimum time to collision observed during the conflict, and its threshold value was set up to 1.5 sec. PET is the minimum time between when the first vehicle last occupied a position and the second vehicle subsequently arrived at the same position. The threshold for PET was set to 5.0 seconds. Both TTC and PET values were selected as the upper limits for time during potential conflicts. For example, SSAM calculated values of 0 seconds would indicate an actual collision, and any value below the threshold would signify a dangerous vehicle-vehicle conflict. In addition, conflict angle variable is an approximate angle of hypothetical collision between conflicting vehicles, based on the estimated heading of each vehicle agent. The threshold for rear angle conflict was set up to 30.0º and for crossing angle conflict to 80.0º.

After 1000 simulation runs were analyzed, no conflict values below the defined thresholds were found between vehicle's trajectories. This is an indication that developed control mechanism has fulfilled safety requirements.

Velocity Adjustment Analysis

As a second part of the testing procedure, research team has tested whether the system is able to operate by adjusting the vehicle's velocity under the acceptable users' acceleration/deceleration rates (Figure 8). The upper part of this figure shows the adjustment of desired while the lower shows the adjustment of real velocity.

Proposed framework was also tested for vehicles arriving with different approach speeds. As you can see from the Figure 9, vehicle agents 1 and 2 are arriving with 60 and 50 km/h, respectively. On the contrary, vehicle 3 and 4 are arriving with 40 km/h. However, since the PL of vehicle 3 and 4 are higher, vehicle agents 1 and 2 had successfully accommodated their approaching velocity. Figure 8 and Figure 9 are two examples of

adjusted vehicle trajectories. The mean value of desired acceleration for 1000 simulation runs was 1.2 m/s^2, while mean value of desired deceleration was 1.1 m/s^2. Maximum value was 3.5 m/s^2 for both variables. These acceleration/deceleration rates are acceptable from the user comfort perspective.
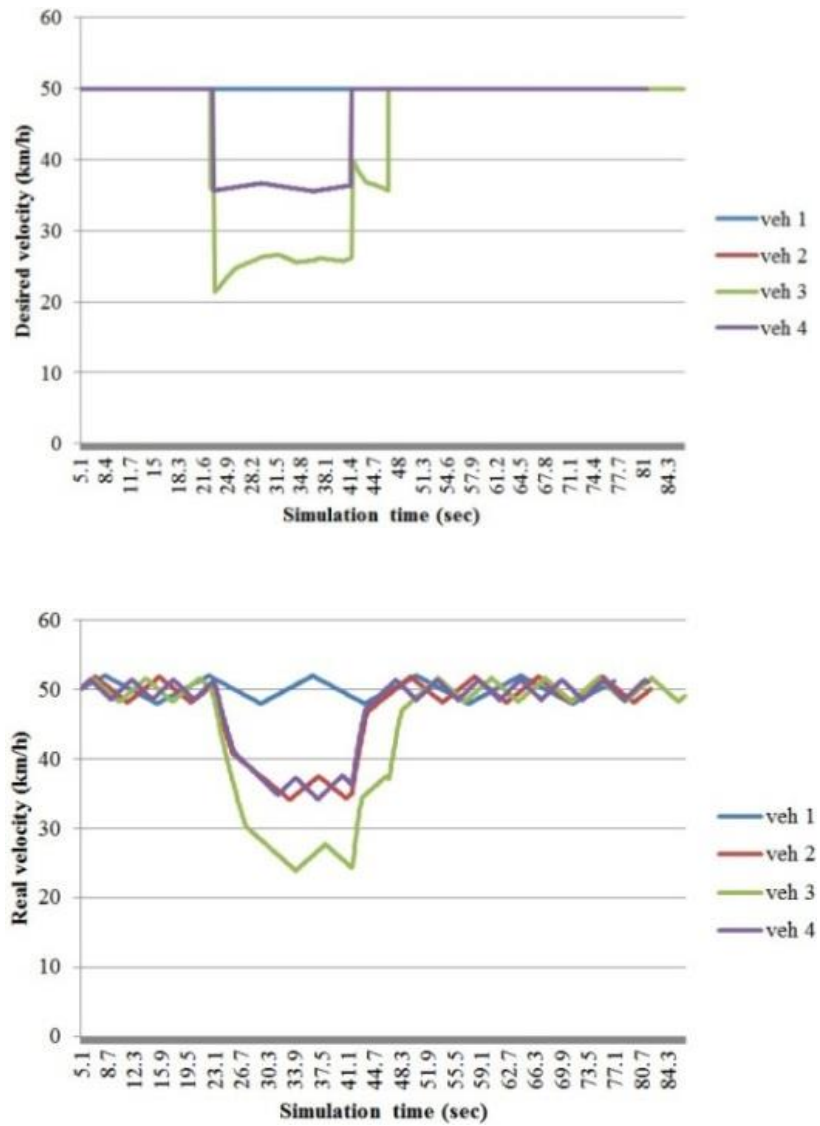
Figure 8: Desired and real velocity adjustment
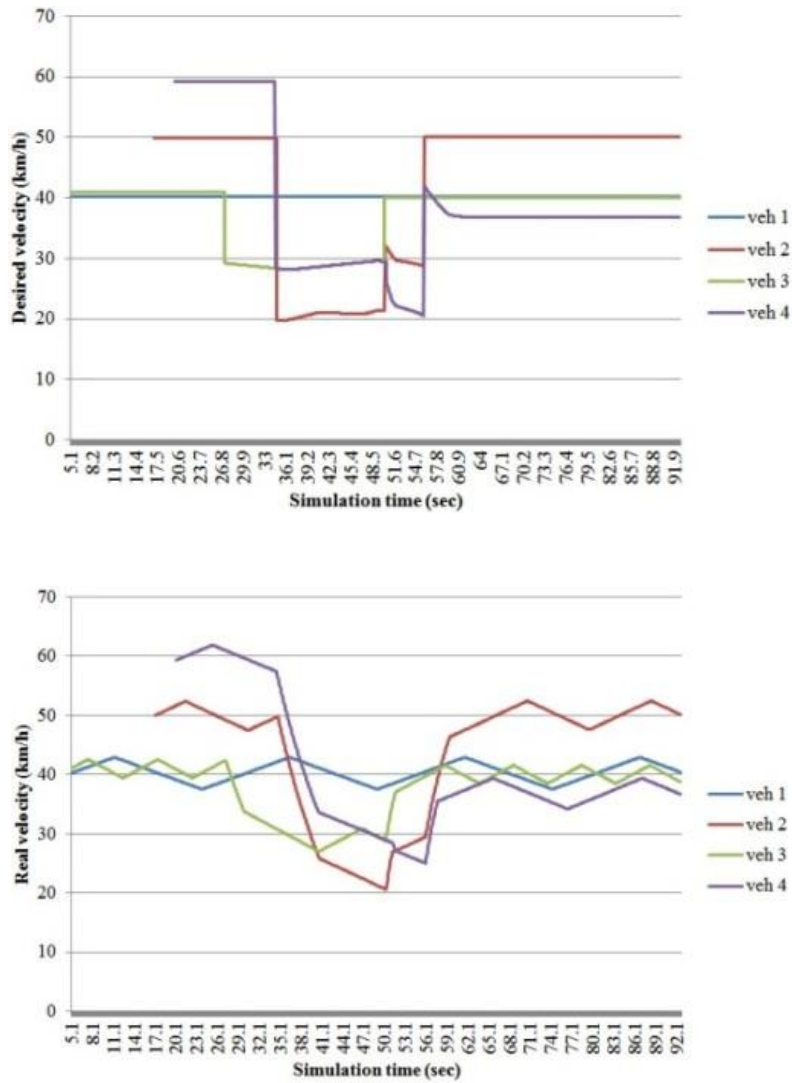
Figure 9: Velocity adjustment for different arrival profiles and PLs

Operational Analysis

In the final step of the testing procedure, research team has deployed software-in-the-loop simulation (SILS) for comparing the proposed control framework with the conventional signal control principles. SILS is a system of microscopic simulation model, virtual traffic controller and interface for communication between these two components [235]. The virtual replica of traffic signal controller used in the simulation has identical operational logic as real traffic controller software. Virtual replica consists of dynamic-link library that microscopic simulation software uses to simulate signal control logic of

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D4 2070 controller. This virtual traffic signal controller has been integrated within VISSIM microscopic simulation, with controller resolution of 10 Hz, as implemented in the actual field controllers. Simulated signalized intersection was fully-actuated, operating in Free mode. Minimum green time for each of the phases was set up to 5.0 sec and maximum green time had the value of 20.0 sec. Vehicle extension was assigned a value of 1.0 sec. Stop bar detectors are 15 m long. Intersection was also equipped with Preemption (PE) check-in/check-out detectors. PE check-in detectors were placed 200 m before the stop bar (identical with accepted communication range for the proposed framework). However, PE programming requires assignment of priority for specific PE input signal, thus limiting the flexibility of PE operation.

There were two tests of conventional control operation: regular actuated operation and PE operation. In the first case, all the vehicles arriving at the intersection are detected only by regular detectors, respecting the controller parameters. In the second case, the vehicles arriving are represented with emergency vehicles, which activate PE call 200 m before the intersection. PE has been tested as one of the state-of-the-art principles that allow signal activation ahead of the intersection.

Simulating proposed control framework, each vehicle agent had certain PL calculated based on vehicle occupancy, vehicle type, vehicle's dynamic characteristics, or intersection characteristics. Based on this PL, the desired and real arrival velocity is adjusted. All three cases (normal actuated operation, PE operation, and proposed distributed control framework) were tested under the identical vehicle, driver, and road characteristics, and using the identical random seed in all 1000 simulation runs. The following Figure 10 represents total delay experienced in all the three test cases in each of the simulation runs. The blue line represents total delay for the proposed control framework, green line is total delay for normal actuated operation, and red line is PE operation. It is observable that proposed control framework is more efficient than both of the conventional control mechanisms. In addition, proposed control mechanism can efficiently resolve conflict at the intersection, even from a standpoint of individual vehicle delay. Under proposed control mechanism, the vehicle with the highest PL experiences no delay, while vehicles with lower PL experience smaller delay compared

to conventional control. On the contrary, normal actuated operation distributes the delay over all the vehicles. Finally, PE operation allows no delay for the vehicle with the highest PE priority, but the transition out of PE significantly affects delay of all the other vehicles.
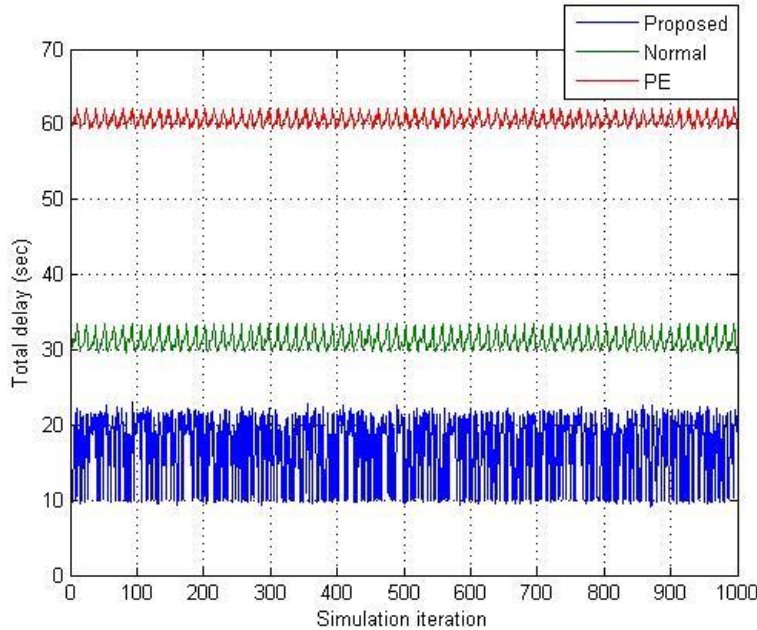
Figure 10: Total delay for actuated, PE, and proposed control

5.5 Conclusion and Future Work

Computation, inter-vehicle communication, and increased sensing capabilities will enable vehicles of the future to dynamically adapt to environment conditions and thus reduce the driver's role. Previous research focused on centralized, first-in first-out, and competition control principles. This paper is proposing a novel control framework for self-organization of driverless vehicles, building upon the potentials of distributed in-vehicle computing power connected via wireless communications. Furthermore, the framework proposed a PL system for determining the right-of-way through the intersection. The PL principle extends queuing theory to include for vehicle, user, or intersection characteristics (e.g., vehicle type, vehicle's breaking capabilities, trip type, approach

grade, etc.). In addition, the framework bases upon principles that allows cooperation among vehicles on the route or network level. Proposed control framework has proven to be without safety conflicts, with acceptable acceleration/deceleration, and reduced delay for all users. In the future, this research will be expanded to accommodate variable traffic volumes and patterns, with extending the procedure for PL calculation.

6. PRIORITY-BASED INTERSECTION CONTROL FRAMEWORK FOR SELF-DRIVING VEHICLES: AGENT-BASED MODEL DEVELOPMENT AND EVALUATION

Submitted for review

Abstract

Development of in-vehicle computer and sensing technology, along with short-range vehicle-to-vehicle communication has provided technological potential for large-scale deployment of self-driving vehicles. The issue of intersection control for these future self-driving vehicles is one of the emerging research issues. Contrary to some of the previous research approaches, this paper is proposing a paradigm shift based upon cooperative self-organizing control framework with end-user responsibility. Distributed vehicle intelligence has been used to calculate each vehicle's approaching velocity. The control mechanism has been developed in an agent-based environment. Self-organizing agent's trajectory adjustment bases upon a proposed priority principle. Testing of the system has proved its safety, user comfort, and efficiency functional requirements. Several recommendations for further research are presented.

6.1 Introduction

The development of in-vehicle computer technology [5], vehicle sensors, and short-range vehicle-to-vehicle and vehicle-to-infrastructure communication [3, 188] has created an opportunity for development of the self-driving vehicle in the next decade or two [6]. As a result, in the last level of automation, these vehicles will be able to "perform all safety-critical driving functions and monitor roadway conditions for an entire trip" [121]. In operating a self-driving vehicle, the driver will only be expected to provide destination or navigation input, and not to take over the control of the vehicle at any point during the trip.

This emerging technology is primarily expected to improve traffic safety [16]. In addition to potential decrease in crashes, there should be improvements to mobility for people currently unable to drive or improvements in environmental effects [9, 10]. However, a true potential of this technology is the potential for forming cooperative vehicle systems, where vehicles coordinate their movements with surrounding vehicles [8]. Consequently, the emerging technology of self-driving vehicle has potential for introducing a radical change in the fundamental premises of traffic control principles.

For over a decade, there have been several attempts to develop approaches for intersection control of self-driving vehicles. These previous efforts are grouped according to the underlying operating principles:

1. Queuing principles (e.g., first-in first-out [101])
2. Conventional traffic control principles (e.g., right-hand side rule [110])
3. Economic principles (e.g., auctions [105])
4. Other efforts (e.g., gap adjustment mechanism [114])

These research efforts provided a range of potential control mechanisms. However, we have to note that these mechanisms were primarily developed with a conventional perspective on traffic operations, while neglecting some important behavioral aspects. The approach presented here differs, considering that our design vision tries to include the principles of sustainable development of technology. The main idea is that control technology for self-driving vehicle should be sustainable, thus satisfying current user

needs, while not preventing the accomplishment of future user needs. Consequently, sustainable design requires inclusion of economic, environmental, and social aspects, since only a holistic approach can achieve intended results. Our starting premise is that in order to design a sustainable control technology, we need also to consider its effect on distribution of positive and negative effects on social aspects. Specific social aspects under consideration here are fundamental human rights, established by United Nations [137]. For impacting the distribution of effects upon human rights, there is a need for incorporating a social justice framework into technology design. In addition to the sustainable design vision, we are also taking into consideration the utilization of the computational capabilities in each vehicle, linking management scenarios on different network levels, and incorporating lessons learned from conventional traffic control.

Besides theoretical starting point, research team has conducted a survey to investigate users' opinions and attitudes towards operation of traffic control systems. The survey included 239 people total. 96% of subjects recognized the importance of safety at intersections, but identified other factors, especially the concern for respect and morality. In addition, when asked about the impact that traffic control systems have on their fundamental rights, 45% identified impact on right to life, 25% on right to work, and 26% identified impact on all the fundamental rights. On the contrary, only 25% of users declined impact on any of the rights. Finally, when asked if they would accept to pay for the right-of-way through the intersection, only 3% of subjects stated they would accept that.

The focus of this paper, aside from theoretical and empirical foundation of control framework, is on presenting a distributed agent-based model for self-organizing and cooperative intersection control of self-driving vehicles. Second section of the paper provides a description of the background for control framework development. Third section presents the control mechanism developed in agent-based environment. Later paper sections present findings from system testing, conclusions, and recommendations for further investigation.

6.2 Framework Background

Principles of Social Justice

The notion of social justice in this research is introduced through the theory of Justice as Fairness, developed by philosopher John Rawls [205]. In essence, Rawls developed his theory as a regulative framework, based on the two principles [204]:

1. Each person is to have an equal right to the most extensive total system of equal basic liberties compatible with the similar system of liberty for all.
2. Social and economic inequalities are to be arranged so that they are both to the greatest benefit of the least advantaged, consistent with the just savings principle, and attached to offices and positions open to all under conditions of fair equality of opportunity.

The first principle above relates to liberty, while the second principle relates to equality. Rawls' notion of social justice argues that every person has inviolability that even the system welfare as a whole cannot override. Consequently, the objective of control is not solely total delay or average total delay, but also the distribution of delay among users or maximum delay. The reason for this shift in performance measures is that the consequences of delay are not the same if person is traveling to a grocery store or to an emergency room. Survey mentioned above has also identified that people would support development of technology with a focus on social justice, since only 8% stated that this approach is not important at all.

Priority System

Considering underlying social relations from traffic interactions at an intersection, the framework is envisioned as mutually-advantageous long-term and large-scale cooperation that relies upon end-user responsibility. This vision is developed as a Priority System (PS), where each individual user can select a specific Priority Level (PL) for their trip, in addition to the destination or route information for self-driving vehicle. The intention of the PS is to protect fundamental user rights, while simultaneously preventing either user or central control usurpation. As a supporting mechanism to the PS, intended to support cooperation among users, we introduce a structure of non-monetary priority credits.

Detailed rules for PL selection and user interaction will be presented elsewhere, considering that the focus of this paper is on presenting the development of the distributed control framework.

Hierarchically Distributed Control Framework

From a technical standpoint, the mechanism is envisioned as distributed intelligence with cooperative communication and computation performed by individual vehicles. Furthermore, the envisioned dynamic and adaptive nature of the framework relates to the principles of self-organization, allowing for higher computational efficiency, robustness against failure, scalability for expansion, and smaller communication capacity requirements [213, 215]. As a result, vehicle agents will be able to perform domain-oriented reasoning and adapt their own actions to changing environments [230].

Envisioned self-organization framework is expanded using principles of cooperation, in addition to individual vehicle's autonomy. The premise is that setting up individual agent's objective as cooperative versus competitive should result in improved system-wide results. The control framework (Figure 11) is envisioned to have three cooperation layers: Network, Route, and Intersection [119]. These are not control layers, since all the computation is performed in-vehicle, but are primarily used for cooperative inter-vehicle communication, where vehicles exchange information on their past and current environment.
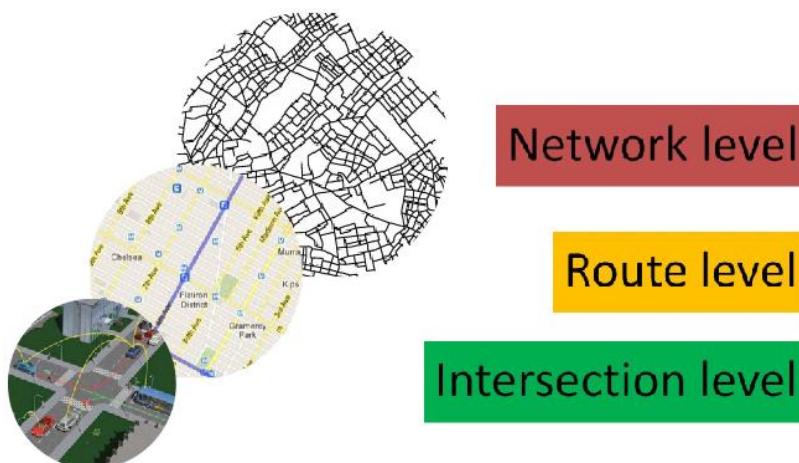

Figure 11: Hierarchical levels of cooperation

Hierarchically the lowest, but the most important procedure will be happening at the intersection. Intersection level procedure will be focused on ensuring the safety of conflicting directions through the intersection. Furthermore, this procedure will focus on assigning the right-of-way for specific vehicles and platoons, according to their time of arrival and PL (PL values for individual vehicle agents are used for conflict resolution upon simultaneous arrival). Individual vehicles, without the influence of external controller, perform computation of parameters, under uniform rules and using the information sensed or communicated from surrounding vehicles. Self-driving vehicle decides to slow down or stop (assuming acceptable deceleration distance) based on the assignment of the right-of-way. The medium cooperation level (route) enables vehicles to create platoons based on their PL value and routes in the network. Cooperation on this level would be arranged through vehicle leaders at the beginning of the platoon. Each vehicle, while entering the network will be emitting a call to join a platoon with similar PL value and appropriate route. Hierarchically the highest level (network) is envisioned so that central control and individual vehicles can disseminate information on global network events. The role of the central control would be limited only to disseminate information on global network events of high importance. This type of self-organizing decentralization will acquire and maintain structure based on the relationships between the behavior of the individual agents (the microscopic level) and the resulting sophisticated structure and functionality of the overall system (the macroscopic level).

In addition to PL being selected by the user based on the estimated urgency of the trip, this value might also depend on the vehicle occupancy, vehicle type (e.g., emergency vehicle), vehicle's dynamic characteristics (e.g., vehicle's breaking capabilities), or constraining intersection characteristics (e.g., approach grade, queuing capacity). However, it is important to emphasize that expanding PS with other information allows for taking into consideration the actual user characteristics. For example, this principle can clearly distinguish vehicles with higher priority, such as emergency or public transportation vehicles. Furthermore, PL principle can allow for development of cooperative platoons of vehicles with similar characteristics on the route level. Stepping further from the reservation first-in first-out principle, the concept of in-vehicle trajectory

computation based on PL can accommodate for different user, vehicle, or intersection characteristics.

6.3 Development of Agent-Based Model

In order to develop decentralized control approach described in the previous section, we have selected agent-based modeling (ABM) approach. This type of modeling is applicable to represent previously described framework since agents can function solely on intelligent interactions with other agents, can detect and respond to changes in the environment, can take actions towards a goal, and can learn and improve [236]. Consequently, using ABM bottom-up approach and defining interaction rules among agents should result in aggregation that establishes a system-level behavior [237]. In addition to capability for modeling decentralized control framework, ABM is useful in this case because we can realistically represent individual vehicle's application for crossing time through the intersection, and individual control commands, but also obtain emerging effects on the macro level and determine consequent influence on user's delay.

Intersection Control Mechanism

The development presented here is primarily focused on the hierarchically lowest self-organization level at the intersection. As the vehicle agent approaches intersection (Figure 12), it first encounters cooperative self-organization zone (CSZ). As the vehicle is traversing CSZ, it communicates with all the other vehicles that are simultaneously in CSZ on all other conflicting approaches. Vehicles communicate their PLs and information on their trajectories that relate to occupied space-time of the intersection. In addition, vehicle agent knows conflict areas of the intersection, predefined in the matrix form. As a result, each vehicle can calculate its own and the arrival time at each of the intersection's cells for all the other conflicting vehicles simultaneously in CSZ. Agent's action space consists in controlling approaching trajectory based on the value of acceleration.

Figure 12 presents two vehicles that are determining their space-time for crossing through the intersection from conflicting approaches. Yellow vehicle coming from the west approach has a higher PL, compared to the blue vehicle coming from the north approach.

Higher PL results in right-of-way over blue vehicle. Each of the vehicles knows which intersection cell it will occupy (rows of the matrix in the upper left corner of figure), and at what time step (columns of the matrix in the upper left corner of figure). This way, each vehicle is searching for specific space-time continuum. Once each vehicle finds the new available space-time for traversing through the intersection, each vehicle agent determines the delay (d) it will experience, added to its travel time considering the desired velocity (Figure 13). While traveling through CSZ, vehicle agent reiteratively computes dynamic parameters, depending on all agents in CSZ in each time step. This iterative computation while traveling in CSZ allows for a vehicle that just entered CSZ to obtain the right-of-way before the vehicle that is already in CSZ on the conflicting approach, if the vehicle farther away has a higher PL.

After CSZ, vehicle agent enters trajectory adjustment zone (TAZ), where it decelerates and accelerates based on the calculated space-time and delay for crossing though the intersection. TAZ is divided into two sections, first for decelerating, and the second for accelerating. The boundaries for these zones depend on communication range, speed limit through the intersection, delay distribution for deceleration or acceleration part of the trajectory, and other constraints. An example presented on Figure 12 is one potential value for the zone boundaries (200, 130, and 65 m). The objective of trajectory adjustment through deceleration and acceleration is twofold. First, it is to accommodate additional delay in the travel time. Second, it is to reach a terminal velocity for traversing the intersection, based on the movement through the intersection. In addition, the constraint is accommodating trajectory adjustment in a predefined distance before the intersection.
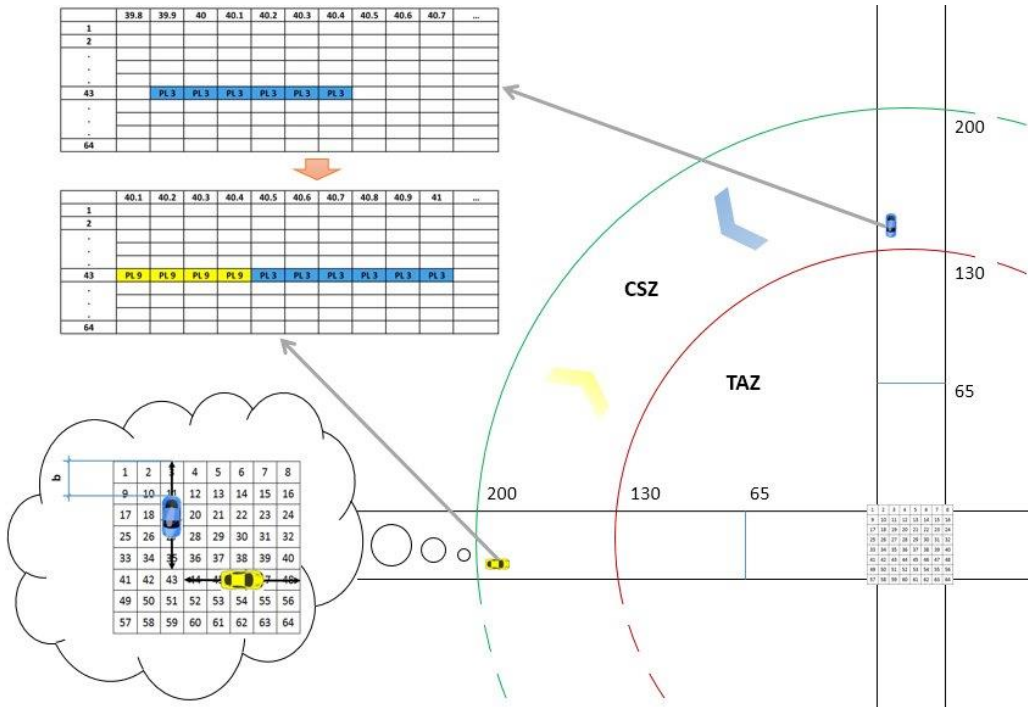
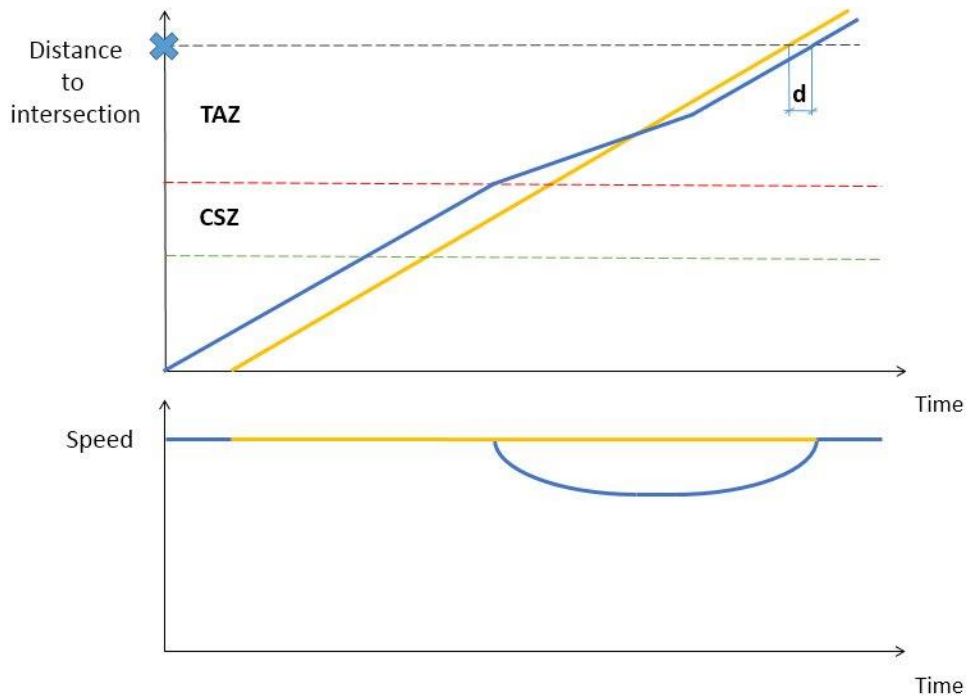**Figure 12: Self-organization structure for trajectory adjustment**

Figure 13: Example of trajectory adjustment and changes in parameters for two conflicting vehicles

The equations presented below specify vehicle's trajectory parameters during deceleration and acceleration part. Equations 1, 2, and 3 relate to the deceleration part of the trajectory, and equations 4, 5, and 6 relate to the acceleration part of the trajectory. In addition, the zone boundaries and consequent calculation of acceleration value is constrained by several parameters:

- Maximum acceptable acceleration/deceleration rate, which is 3.4 m/s^2 [238];
- Communication range around the intersection, assumed to be 200 m [239];
- Geometry of the road and intersection, which consequently constraints maximum desired velocity through the intersection (for minimum time spent in the intersection conflict area) and breaking distance on icy surface;
- Minimum velocity, taking into consideration vehicles with different dynamic characteristics;
- Safety buffers between conflicting vehicles (e.g. based on psychological effect on user);
- Allowed turning lane - in the proposed approach, vehicles will not turn from any lane in the intersection, since this is considered to increase the number of conflicts and it disables potential for platoon formation in the route cooperation level.

$$t_1 = \frac{S_1}{V_0} + d \cdot TAZ_1 \tag{1}$$

$$a_1 = -\frac{(2 \cdot V_0 \cdot t_1) - (2 \cdot S_1)}{t_1^2} \tag{2}$$

$$V_1 = V_0 + a_1 \cdot t_1 \tag{3}$$

$$t_2 = \frac{S_2}{V_0} + d \cdot TAZ_2 \tag{4}$$

$$V_2 = V_0 \ OR \ V_3 \tag{5}$$

$$a_2 = -\frac{V_2 - V_1}{t_2} \tag{6}$$

Where:

t_1 – travel time for deceleration part of the trajectory, with portion of the delay included

S_1 – distance travelled during the deceleration part of the trajectory

V_0 – desired velocity before entering VAZ

d – additional travel time required for avoiding conflicts in the intersection

TAZ_1 – delay coefficient used for distributing part of the delay to deceleration part of the trajectory (here, constant value of 0.33)

a_1 – deceleration value for the first part of the trajectory adjustment

V_1 – terminal velocity for the end of the deceleration part of the trajectory

t_2 – travel time for acceleration part of the trajectory, with portion of the delay included

S_2 – distance travelled during the acceleration part of the trajectory

TAZ_2 – delay coefficient used for distributing part of the delay to acceleration part of the trajectory (here, constant value of 0.67)

V_2 – terminal velocity for the end of the acceleration part of the trajectory, and velocity used for traversing through the intersection

V_3 – terminal velocity depending on the turning direction of the vehicle

a_2 – acceleration value for the second part of the trajectory adjustment

System Development

The proposed system is developed using application programming interface (API) in VISSIM traffic simulation environment [233]. API bases on C++ programming language. API programming allows development of vehicle agents, integrated with VISSIM using external dynamic link library (DLL). DLL code replaces the internal driving behavior for all the vehicles in the simulation, making them effectively self-driving vehicles. The vehicle agent code has three parts, performing agent's sensing, cognition, and actuation.

1. With the first function, DriverModelSetValue, each vehicle agent receives its current state and state of surrounding agents from VISSIM simulation model (e.g., acceleration, GPS coordinates, simulation time (GPS clock time), route, vehicle length, PL, etc.).

2. Second, using DriverModelExecuteCommand function, each vehicle agent computes new trajectory parameters. This function has four commands: Init (used

to initialize DLL parameters), CreateDriver (executed when vehicle enters the network), MoveDriver (executed in every time step), and KillDriver (executed when vehicle leaves the network).

3. Finally, via DriverModelGetValue function, vehicle agent sends new parameters to VISSIM simulation model. As a result, API programming allows execution during simulation initialization, for every agent initialization, and for every simulation step (simulation frequency used in this research is 10 Hz).

Vehicle agent uses several additional functions to determine the time-space for crossing through the intersection. First, vehicle agent uses Get_Delay function that is searching for available intersection time-space as the vehicle is traveling in CSZ. Available time-space is considered any continuous intersection time-space that vehicle requires based on its length and desired speed, and that is either completely unoccupied or occupied by a vehicle with lower PL. Second function, Revoke_Reservation, is activated for vehicle agent that lost its time-space from the vehicle with higher PL, and while traveling in CSZ. The vehicle with revoked reservation then needs to execute Get_Delay function again. Third function is Finalize_Reservation, which is activated as the vehicle enters TAZ. This function ensures that vehicle agent has assigned a specific time-space, which no any other vehicle agent can override as soon as vehicle is in TAZ. Finally, there is a set of functions that adjust parameters for trajectory profile as the vehicle is traveling in TAZ. A generalized pseudo-code for in-vehicle computations while vehicle is in CSZ and TAZ is as following:

WHILE agent in CSZ AND does not have reserved time-space for crossing the intersection

    CALCULATE agent's trajectory AND execute GET_DELAY

        IF conflict exist with lower PL agent

            Execute REVOKE_RESERVATION for lower PL agent

WHILE agent in TAZ

    Execute FINALIZE_RESERVATION AND adjust agent's trajectory

Model Validation

In order to validate the developed model, research team has decided to test its safety. To test the safety of self-driving vehicle trajectories, research team performed conflict analysis using Surrogate Safety Assessment Model (SSAM) [234]. In order to perform conflict analysis, SSAM uses VISSIM-generated trajectory files from each simulation run. The focus of analysis was on the frequency and character of narrowly averted vehicle-to-vehicle collisions. The parameters used were:

1. Maximum time-to-collision (TTC) - the minimum time to collision observed during the conflict, and its threshold value was set up to 1.5 sec.

2. Maximum post-encroachment time (PET) - the minimum time between when the first vehicle last occupied a position and the second vehicle subsequently arrived at the same position. The threshold for PET was set to 5.0 seconds.

3. Conflict angles - an approximate angle of hypothetical collision between conflicting vehicles, based on the estimated heading of each vehicle agent. The threshold for rear angle conflict was set up to 30.0º and for crossing angle conflict to 80.0º.

Both TTC and PET values were selected as the upper limits for time during potential conflicts. For example, SSAM calculated values below the threshold would signify a dangerous vehicle-vehicle conflict, while value of 0 seconds would indicate an actual collision. In addition, conflict angles would determine if trajectory had a rear or crossing angle conflict. After analysis of 1000 simulation runs, no conflict values below the defined thresholds were identified in vehicle's trajectories. Consequently, this is an indication that developed control mechanism and simulation model have fulfilled safety requirements.

6.4 Simulation Setup and Results

Simulation Setup

The proposed control mechanism has been comparatively tested with conventional state-of-the-art traffic signal control. Testing was performed on a four-leg isolated intersection. The test VISSIM model has desired speed of 50 km/h for through vehicles, with left-

turning velocity set to 25 km/h, as generally accepted value for left turning velocity. There were 10 simulation iterations for each volume scenario used, with different random seeds. Each volume scenario was simulated as one hour volume. The exact volumes per scenario are in the left columns of Table 4 and Table 5, showing east-west through, east-west left, north-south through, and north-south left traffic volume per hour, respectively. First 300 simulation seconds are not included in the analysis as the network loading time, and simulation would last up to 3800 seconds for measuring a broader impact of control mechanisms. Routing and lane change of the vehicles has been under control of static routing and lane change decisions, made upstream from the intersection (approximately 500 m).

Proposed control mechanism was simulated in three versions. In the first version, vehicle agents were assigned uniformly random PL. In the second, all the vehicle agents had uniform PL, and lastly, in the third version, PL was set to 5 or 10, based on the approach. Conventional traffic signal control was represented using fully actuated ring-barrier NEMA operation [56], with actuation by 15 m long stop bar detectors. NEMA phase configurations included from two to eight phases. Optimized signal timing parameters were converted into minimum and maximum green for through and left turning traffic in different volume scenarios (Table 4). Signal is operating in Free mode, without fixed cycle length, thus allowing for full signal controller flexibility (e.g., gap out, conditional service, etc.). The upper part of Table 4 shows signal timing for the case of equal traffic on all approaches, while the lower part of Table 4 shows signal timing for volume scenarios based on the premise of minor and major approaches.

Table 4: Ring-barrier controller signal timing parameters

E+W Through	E+W Left	N+S Through	N+S Left	NEMA	Min Green	Max Green 1	Max Green 2
120	30	120	30	2 ph.	5	15	N/A
240	60	240	60	2 ph.	5	20	N/A
360	90	360	90	8 ph.	5	25	15
480	120	480	120	8 ph.	8	36	15
560	140	560	140	8 ph.	8	65	20

E+W Through	E+W Left	N+S Through	N+S Left	NEMA	Min Green	Max Green 1	Max Green 2	Min Green	Max Green 3	Max Green 4
120	30	60	15	2 ph.	5	10	N/A	5	10	N/A
240	60	120	30	2 ph.	5	10	N/A	5	10	N/A
360	90	180	45	6 ph.	8	15	10	8	15	N/A
480	120	240	60	6 ph.	8	25	10	8	20	N/A
600	150	300	75	8 ph.	8	40	15	8	20	10
720	180	360	90	8 ph.	8	65	20	8	35	15
840	210	420	105	8 ph.	8	110	35	8	65	20

System measures focused primarily on delay, as the difference between the desired and actual travel time through the intersection. We have selected average and maximum delay as the representative measures. Average delay shows the overall system performance, and maximum delay is a measure of potential most significant negative impact on the individual user. Table 5 shows average and maximum delay for proposed mechanism with uniform and random PL distribution, in comparison to actuated signal control. From Table 5 we can see that, in general, proposed mechanism has lower average and maximum delay until volume distribution for scenarios five and twelve. The potential reason for this is that in the cases of higher volume, traffic signal uses queue formation and dissipation for the advantage of forming platoons and reducing gaps between vehicles, thus dissipating queue with a saturation flow rate.

Table 6 shows the results from PL assignment according to approach and volume. This test cases were intended to investigate the impact upon average and maximum delay in the case of major-minor street interaction, under opposing PL assignments and traffic volumes. The information in this table shows that in cases of higher volume with PL 10,

system operates with higher average and maximum delay for total traffic, and per PL. Basically, this implies that system operation should encourage smaller use of highest PL, since the greater the number of vehicles uses it, it has negative impact upon delay distribution. This is one of the points that will be considered for development of PL system from the standpoint of user behavior.

Finally, we have investigated the potential of vehicle agent for self-organization as the emerging effect of trajectory adjustment. Figure 14 shows a vehicle trajectory diagram for a group of east bound vehicles as they are approaching the intersection. The distance is measured from the beginning of the link. PL is randomly assigned to each vehicle agent. Space-time diagram for C2 control mechanism shows there is no specific predefined periods when movement through the intersection is allowed, but that each vehicle has its own dedicated time for crossing through the intersection. The figure shows two emerging phenomena:

1. When a platoon is randomly formed in such a way that it cannot pass through the north-south traffic, agents adapt by dispersion to fit within gaps in north-south traffic (red circle),
2. When a relatively dispersed traffic meets large gaps in north-south traffic, agents adapt by forming a dense platoon to pass through large gaps more efficiently (blue circle).
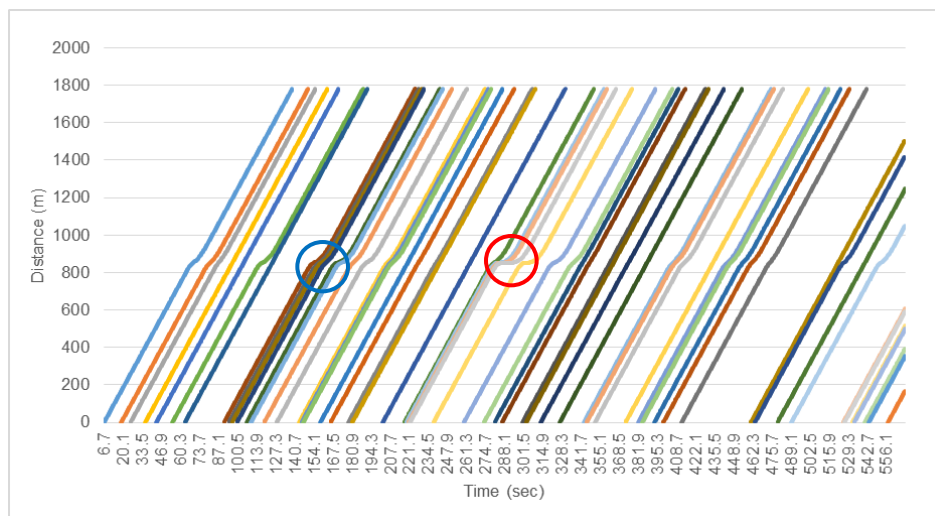

Figure 14: Vehicle agents' trajectories

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Table 5: Average and maximum delay per testing scenario

Scenario	Traffic volume				Uniform PL		Random PL		Actuated Signal	
	E+W Through	E+W Left	N+S Through	N+S Left	Average	Max	Average	Max	Average	Max
1	120	30	120	30	0.60	11.30	0.62	10.60	6.49	30.48
2	240	60	240	60	1.55	16.50	1.65	20.20	8.21	44.79
3	360	90	360	90	3.72	28.40	3.49	32.50	21.02	83.19
4	480	120	480	120	10.65	53.40	10.36	59.60	29.03	103.52
5	560	140	560	140	54.69	137.10	59.07	141.30	40.27	168.14
6	120	30	60	15	0.35	7.50	0.39	8.40	5.36	24.60
7	240	60	120	30	0.93	13.70	1.07	14.90	6.44	27.86
8	360	90	180	45	1.78	18.70	2.01	20.50	12.35	59.57
9	480	120	240	60	3.48	35.30	3.49	32.70	15.01	62.90
10	600	150	300	75	6.54	34.60	7.14	55.40	25.28	93.61
11	720	180	360	90	30.15	105.80	29.32	114.10	33.88	137.21
12	768	192	384	96	88.65	221.70	99.66	219.30	41.05	194.75

Table 6: Average and maximum delay for all vehicles, vehicles with PL 5, and vehicles with PL 10

Scenario	North/South	East/West	Total		Average		Max	
	PL 5	PL 10	Average	Max	PL 5	PL 10	PL 5	PL 10
13	135	15	0.12	4.80	0.13	0.02	4.80	2.10
14	270	30	0.30	6.80	0.32	0.06	6.80	2.10
15	405	45	0.54	11.00	0.57	0.07	11.00	4.00
16	540	60	0.82	11.80	0.87	0.14	11.80	5.90
17	675	75	1.22	14.40	1.30	0.22	14.40	7.50
18	810	90	1.97	18.90	2.08	0.75	18.90	11.80
	North/South	East/West	Total		Average		Max	
	PL 5	PL 10	Average	Max	PL 5	PL 10	PL 5	PL 10
19	15	135	0.14	5.00	0.37	0.12	5.00	4.40
20	30	270	0.30	11.80	1.30	0.24	11.80	7.10
21	45	405	0.53	11.60	2.44	0.42	11.60	9.60
22	60	540	0.85	12.10	3.47	0.65	12.10	8.90
23	75	675	1.25	15.00	4.61	0.96	15.00	11.00
24	90	810	1.87	23.20	6.12	1.48	23.20	18.60

Table 7: Average and maximum delay for increased CSZ and TAZ length

Scenario	E+W / T	E+W / L	N+S / T	N+S / L	Average Delay	Max Delay
25	120	30	120	30	0.60	11.30
26	240	60	240	60	1.54	16.50
27	360	90	360	90	3.73	28.40
28	480	120	480	120	10.56	52.60
29	600	150	600	150	174.55	375.30
30	120	30	60	15	0.34	8.10
31	240	60	120	30	0.93	13.70
32	360	90	180	45	1.77	18.70
33	480	120	240	60	3.45	35.30
34	600	150	300	75	6.52	34.60
35	720	180	360	90	30.22	108.90

Table 8: Average and maximum delay for increased safety buffer around vehicle

Scenario	E+W / T	E+W / L	N+S / T	N+S / L	Average Delay	Max Delay
36	120	30	120	30	1.13	15.40
37	240	60	240	60	3.73	25.20
38	360	90	360	90	22.58	89.30
39	480	120	480	120	214.92	427.10

We have to note two other things. Testing (Table 7) have shown that if CSZ is lengthier and starts further away from the intersection, delay has lower overall values. The reason might be that vehicles have longer time to organize and determine their best time to cross through the intersection. On the contrary, increasing the safety buffer around the vehicle consequently increases delay (Table 8), since vehicle agent requires longer space-time continuum through the intersection, thus reducing the effective time available for other vehicle agents.

6.5 Summary and Conclusion

This paper has started with the idea that self-driving vehicle technology, currently under foundational development, should include an aspect of social sustainability. The aspect of social sustainability has been introduces through a framework of social justice, originating from John Rawls' Theory of Justice as Fairness. Based on this theory, we develop a priority system, intended to protect the inviolability of each user. Priority System also introduces a paradigm shift by introducing end-user responsibility in the control process. In addition, by relying upon cooperative control of self-driving vehicles with increased potential for automation and self-organization in traffic, we propose a decentralized control approach for trajectory adjustment.

Representation of the framework relied upon agent-based modeling approach, where vehicle agents calculate their approach trajectory to the intersection. Vehicle agent performs its actions in a cooperative framework, interacting with other vehicle agents under realistic constraints, and solving control task for trajectory adjustment. The agent-based model has been programmed using C++, and integrated into VISSIM simulation environment.

Test scenarios involved random arrival of vehicles at an isolated four-way intersection. We have validated the developed control mechanism from the safety perspective. In addition, the proposed framework has showed improved benefits in different measurements of social impact. In addition, experimental results showed the potential of agents to adapt and form high performance streams on the link level, even without explicit coordination mechanism. Conclusively, this framework provides a flexible

structure for incorporating social sustainability into the development of self-driving vehicle technology.

Points for Further Investigation

The research presented here identifies several topics for further research. First, there is a need for comparison with other control approaches for self-driving vehicles, under a common testing procedure and platform. Previously, there have been limited number of research efforts that tried to compare control mechanisms, and they have shown that control principles can be heavily influenced by traffic volume (e.g., FIFO principle has been proven not to work well for high volume situations [240]). This would potentially result in varying different control approaches for different traffic situations or network routes. Second is the need for mechanism for platoon coordination on the arterials, for adjusting the vehicle speeds ahead of the intersection through multi-hop communication, without waiting for each vehicle to be in the communication range of the intersection. The mechanism could operate based on PL, where vehicles with the same PL create platoons on the network links. In addition, the framework can be potentially expanded using knowledge on human decision-making in relation to social justice. Furthermore, there is a potential for investigating optimal trajectory parameters and constraints, which can minimize fuel consumption and emissions. Finally, the ultimate intention of this research is initiating a broader discussion on the objectives and parameters for developing a sustainable future transportation systems, with a self-driving vehicle as its central column.

7. DEVELOPMENT OF TRAFFIC CONTROL FRAMEWORK FOR SELF-DRIVING VEHICLES UNDER CONSIDERATIONS OF SOCIAL JUSTICE: ENABLING END-USER RESPONSIBILITY

Submitted for review

Abstract

Advances in communication, sensing, and in-vehicle computing technology in the last two decades have enabled the development of self-driving vehicle technology. This technological development has a potential for revolutionizing traffic control technology. Contrary to some previous approaches, this research originates from investigation of ethical dimension of the design of traffic control technology. This approach is attempting to consider the development of technology from a wider, sustainable, perspective. Consequently, we will present the development of the traffic control framework that includes a perspective of social justice. First, the paper will present methodological approach and foundational considerations from one of the leading social justice theories in addition to social science considerations. This information will be used to establish some points for next generation traffic control framework. In the following two sections, the paper will present the information collected about the proposed framework based on surveys and interviews. Finally, we will present the current development status and recommendations for further research considerations.

7.1 Introduction

Advances in communication, sensing, and in-vehicle computing technology in the last two decades have enabled the development of self-driving vehicle (SDV) technology [6, 241]. Consequently, SDV will be able to perform all safety-critical driving functions and monitor roadway conditions for an entire trip, while the user will only be required to provide destination and navigation input [121]. This emerging technology promises several potential benefits:

- to improve traffic safety, by replacing less reliable human driving [63];
- to improve the mobility of people unable to drive [122];
- to mitigate the environmental impacts of automotive transportation[122];
- to more efficiently use existing roadways, and hence reduce need for new infrastructure [6].

This emerging technology will also permit significant evolution in the possible structure and mechanisms of traffic control, potentially leading to a radically different traffic control technology – traffic control 2.0 (C2). Until now, there has been several research efforts in developing traffic control mechanisms for SDVs (e.g., [101, 105, 114]). All of these previous research efforts have technical approach to development. On the contrary, this research originates from investigation of ethical dimension of the design of C2.

Ethical Design Dimensions

Initially, it may not seem obvious that traffic control contains a significant ethical dimension. However, the fundamental function of traffic control technology is to control (and hence restrict) freedom of movement in public spaces, by determining who receives right-of-way at a given time. The restriction of right-of-way is justified by one central goal of traffic control: to protect the life and limb of roadway users. In fulfilling this goal, traffic control respects the human right to life, one of the fundamental human rights recognized by the United Nations [137].

Consequently, traffic control technology restricts (as well as enables) freedom of movement. Determining the right-of-way for some vehicles implies that other vehicles have to experience delay at an intersection, and thus have longer travel time to their destination. Furthermore, roads and intersections as typically publicly-owned and maintained spaces are pure public goods [138], and should provide non-excludable and non-rival benefits to all people. This means that traffic control technology should respect rights to equal access to public services (another fundamental human right recognized by the United Nations [137]). In addition, the relations between traffic control principles and fundamental human rights are complicated by the fact that freedom of movement is often needed to fulfill other fundamental human rights, such as the right to life, the right to work, the right to leisure, the right to a standard of living adequate for health, and the right to education. For example, a person waiting excessively at an intersection on his way to the hospital might die; a person waiting excessively at an intersection might be late for an important job interview, leaving his family without income.

Considering that these rights are universal and fundamental for every human being, as prerequisite for carrying out life's plans, it becomes an imperative for traffic control technology not to promote unjust distribution of restrictions to these rights. When we are considering alternative traffic control technologies that all protect user safety to a high degree, ethical considerations related to other fundamental human rights become highly significant. This is especially related to *delay per user and per trip purpose*. Here, a question emerges – to what extent and in what situations should right to freedom of movement and right to equal access to public service be restricted or protected. Therefore, traffic control technology needs to take into consideration perspective of social justice, as a structure or framework for distribution of advantages and disadvantages in a society, including certain rules for distinguishing what is just and what is not [168].

However, these ethical dimensions could easily be neglected. For example, developing traffic control technology might suffer from 'design inertia' – maintaining design assumptions that are tailored to earlier technology. Second, the development of traffic control might be driven largely by market incentives and shaped significantly by interests

of companies producing the technology, therefore neglecting distribution of the potential effects from technology. The paper will present the development of the traffic control framework that includes a perspective of social justice. First, the paper will present methodological approach and foundational considerations from one of the leading social justice theories in addition to social science considerations. This information will be used to establish some points for C2 framework. In the following two sections, we will present the information collected about the proposed framework based on surveys and interviews. Finally, we will present the current development status and some recommendations for further research considerations.

7.2 Methodology

In addition to the importance of social justice questions, technology designers might not be aware that, like other technologies, traffic control evokes and influences user's behavior [126-128]. In addition, focusing on assessing how efficiently technology achieves its operational goals, might neglect how responsive technology is to social, moral, and political values [129, 130]. Considering that SDV technology is in its foundational stage of development, this is a crucial stage allowing us to rethink some fundamental premises and develop a sustainable technology – technology that can fulfill our current needs but not restrict the needs of the future generations [21, 22]. With this in mind, the approach presented here will be analogous to the Value Sensitive Design approach [165-167].

Figure 15 shows the methodological steps for this research. First, we start with information on existing technology (both traffic control and SDV technology), one theory of social justice, and human behavior considerations. This information is used to establish initial setup for a control framework. In the next steps, we have performed surveys and interviews. Information from these two steps are used for first iteration of system redesign. For the next steps, we suggest greater public involvement that should be followed by technological developments. Consequently, system would be in a continuous redesign loop, as represented in the lower part of the figure.
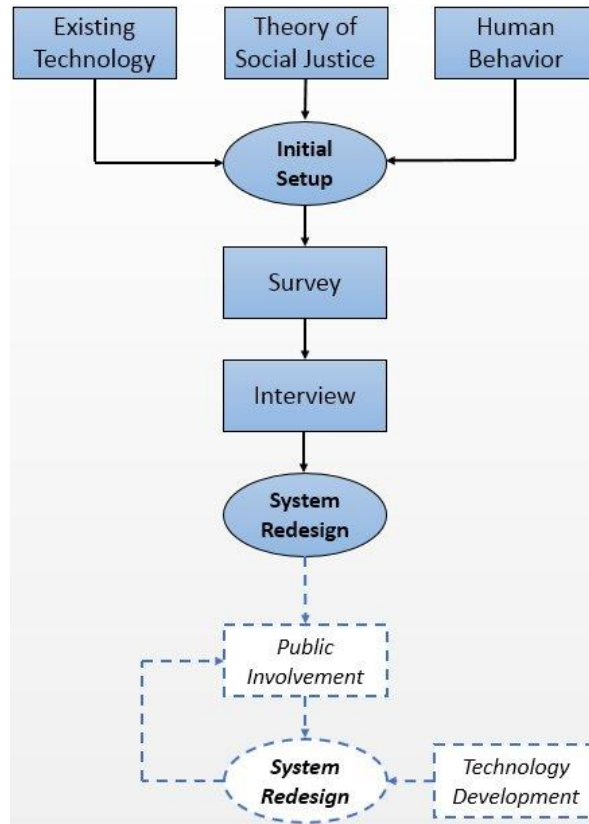
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Figure 15: Methodological steps for Priority System redesign

The Framework of Social Justice

Some engineering fields have already recognized the importance of ethics and social justice in designing various new technologies [170, 172, 173, 189]. In this research, the notion of justice is introduced through the theory of justice as fairness, developed by philosopher John Rawls [205]. In essence, Rawls developed his theory as a regulative framework, based on the two principles [204]:

1. Each person is to have an equal right to the most extensive total system of equal basic liberties compatible with the similar system of liberty for all.

2. Social and economic inequalities are to be arranged so that they are both to the greatest benefit of the least advantaged, consistent with the just savings principle, and attached to offices and positions open to all under conditions of fair equality of opportunity.

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The first principle above relates to liberty, while the second principle relates to equality. Essentially, Rawls' framework is arranged to protect the inviolability of the user and maximize the benefits of the least advantaged in the complete scheme of equally shared by all. These guiding principles have been used to structure a framework for development of new technology.

Human Behavior Considerations

Considering that technology evokes and influences user's behavior, there is a need to take into consideration behavioral considerations. These behavioral considerations originate from human tendency to cooperate, especially at a group level [146]. Social science research tells us that people cooperate:

- When there is direct [147] and indirect reciprocity [148];
- Because they care about the outcome other people in the system receive or because of greater social goals [145, 149];
- If they perceive that other people cooperate [20];
- If the payoff from the cooperation and the degree of the common interest increase [150, 151];
- If the structure can be modified by the agreement among members [20, 218];
- If there is more and better communication among members [20, 152];
- If there is an opportunity to build reputation [20, 148, 155];
- If there is a sanctioning system [20, 143-146, 153, 154, 157, 158, 219].

7.3 Initial Framework for Priority System

Considering that the inviolability of the user is the most important point in this framework, this can be translated as emphasizing the distribution of delay among individuals, and not solely emphasizing upon the total delay for the approach or intersection. In order to protect the inviolability of the user, control principles are developed to allow for greater responsibility of end-user in the control process. Enhancing end-user responsibility is envisioned to emphasize long-term and large-scale cooperation, for the mutual advantage of individual user and to support a just structure. In

addition, the framework needs to assure that there will be no usurpation of the system from central control or individual users.

The proposed framework of social justice is developed through a Priority System (PS). Using PS, a user is able to assign a Priority Level (PL) for each individual trip, besides inputting the destination for SDV. PLs are defined on the ordinal scale, ranking from the least important to the most important PL. Selection of individual PL allows control responsibility to be partially in the hands of the user, and each person choosing PL will have the choice of "opportunity benefit". In cases when a user drives regularly on a "normal/everyday priority level" and behaves properly in the system of cooperative production, you have the "opportunity benefit" to choose the higher priority level if/when needed. If a need for urgency or faster crossing through the intersection exists, then the user has the choice to use higher priority level and receive the right-of-way earlier. For example, one person would assign "very high priority" one day, due to the emergency that trip has (e.g., trip to the hospital). The other person for the same day would assign "low priority" since the trip has leisure as a purpose. In the case when these two vehicles approach the same intersection at approximately similar amount of time, the vehicle with "very high priority" would be the first one to receive right-of-way, relative to the vehicle with "low priority". The users in this situation might have respectively inverse roles in other situation, and would achieve the respectively inverse result. This is underlying an agreement between vehicles in a system of cooperative production – person A will yield to person B today when person B needs right-of-way, under agreement that person B will yield person A tomorrow, when person A needs right-of-way.

Selected PL is then used to as a numerical factor used to determine the right-of-way for the SDVs approaching the intersection. The initial proposed operational principle of PL system is similar to the priority queuing principles [232]. Priority queuing principles assume N priority classes, with class 1 having the highest priority. Under this queuing discipline, a user is selected for service if it is the member of the highest priority class. However, the users within a class are selected upon FIFO principle. The complete description of the actual traffic control principles will be presented elsewhere.

However, in order to avoid user usurpation of the PS, there has been developed a system of Priority Credits (₵), that can be gained or lost based on the PL (Table 9). In the initial assignment, each user should receive identical amount of ₵. The initial case was assumed that this should be 20 ₵. Spending/gaining of ₵ will be only through PL selection, with uniform rules for all users. Dynamic ₵ celling would be another feature of the mechanism that would allow the increase in the initial value of ₵, up to a predefined maximum value. The ₵ celling would be a maximum number of ₵ that individual user can have. Dynamic ₵ celling would support reputation building, since the increase in the celling would happen in the case when the user had no records of abuse of the system.

Table 9: Initial ₵ system in relation to Priority Levels

PL	1	2	3	4	5	6	7	8	9	10
₵	4	3	2	1	0	-1	-2	-3	-4	-5

In order to activate the highest PL, user can also use Emergency Priority Credits (E₵), which are intended to be used in emergencies, and are separate from ₵. The initial assignment of E₵ would be different among individuals. The initial suggestion is that people with disabilities or special medical conditions should be assigned higher initial number of E₵, considering that these credits are used for emergencies, which are more likely to happen to these people. However, in order to protect against user usurpation, there should be a system for pre- and post-activation verification, with penalties for misuse.

7.4 Empirical Information from Survey

Information about Survey

In order to investigate the idea of PS, the research team developed an online survey (approved by Institutional Review Board VT IRB 13-1060). The purpose of this survey was to identify user perceptions related to the effects of intersections upon social justice, and elements of moral decision-making related to the intersections as public assets. Specifically, we were are interested in knowing the opinions related to fulfilment of

individual needs and rights that can be used as a part of intersection control mechanism for SDVs. Moreover, anticipated findings included opinions on the effect of traffic control technology on individual needs, rights, decision-making within a specific framework of social justice, and willingness to pay and support emerging technology of SDVs. Survey was developed using Google Documents form, and was distributed using listservs. Participants were first asked to answer six demographic questions. After that, there were 18 questions related to the relation of social justice and traffic control technology. Moreover, participants were provided with explanations throughout the survey.

Survey had total 239 participants, 56% being male and 44% female. Respondent's age was ranging from 20 to 80 years old, with majority of respondents being people between 25 and 35 years old. Respondents were mostly white/European, but other racial groups were all present. Most of the respondents had college education, with 54% having a graduate degree, and 32% having a bachelor's degree. Greatest percentage of respondents (36%) had annual income less than $27,000. In addition, 29% had income between $27,000 and $73,000, 18% had income between $73,000 and $147,000, 5% had income greater than $147,000, and 12% preferred not to answer. Half of the respondents drive regularly on urban streets, with 34% driving regularly in suburban areas, and 16% on rural highways.

Survey Results and Interpretation

First question related to the topic of the survey was asking participants to briefly describe their understanding of the term "better intersection control technology". The answers are grouped in the following categories:

a) "Smarter" devices that adjust to the current traffic situation
b) Better education and understanding of human behavior
c) Better rules and better enforcement
d) General improvement or broad technology (roundabouts)
e) Efficient, quicker, economical, fuel efficient, safer, pollution, noise
f) Fair, feasible, moral and effective factors – everyone happy

g) Does not know

Overall, this question showed that there is a sense of "common good" among users. In addition, it showed that user's perceptions are influenced by their perception of conventional technology. Moreover, there is a sense of "fairness" in traffic, so that no one should wait very long, but also a general sense that this "better technology" is not implemented in practice. Next question was asking people to determine if traffic control technology impact the fulfillment of their needs. The list of needs was assumed according to Maslow's hierarchy of needs [242], including physiological, safety, love/belonging, esteem, and self-actualization, with specific examples for each of the needs. Survey responses show that almost all people (96%) recognize the importance of safety at intersections, but other factors are also present – especially the question of respect (26%) and morality (23%). Question number nine was asking users if driving through a red light at an empty intersection because you are late for work is a wrong action. Results show that 33% of people do not think strongly or at all that this is a wrong action. This might imply that still a significant number of people would disobey the signal indication in the case of this important trip. Question number ten was asking how important is to include principles of social justice into technology design. This question was asked early in the survey, to obtain unbiased opinion based on the following survey questions. As a result, majority of people consider that it is important to include principles of social justice into technology design, with only 8% thinking it is not at all important to include them.

Question number eleven was asking about the effect from traffic control technology on safety, travel time and environmental effects. Majority of answers identified that traffic control technology affects safety and travel time. However, only a quarter of responses identified relation to environmental effects. Other comments included frustration, anger, satisfaction, happiness, other people's safety, people's skills, and quality of a neighborhood for the people who live there. Question number twelve was related to the previous question, asking that if the respondent identified an effect on travel time, to identify relation towards fundamental human rights. Human rights listed were right to life (e.g., while traveling to the hospital), right to work (e.g., while traveling to a job interview), right to leisure (e.g., while traveling to a movie theater), right to standard of

living adequate for health (e.g., while traveling to a dentist), and right to education (e.g., while traveling to school). As a result, 75% of people think that at least one right is affected, and most often people recognize the relation to the right to life. In addition, other comments related to time usage, time planning, and life quality.

When asked under question thirteen if the user would pay to receive the right-of-way through the intersection before someone else, only 3% of respondents would directly accept to pay for their right-of-way through the intersection, with majority of those respondents being with income greater than $73,000. Last question in this group was asking if the user would accept waiting at an intersection while having different trip purposes and considering that timing was set-up to benefit all the users. From the results, we see that 19% would accept waiting while going to a hospital, 38% while going to a funeral, 32% while going to a job interview, 49% while going to a grocery store or beach, with 5% that would never and 35% that would always accept waiting. Other answers included if waiting is predictable and only in non-emergency situations. However, the wording of the question might have introduces a bias in answers, since some respondents did not relate as going to a hospital as a straightforward relation to an emergency.

For questions fifteen to seventeen, the users were asked to imagine the following scenario: "You are approaching a four-way stop intersection. At the same time, another vehicle is about to arrive to the intersection from a different street. You have a way to know a trip purpose for the person in that other vehicle. In addition, there is a mechanism for reciprocity – i.e., if you decide to let that other vehicle go through the intersection before you, you will receive the right-of-way next time in the near future." Each of the questions was then asking the respondent to imagine a specific purpose for their trip, and answer would they let the other person pass in the case that person has different trip purposes (hospital, funeral, interview, grocery store, beach). In the question fifteen, the user was asked to assume going to a vacation. As a result, 93% of respondents would let the other person pass if they are going to a hospital, 68% if the other person is going to a funeral, and 58% if the other person's trip purpose is interview. This show a clear willingness of majority to wait in important cases. In the comments, some users raised the issue of how will the system distinguish "real" emergency (life-threating event) from

other cases. In the next question, respondent had to assume his trip purpose to be going to a job interview. In this case, 92% of respondents would let the other person go if they are going to a hospital, 55% if they are going to a funeral, 23% if they are going to a job interview, 10% if they are going to a grocery store, and 6% if they are going to a beach. Comparing to previous question, there is a drop in the percentage of users that would let the other person go in the cases that are not going to a hospital. In the question seventeen, respondent had to assume their trip purpose to be going to a hospital. Consequently, there is a drop in percentage of users that would let the other person go 77%, 17%, 8%, 4%, 3%, for that user going to a hospital, a funeral, a job interview, a grocery store, and a beach, respectively. However, these percentages were determined based on the people that have selected any of the answers. On the contrary, 41% of all the participants have not selected any of the options, which implies that they would not let the other person.

For questions eighteen to twenty, respondents were asked to imagine if they could assign a Priority Level from 1 to 10 to their trip, and that number will be compared to Priority Levels of other vehicles to determine when will user receive the-right-of-way (assuming that 10 is the most important, and 1 is the least important). Moreover, the respondent was asked to imagine each individual, has a certain number of non-monetary Priority Credits that are used to select Priority Level for the trip. For question eighteen, the respondents were asked to provide examples of what the trip purpose would be when you would assign Priority Level 1 (extremely unimportant), Priority Level 5 (neutral), and Priority Level 10 (emergency). For PL 10, users assigned medical emergency (threat to life or limb), very urgent situations, late for a flight/train/bus, late for important meeting, late for daughter's wedding, church meeting, and none. For PL 5, they assigned work, school, shopping, visit friends, errands, funeral, traveling long distance, rush to help someone, late for meeting/event, errands, take/pick up child, post office, appointments, gas station, love problems, sport events, visit a sick relative, 5 min to spare, set arrival time. For PL 1, users selected leisure, vacation, groceries, going out, entertainment, social, shopping, errands, sport, dinner, gym, coffee, park, dog-park, more than 10 min to spare, and no time sensitivity. In the question nineteen, users were asked to provide their perceived PL for several trip purposes. The results are presented on the following Figure 16. From this

figure, we can see that respondents used all PLs for every trip purpose. With further investigation, we could see that there was some small percentage of people that always selected high PLs. Consequently, this means that PL system could not operate without a supporting system, such as Priority Credits.

Last set of questions started with question twenty, asking respondents how should Priority Credits be initially assigned. As a result, 24% of respondents think everybody should have the same number, 22% of respondents think that credits should be distributed to meet the basic needs of everyone, 15% of respondents think that people with disabilities should have more credits, 14% of respondents were not sure, while 12% of respondents think that credits should be distributed to produce the greatest total amount of good in the world. Other comments included people in the greatest need (e.g., pregnant woman, very sick people) and that people should earn credits by allowing other people right-of-way. Again, there is concern of how we will know people's emergencies in advance to distribute them more credits. In addition, there is a concern of central planning that might restrict freedom and if credit operation is machine's responsibility. Finally, some users have identified the need to increase awareness about basic needs of everyone. When asked if they think that the mechanism for assigning the right-of-way at the intersection for SDVs should be publicly decided, 48% of people answered affirmatively, while only 23% answered no. In addition, when asked will they be willing to pay higher price for a SDV technology that will protect your human rights (e.g., by ensuring you receive the right-of-way in urgent situations), 31% of respondents answered positively, 31% answered maybe, and 38% answered no. Finally, in question twenty three, when asked would they provide support for including social justice into the development of control technology for SDVs, 34% of people would provide political support (e.g., voting, lobbying), 42% of all the respondents would provide social support (e.g., volunteering, public discussions), and 12% would provide financial support (e.g., donation, fund-raising). These results show that majority of people are interested in providing support for development of broader vision in SDV technology.
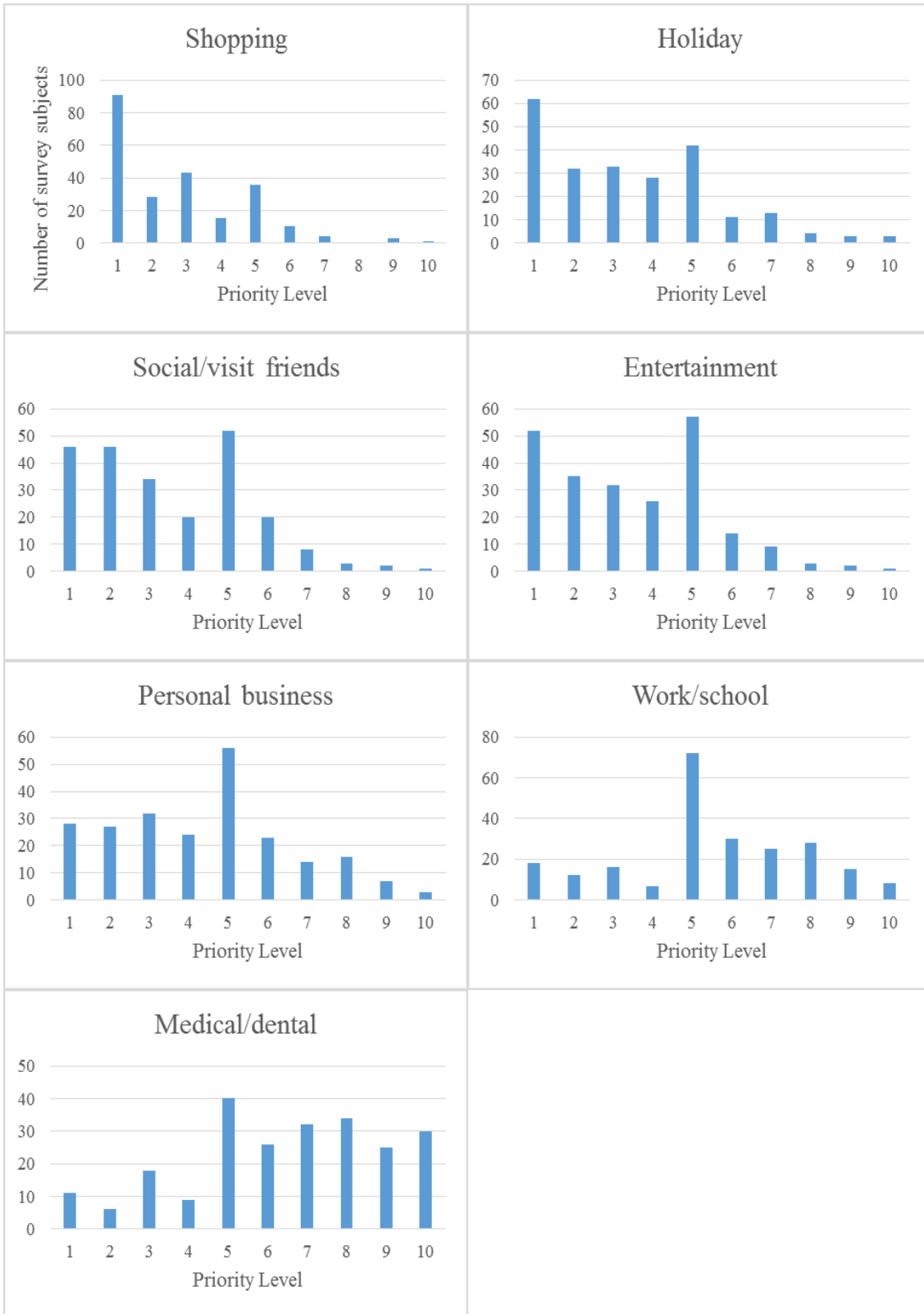
Figure 16: Distributions of PL assignment based on the trip purpose

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In the last question, respondents were asked to provide comments or recommendations regarding including social justice into the development of traffic control technology. First, respondents identified some factors that might influence their PL selection. For example, in the cases of added urgency of the trip based on being late, or based on their emotional state. Second, respondents were providing some suggestions, such as, there is no need for many PL, that PL 10 trips should be preprogramed to go to the hospital, and that there should be a system for people from always assigning high PL. Third, respondents, although most of them recognizing that transportation facilities are a "common good", were issuing concerns if other users will be socially responsible. Furthermore, they were suggesting that users need to take into account inevitable delay in travel.

Finally, respondents were concerned for the importance to include public transportation, public service vehicles (e.g., emergency, fire, and police), pedestrians, and bikes in the notion of SDV technology development. In addition, respondents were concerned with not involving politicians and not paying for service. Moreover, this development should take into account existing legislation for vehicles. A small number of respondents were suggesting first-come, first-serve principle instead of priority principle, which development should not focus on social justice, but on throughput, travel times, and environmental effects, and that aiming at global efficiency will benefit everyone. Lastly, respondents suggested that more information on the system is needed, thus showing their interest in complete development.

7.5 Empirical Information from Interviews

Information on the Interview

In addition to the survey, research team decided to perform interviews (approved by Institutional Review Board VT IRB 14-140) for obtaining in-depth understanding of some crucial relations for system development. The purpose of the interview was to identify user opinion and decision-making related to the initial proposal of the intersection operating mechanism. Specifically, research team was interested in knowing

the users' opinions related to the capability of the proposed operating mechanism to fulfill individual needs and rights. Specific anticipated findings from the interview were:

1. Determine the factors of heterogeneity in human decision-making, and use these factors to model and improve system operation.
2. Determine other factors of decision-making that need to be accounted for in modeling or for further investigation.
3. Learn about the interaction and feasibility of credit system (speed of spending, final credit number, consistency of PL selection, etc.).

The initial anticipation is that at least thirty people should participate in the study. The only criterion is that all participants must be over 18 years old. Participants were recruited by sending emails to ListServs administrators at Virginia Tech and through word of mouth. Subjects are invited to participate in a research study, in Patton Hall, on the campus of Virginia Tech. Participants were provided with the written consent form, including all the information regarding the purpose of the study, study procedure, risks, and benefits before conducting the study. Consent is obtained on the day of conducting the study, before the interview begins. The complete process of the interview goes as:

1. Person arrives, reads, and signs the consent form. (5 min)
2. Subject is handed over the first questionnaire to answer the questions. (5 minutes)
3. Interviewer presents information on SDV technology and control framework (there might be discussion with the subject during the presentation). (5 min)
4. Subject interacts with the control framework in a simulated environment. (15 min) This consists of the subject selecting PL based on the randomly assigned trip purpose and traffic level. The interaction will be tracked using Excel based table, which will generate and track parameters of Priority System.
5. Subject is asked to provide concluding comments. (5 min)

Information is collected on the questionnaire form distributed to the participant. In addition, the researcher takes notes of the subject's answers and the whole conversation with the test subject is recorded. Audio recordings of the whole interview will be made using audio recording device. In the case test subject provides comments during the

discussion or during the interaction with PS, audio recording will be used to verify the written comments by the researcher - for example, in the case something has been missed during the writing.

In total, there were 33 participants. Participants' average age was 41, median 39, with oldest participant being 67 and youngest being 18. There were 19 male (58%), 14 female (42%) participants. Most of the participants had graduate education (15), 11 have a BSc, 1 BSc/some Grad, 3 Associate degree, and 3 some BSc. In addition, 29 participants were white, 2 black or African/American, and 2 Hispanic or Latino. All participants had a driving license, with 26 driving almost every day, 2 driving few days per week, and 5 driving few days per month. Participants were mostly driving in suburbs (24%) and urban environment (24%), while there were also other combinations of driving environment present.

Interview Results before Presenting Priority System

At the start of the interview, the first question participants were asked was to briefly describe their understanding of the term "better intersection control technology". Most of the responses focused on technology as being adaptive, responsive, with sensing and predicting capabilities, etc., and were frequently influenced by popular knowledge on traffic signals (e.g., having green wave). In addition, responses focused also on technology that can address efficiency (e.g., minimizing delay, improving flow, prevents unnecessary delay, managing queues), safety, and fuel consumption. Some participants commented that technology should support improved interaction among people and more intuitive instructions, which lead to better driver's behavior. Finally, some participants focused on emotions (less frustration), being fair for side-street traffic, and improving delay for everyone, not just for a subset of users.

The following question was asking participants how they perceive the impact of traffic control technology on their needs. Great majority of participants (32) recognized the impact on safety. The one participant that did not recognize any impact on the needs, later on in the interview recognized the impact on safety. In addition, eight participants recognized the impact on esteem, six identified impact on psychological and self-

actualization needs, and four identified a relation with love/belonging needs. In the next question, when asked does traffic control technology affect safety, travel time, and environment, 28 participants identified impact on all three, while five participants identified only a relation to safety and travel time.

Interview Results from Interaction with Priority System

After initial questions, the participant is interacting with a Priority System. Each participant was presented a scenario of approaching an intersection in a self-driving vehicle. Each time, participant was assigned a hypothetical trip purpose from the following: Holiday, Shopping, Social/visit friends, Entertainment/sport, Personal business, Work/school, Medical/dental. According to this trip purpose, participant was asked to pick one Priority Level from one to ten. Each participant starts with 20 ₡ (max 25 ₡, min 0 ₡), and after PL selection, the ₡ number is automatically recalculated. In addition, the user is presented with a case of low, medium, or high traffic. In total there was 21 trials, considering the number of combinations of trip purposes and traffic levels. However, each participant was presented with a random order of these combinations. Besides selecting PL, participants were asked to provide an explanation of their decision making and amount delay that would make them increase their PL. For cross-validation purpose, participant was again assigned PL selection task after completing these 21 trials. This time, participant was presented with all trip purposes in combination with low and high traffic scenario. The order of combinations was identical for all participants.

Following Figure 17 and Figure 18 present number of total PL selections for low, medium, and high traffic and for each trip purpose. In addition, cross-validation cases were presented on the right, including only low and high traffic. Similarly to Figure 16, we can see that different trip purposes have different distribution of PL assignment. People tend to select lower PL for holiday and shopping trip purpose, medium for social, entertainment, and personal business, while they assign high for work and emergency situations. However, we can see that there are no cases of selecting all PL for every trip purpose, with PL 10 present only in work and emergency trip purpose. Moreover, we can see that there are discrepancies between starting and cross-validation case.
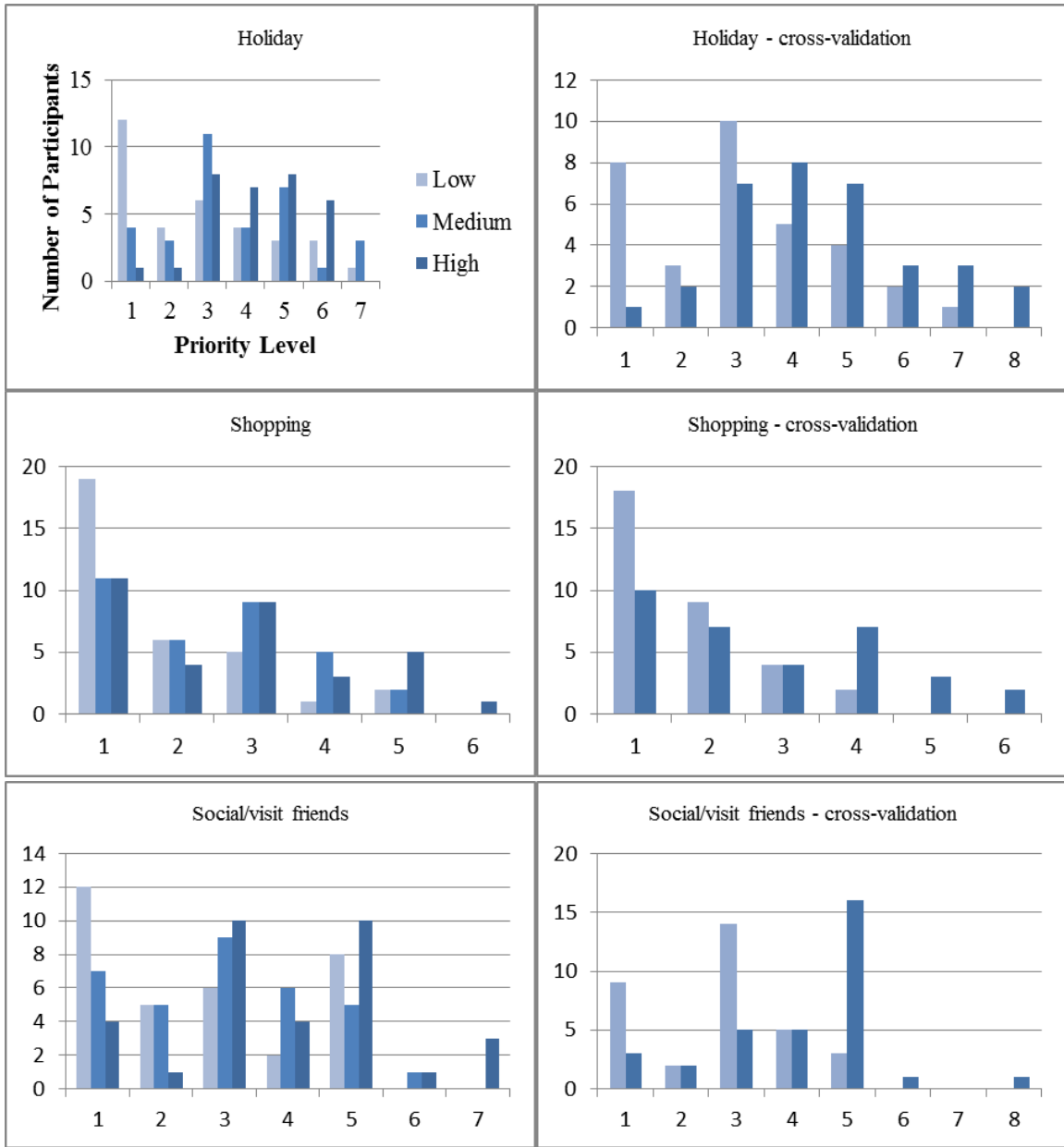
Figure 17: Distribution of number of PL selections for low, medium, and high traffic in the case of Holiday, Shopping, and Social/visit friends trip purpose
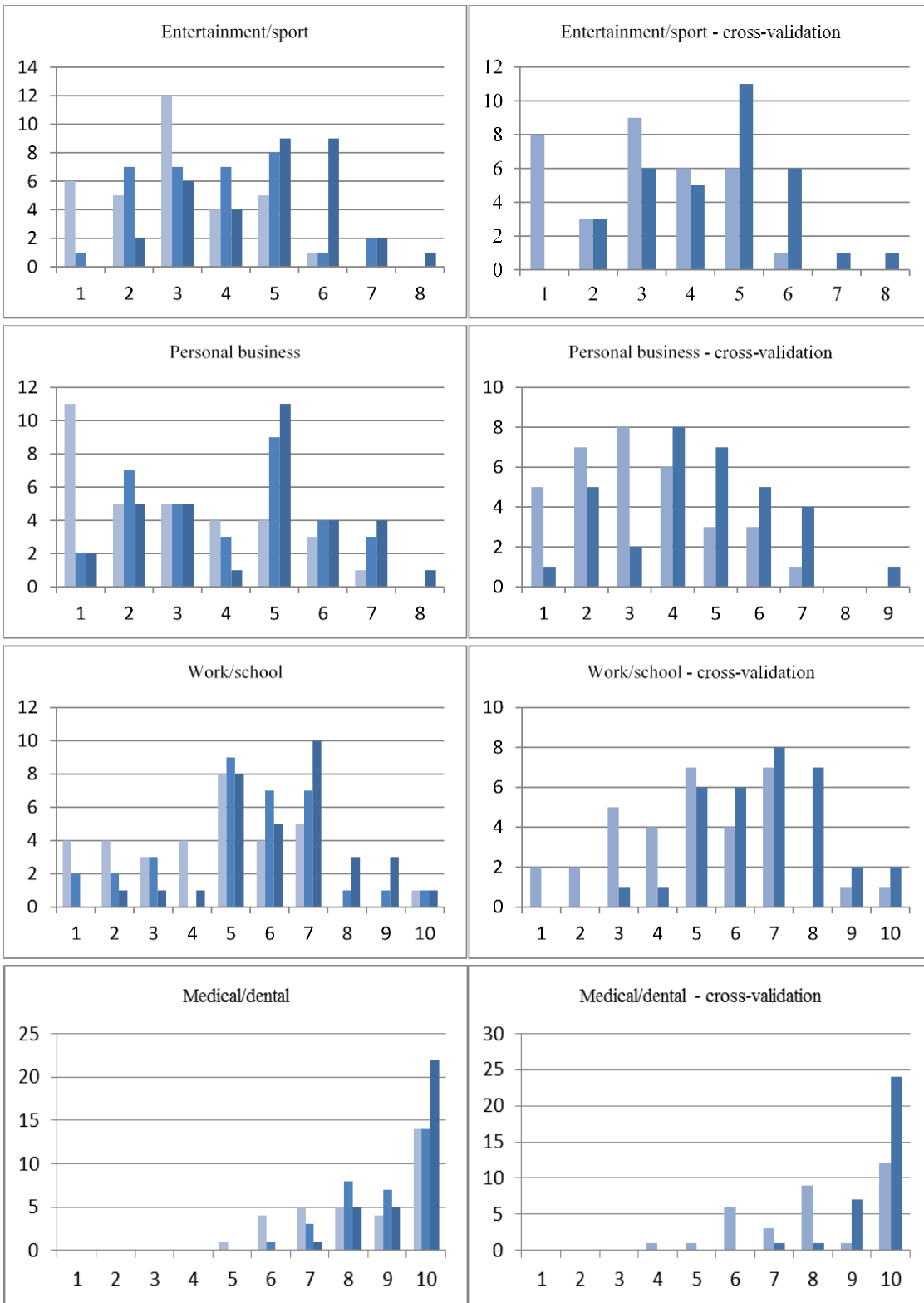
Figure 18: Distribution of number of PL selections for low, medium, and high traffic in the case of Entertainment, Personal business, Work/school, and Medical/dental trip purpose

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Figure 19 shows PL selection on the left side and dynamics of $\mathbb{C}$ spending/gaining on the right side. Data is for research subjects R06, R01, and R11, from top to bottom, respectively. These three subjects were typical representatives of three groups of participants observed during interviews. For R06, we can see that participant is altruistic, clearly separating trip purposes into two categories, i.e., using low and high PLs. Similarly, participant R01 has two categories but this participant uses higher PLs for lower category. On the contrary, participant R11 uses a range of PLs, but clearly groups them per trip purpose. Dynamics of $\mathbb{C}$ spending/gaining is showing different pattern for each of the participants, having more dispersed values as the participant selects wider range of PLs. Finally, Table 10 shows the amount of delay that would make user increase their PL. One can see that values for acceptable delay decreases as trip purposes change towards work and medical emergency trip purpose. This is similar relation as on previous figures, where people place higher importance on some trip purposes (e.g., medical emergency) over the others (e.g., shopping).
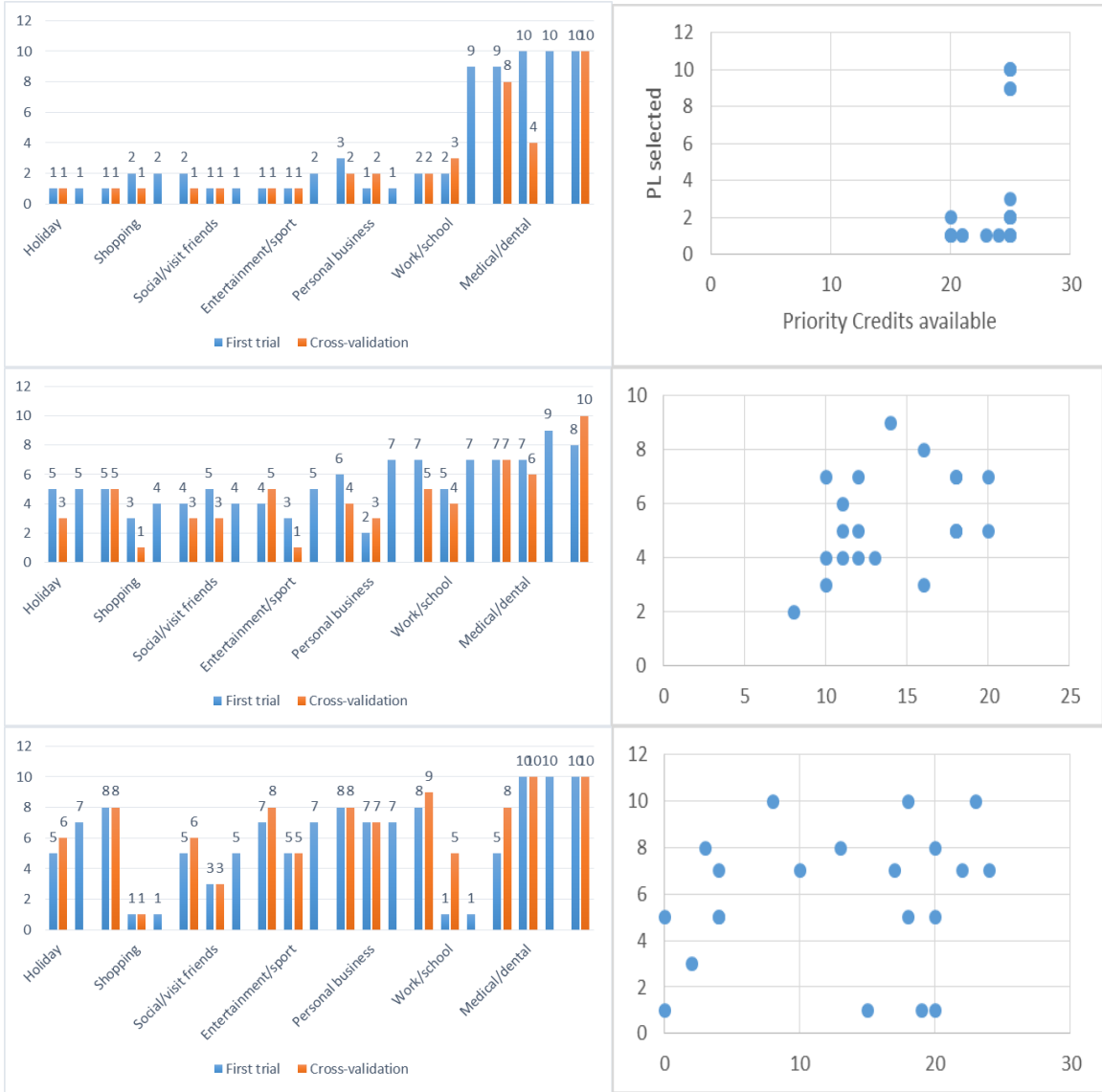
Figure 19: PL selection and Priority Credit dynamics for research subject R06, R01, and R11

Table 10: Amount of delay that would make user increase PL based on trip purpose and traffic level

Trip purpose	Traffic	Average	Max	Min
Holiday	Low	43.90	120	0
	Medium	44.63	120	8
	High	37.61	120	5
Shopping	Low	29.71	120	0
	Medium	18.24	40	0
	High	19.74	60	0
Social/visit friends	Low	28.86	120	10
	Medium	23.76	60	0
	High	20.62	60	0
Entertainment/sport	Low	21.52	60	5
	Medium	16.91	60	0
	High	16.04	60	0
Personal business	Low	23.86	60	5
	Medium	20.87	60	5
	High	16.91	60	4
Work/school	Low	15.12	60	1
	Medium	13.93	45	1
	High	15.13	60	1
Medical/dental	Low	6.37	20	0
	Medium	5.93	30	0
	High	5.33	20	0

Interview Results after Interaction with Priority System

After completing the interaction with PS in a simulated environment, participant was asked a series of questions related to PS. Questions were asking if the participant can think of the way to abuse the system solely for their own benefit, if there is a potential for failure of the system, if PS could operate differently, or to provide any other comments. We have to note immediately that none of the participants had a completely negative opinion towards PS. We have grouped the answers as positive comments, comments about system failure, and factors influencing PL selection.

Positive comments:

- System could save time and lives, and have positive environmental effects.
- System is fair, identical for everyone, allows user to choose their own priority and can influence their travel time to destination.
- Credit system is good because it allows gaining and spending, it is non-monetary, deters abuse, allows people to save and plan the future.
- System accounts for actual situations through relative importance, and can include special vehicles.
- System could increase awareness of other's needs and nudge people to think during trip planning.

System failure:

- Concern that some people do not think much about the future and will try to go around the rules.
- Concern that people will drive more to accumulate credits, use high PL for longer trips or during peak traffic, or aim to stay around maximum value of $\mathbb{C}$.
- Concern about the actual effects on travel time.
- Concerns for operation in special situations (e.g., large events, bad weather).
- Concern for emergency situation in the case of lack of $\mathbb{C}$.
- Concern for changes in routing choices (e.g., to accumulate $\mathbb{C}$).

- Long-term psychological effects (e.g., if people become primarily focused on ₵ instead on people, if people are stimulated to compete in higher traffic, or if start overvaluing their low PL selection).

Factors influencing PL selection

- The level of pain (e.g., strained ankle vs. severe abdominal pain)
- Perception of available time (e.g., store is closing, movie is starting)
- Perception of trip purpose importance
- Perception of traffic congestion and estimated travel time
- Delay thresholds (e.g., delay as a ratio of total travel time and in relation to trip purpose)
- Other people in the vehicle
- Esthetic experience of the trip
- Perception from other people (e.g., selecting lower PL to avoid group pressure)
- Priority Credits available (e.g., temptation to use higher PL when having more ₵)
- Caring for other people not to use high PL
- Willingness to complete trip (e.g., low willingness could result in selecting low PL)
- Culture (e.g., a custom to arrive before the event starts)
- Monetary relation (e.g., bought tickets for concert)
- Trip chaining (e.g., going to shopping than picking up children)

Suggestions for System Development

In addition to providing comments on the current stage of system development, participants have provided a set of suggestions for system improvement.

- The system should be in a continuous development, with input from the public.

- There should be a capability to over-ride the system in some situations (e.g., traffic congestion).
- Priority Credits should not be per vehicle.
- Everyone should be assigned the same number of Priority Credits or people with greater need should have a greater number.
- There should be smaller number of Priority Levels.
- Spending/gaining Priority Credits should be based on trip duration or level of traffic.
- There should be capability to change PL during the trip, certain number of times or after some period of time, but number of $\mathbb{C}$ used might depend on the scale of change in PL.
- There should be clear reward system for people that do not select higher PL over certain period of time (e.g., increase maximum number of $\mathbb{C}$ or E$\mathbb{C}$).
- Default PL for emergency vehicles, public transportation, bicycles, and pedestrians should be higher than PL for passenger vehicles.
- Higher PL should cost more $\mathbb{C}$.
- There should be a separate set of emergency $\mathbb{C}$ and they can be not spend if there is verification at destination (e.g., hospital).
- Priority Credits should reset after some time, or provide additional credits after certain vehicle's mileage or time.
- There should be free-market for buying and selling $\mathbb{C}$. However there are also participant that are strongly against buying and selling $\mathbb{C}$.
- There should be an option for donating $\mathbb{C}$.
- Credit misuse cases should be publicly announced.
- System should require log-in for use.
- Provide incentive through $\mathbb{C}$ gain/loss for people to use less congested routes.
- In the case vehicle is used to provide transport to some other user, $\mathbb{C}$ should be used from transported user.
- Priority in a multi-person vehicle should be given to the person with the most important thing.

- Routine/every day trips should account for 0 ℂ or some default value.

- Vehicle could drive faster on the links based on PL or assigning routes based on PL.

- User should not be allowed to assign PL 10 many times in a row.

- Use additional credits to get to the destination in time – guaranteed travel time.

- There could be a rating system that would influence how much ℂ are gained or lost.

- If user selects a higher PL during the trip, ℂ are accounted for the highest PL, but if they select lower PL, ℂ are accounted for smaller PL.

- Provide examples of what different PL should be.

General Comments related to SDV Technology

In addition to comments related to PS, participants have provided a series of comments related to SDV technology in general. First, participants have expressed many concerns about the safety of technology (e.g., hacking, technological failure, use of radar technology on a wide scale, safety distance between vehicles crossing the intersection). In addition, some users were against autonomous vehicle in general, preferring to maintain overall control over their vehicle. On the contrary, almost all the participants recognize technological benefit for elderly, impaired and disabled users. In addition, they recognize that user in SDV is freed to engage in other activities. However, participants have expressed certain level of understanding for decision-making irrationality in themselves and in other people. Consequently, they recognize the potential for change of lifestyle, change in departure time or trip rescheduling, but also potential for continuous adjustment of experienced delay expectations. Finally, participants were concerned with other technical points (e.g., at what point can user change her destination during the trip, influence on transportation system in overall by having more long-distance trips, and different ownership model for SDV use).

7.6 Current Development Stage

As we have seen from the survey, and what previous social science research tell us is that, in each system, people belong to one of the three groups: reciprocal types, free-riders, or pure cooperators. Reciprocal types are people who contribute to the public good as a positive function of their beliefs about others' contributions, and they usually constitute the majority in the system (around 65%). On the opposite, there are only around 20% of free-riders that by default do not try to cooperate, and around 15% pure cooperators, that by default always try to cooperate [20, 143-145]. However, we know that people are willing to cooperate more in the fair system, where they have the potential of giving their input [218]. This notion of cooperation will remain one of the key structural elements for PS.

However, cooperative acts are vulnerable to being exploited to selfish partners [146]. The problems may arise due to the time delay inherent in reciprocity, or when an individual does not (equally) contribute to the creation or maintenance of a shareable benefit or good. When public good is free for overusing, individuals or groups will usually overuse it. This problem is known as the "tragedy of the commons" [153]. In additions, problems may arise between parties, that can result in bargaining impasse [243, 244]. For example, this can happen in the case when parties believe that system is fair, but there is aggressive bargaining by other party, or if the negotiators are strongly averse to settling even slightly below the point they view as fair. [245]. Cooperation in C2 should avoid the assurance problem [154]. This problem exists when individuals are better off if they follow the same minimal standard, but are second best off if, in the case when there are defectors, and they join the defectors rather than continue to follow the standards. In addition, they are worst off if there are defectors but they do not join them. Without the external incentive (e.g. reputation, punishment, etc.) this cooperation might not stable. C2 cannot only rely upon people's intrinsic readiness to cooperate – there is a need for a just structure, modifiable by the agreement among the members [20]. C2 needs to have a structure that will prevent too many defectors from receiving the benefits of long-term cooperation So, in addition to supporting the cooperation, individuals need to realize the undesirable consequences of free riding through the established sanctioning system [157,

158, 219] and social pressure [160]. Finally, people are willing to provide a sanctioning system, as a part of the public good [20]. Humans often care strongly about fairness and they are prepared to punish others who deviate from a fair principle, even a cost to themselves [161] in order to maintain stable cooperation [145]. A good example is altruistic punishment, when individuals punish free riders that negatively deviate from the cooperation standard [20, 162].

Priority System Redesign

Considering the input obtained from survey and interview, the research team has decided to:

- Decrease the number of PLs to 4.
- Change the number of $\mathbb{C}$ gained and lost for each PL (+2 $\mathbb{C}$ for PL 1, 0 $\mathbb{C}$ for PL 2, -2 $\mathbb{C}$ for PL 3, and -10 $\mathbb{C}$ for PL 4).
- Starting number of $\mathbb{C}$ remains 20, but maximum is 24 $\mathbb{C}$.

Besides these three important changes, the research team will continue to obtain feedback from general public by establishing a public discussion forum. In addition, testing of operational effects in different traffic conditions are essential part of the development.

7.7 Conclusion and Recommendations for Further Research

This paper starts with a point that the question of justice applies to technology in general, and consequently to the traffic control technology, since traffic control technology can affect the common good of the man by restricting the right to free movement and equal access to public service. Considering new technological tendencies in the communication, sensing, and in-vehicle computing fields that can enable further development of traffic control equipment, the responsibility is upon transportation engineers to develop long-term vision for evolution of traffic control technology. In the case of traffic control, an alternative to the conventional control needs to include a framework of social justice.

We have started this paper by explaining the expanded "design horizon", with the reasons why a framework of social justice is an essential component. In addition, considering that technology influences and evokes human behavior, our methodology includes consideration of essential feature of human behavior – tendency towards cooperation, along with conditions for establishing a system of cooperation. Taking into consideration current and potential development of SDV technology, a framework of social justice developed by John Rawls, and human behavior considerations, we introduce a Priority System. This system bases on the premise of end-user responsibility to select a Priority Level for their trip with a SDV. In support of the Priority System, we have introduces a structure of non-monetary Priority Credits.

The main part of the paper presents a survey and interviews conducted to collect feedback on the proposed system design. Survey did not specify complete set of details related to Priority System, but was intended to collect perceptions related to the effects of intersections upon social justice, and elements of moral decision-making related to the intersections as public assets. Survey has showed that user's perceptions are influenced by existing technology but that they perceive the effect traffic control technology has on all life aspects. In addition, survey has shown that there is a potential for development based on social responsibility, despite the respondents concerns and lack of trust in both technology and other citizens. However, the survey has showed us that Priority Level selection cannot exist without a supporting system.

Information from both survey and interviews have showed that PL selection follows a certain global patterns, since people distinguish between low, medium, and high importance trip purposes. Moreover, the results showed us that people can behave altruistically and cooperatively, but that Priority System can also be resilient enough to the fact that people do not follow straightforward rational rules based solely on utility. Moreover, interview participants have provided a set of positive comments, concerns for system failure, a range of factors influencing PL selection, and recommendations for improvement. Finally, we also present some general concerns participants have expressed in relation to SDV technology. All this information is similar to previous findings from social science research, and has provided a basis for further system redesign.

Throughout the empirical investigations, there was a notion that some people perceive time as continuous and arrange their activities depending on their importance and their duration, consequently planning their mobility (e.g., running behind schedule). Moreover, the topic opened up some other complex question in relation to societal structures and implied for further need to educate users (e.g., confusing social justice with socialism, not understanding the fundamental human rights). As our intention is, the framework presented here is including one perspective on one framework of social justice, which is again only one of the potential values we can include in the design of SDV technology. This research endeavor was not planned to provide a final solution, but to be used as proof that such an endeavor is possible. The long-term vision for the C2 control systems, will need to achieve a careful balance between the needs of multiple segments of population in the current and future generations. This result, will never be accomplished without a wider discussion, including not just engineers and entrepreneurs, but general public as well.

8. WEB-BASED EXPERIMENTATION WITH HUMAN SUBJECTS AND SIMULATION-BASED EVALUATION

Submitted for review

Abstract

With the development of self-driving vehicle (SDV) technology arising, there is a range of questions that emerges alongside. This research focuses on a question of traffic control framework for SDVs, while also attempting to incorporate how advantages and disadvantages from control framework will be distributed in a society. The framework developed from these considerations is a version of Priority System (PS). Considering that PS depends on end-user responsibility, research presented here is trying to evaluate proposed control framework by including human decision-making. First, this paper focuses on development of web-based experimentation for allowing user interaction with PS. In addition, this paper will use the information collected from web-based experiment to develop models of human decision-making within PS framework. The models are used as part of the Monte Carlo simulation scenarios. Consequently, simulation results are used to evaluate PS operation at an isolated intersection. Finally, we will present summary of results, conclusions, and recommendations for further research.

8.1 Introduction

With the development of self-driving vehicle (SDV) technology on the horizon [6, 241], there is a range of questions that emerges too. Considering that SDV will be perform all safety-critical driving functions and monitor roadway conditions for an entire trip, the current vision is that user's input will be limited solely to destination and navigation input [121]. As a result, SDV technology could improve traffic safety [16], improve the mobility of people unable to drive [10], mitigate the environmental impacts of automotive transportation [10], and increase operating capabilities from road infrastructure [6].

However, the vision for self-driving vehicle technology primarily focuses on potential benefits from this technology [246], underestimating the complexity of technological evolution. One important point that technology designers might not be aware is that, as other technologies [126-128], transportation technology evokes and influences user's behavior. In addition, focusing on assessing how efficiently technology achieves its operational goals, might neglect how responsive technology is to social, moral, and political values [129, 130]. Considering that SDV technology is in its foundational stage of development, this is a crucial stage allowing us to rethink some fundamental premises and develop a sustainable technology – technology that can fulfill our current needs but not restrict the needs of the future generations [21, 22]. With this in mind, the approach presented here will be analogous to the Value Sensitive Design approach [165-167].

One of the values taken into consideration is social justice. In essence, social justice refers to the structure that determines how advantages and disadvantages from certain technology are distributed in a society. We have based our consideration of social justice upon a framework proposed by John Rawls [205]. This philosophical framework has been developed as a Priority System (PS). This PS allows the user to select a Priority Level (PL) for their trip with SDV. A general ideas is that each vehicle is supposed to use their PL and in communication with other SDVs at an intersection, determine the right-of-way. Although there have been several previous research efforts for developing traffic

control mechanism for SDVs (e.g., [101, 105, 114]), this is the first attempt to enable end-user responsibility.

Considering that development of PS using user input is presented elsewhere, this paper will focus on web-based experimentation for allowing user interaction with PS. In addition, this paper will use the information collected from web-based experiment to develop simulation scenarios and consequently evaluate PS operation at an isolated intersection. First, we will present our methodological approach, followed by the development and results from web-based experiment. Later, paper will present simulation setup and results with analysis. Finally, we will present summary of results, conclusions, and recommendations for further research.

8.2 Methodology

Priority System

As argued elsewhere [247], traffic control technology directly affects following universal and fundamental human rights [137]:

1. right to life,
2. right to freedom of movement, and
3. right to equal access to public service.

Considering that these rights are universal and fundamental for every human being, as prerequisite for carrying out life's plans, it becomes an imperative for traffic control technology not to promote unjust distribution of restrictions to these rights. This is why an underlying framework of social justice within SDV technology is an important point to consider. Consequently, there is a relation to traffic control objective, and in our case we relate it to delay per user and per trip purpose.

The first Rawls' principle relates to liberty, while the second principle relates to equality. Essentially, Rawls' framework is arranged to protect the inviolability of the user and maximize the benefits of the least advantaged in the complete scheme of equally shared by all [204]. These guiding principles have been used to structure a framework for development of new technology. Considering that the inviolability of the user is the most

important point in this framework, this can be translated as emphasizing the distribution of delay among individuals, and not solely emphasizing upon the total delay for an approach or an intersection. In order to protect the inviolability of the user, control principles are developed to allow for greater responsibility of end-user in the control process. Enhancing end-user responsibility is envisioned to emphasize long-term and large-scale cooperation for the mutual advantage of individual user, and to support a just structure. In addition, in order to prevent user usurpation, we have considered human behavior. We have primarily focused on human tendency to cooperate [146], especially in cases with reciprocity [147, 148], because people care about outcome for other people and greater social goals [145, 149], if they perceive that other people cooperate [20], or if there is reputation building [20] or sanctioning system [146].

At this current stage of development, user can select a PL for each trip, in integer value from one to four. These PL is then used to determine the right-of-way between SDVs approaching intersection, where SDV with the higher PL has the right-of-way over the SDV with lower PL. Consequently, PS is similar to the priority queuing principles [232], where a user is selected for service if it is the member of the highest priority class. However, the users within a class are selected upon FIFO principle. For example, one person would assign "very high priority" one day, due to the emergency that trip has (e.g., trip to the hospital). The other person for the same day would assign "low priority" since the trip has leisure as a purpose. In the case when these two vehicles approach the same intersection at approximately similar amount of time, the vehicle with "very high priority" would be the first one to receive right-of-way, relative to the vehicle with "low priority". The users in this situation might have respectively inverse roles in other situation, and would achieve the respectively inverse result. This is underlying an agreement between vehicles in a system of cooperative production – person A will yield to person B today when person B needs right-of-way, under agreement that person B will yield person A tomorrow, when person A needs right-of-way.

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However, in order to avoid user usurpation of the PS, there has been developed a system of Priority Credits ($\mathbb{C}$). In the initial assignment, each user should receive identical amount of 20 $\mathbb{C}$. Spending/gaining of $\mathbb{C}$ will be only through PL selection, with uniform rules for all users (Table 11). In addition, there is a $\mathbb{C}$ celling, being a maximum number of $\mathbb{C}$ that individual user can have. In addition to these rules, there is a series of other rules proposed elsewhere, but considering that this is the initial testing stage, research team has decided to implement the simplest version of PS.

Table 11: Initial $\mathbb{C}$ system in relation to Priority Levels

PL	1	2	3	4
$\mathbb{C}$	+2	0	-2	-10

Methodological Approach

For the research approach, the research team has decided to use:

1. Web-based experiment
2. Monte-Carlo simulation

Web-based experiment is selected because of faster speed, lower cost, greater external validity, the ability to experiment around the clock, high degree of automation of the experiment leading to low maintenance costs and limited experimenter effects, and wider samples than in person experiment [248]. Moreover, comparison of web-based experiments with in person surveys have showed similar results [249]. For example, Gosling et al. found that internet samples are relatively diverse with respect to gender, socio-economic status, geographic region and age; that findings were not adversely affected by non-serious or repeat responders; that findings are consistent with those from traditional methods [250]. Similarly, Meyerson and Tryon conducted a study to evaluate the psychometric equivalence of online research, and concluded that data gathered was reliable, valid and reasonably representative, as well as noting that the process of gathering data was cost effective and efficient [251]. However, there are comparisons which have shown differences. Dandurand, Shultz and Onishi found that online

participants were less accurate in their performance of tasks than lab-based participants completed their task less accurately than their lab-based participants, they attributed it to the possibility that online participants may have been simultaneously working on other things or have been distracted while completing the task [252]. With this in mind, the design of this web experiment will specifically focus on attracting and maintaining attention of the participant.

Microscopic simulation is selected because of the capability to simulate movement of individual vehicles that can be tracked through the network over sub-second time intervals [253]. The simulation framework used in this research will base on Monte Carlo simulation approach. Monte Carlo simulation focuses on using sample means to estimate unknown population means [254]. Essentially, this approach applies a large number of random sampling of the model resulting in a large number of random samples of model output. Considering that model is run n times, using a different array of continuous uniform u ~ U(0,1) random variables for each run, the output data is independently generated, and we can determine properties using ordinary statistical methods.

8.3 Web-based Experiment and Data Collection

Experiment Development

For user experiment, a custom website was developed (approved by Institutional Review Board VT IRB 14-542). The purpose of web-experiment was to collect information on user decision-making, based on hypothetical information, and opinions related to PS. Experiment was anonymous and subjects had to be over 18 years old to participate. In total, the experiment was developed not require more than 10 to 15 minutes of time commitment. Since it is web-based, experiment can be performed at any location with Internet connection. Information from the experiment was collected in a database on a secure server. In addition, the website (https://self-driving-priority-level.info/) is stored on external service with Secure Sockets Layer (SSL) encryption. Hyperlink for experiment was distributed via Virginia Tech news, listservs, and using LinkedIn website, mostly on groups related to transportation or autonomous vehicles. In addition to

root page, where subjects starts the experimental process, there were five more pages: consent, info, experiment, exit, and contact page.

As already mentioned, web-based experiment provides respondent with autonomy and convenience for participating. However, previous research recommends that other elements are incorporated (e.g., shortness of experiment, shortening loading times, interesting content, emphasizing contribution, etc.) [255]. Recommendation is that website needs to have aesthetic quality, convey trust in online entity, has interactive elements, simplified instructions and extroverted writing style. Moreover, design needs to take into consideration elements such as font size, color, ability for normal reading, expected location of the content, etc. [256]. These design elements were implemented throughout the website pages. Figure 20 shows a diagram of web-page structure and diagram of user activities and decision-making steps during an experiment. Finally, the user can enter a raffle for a change to win a $50 gift card or to provide their name and approximate location for a list of contributors that will be publically listed on the experiment's website.
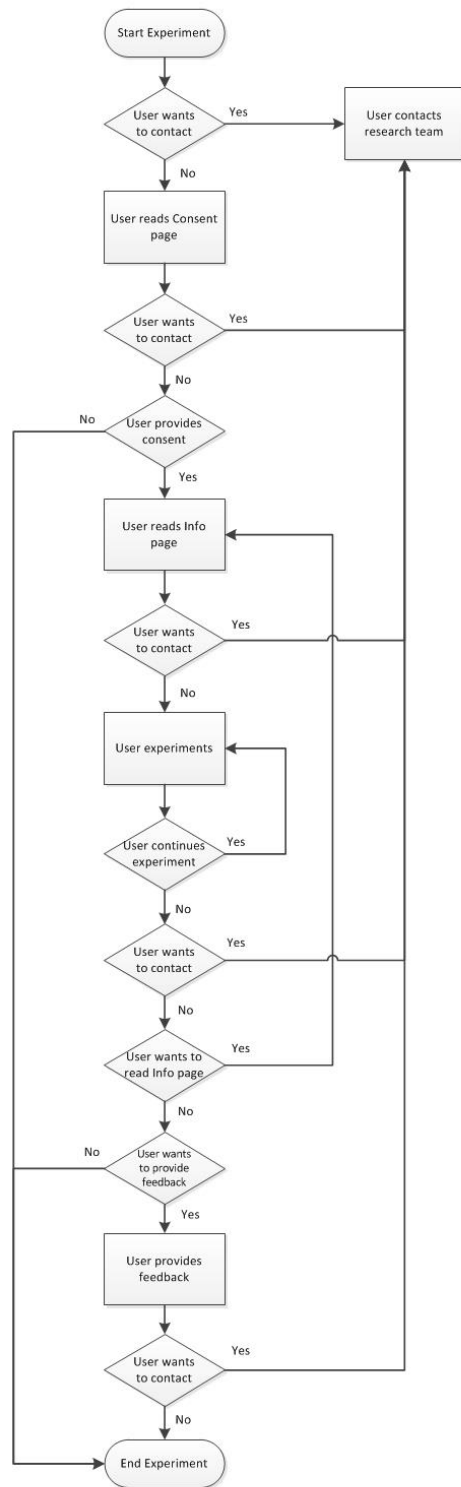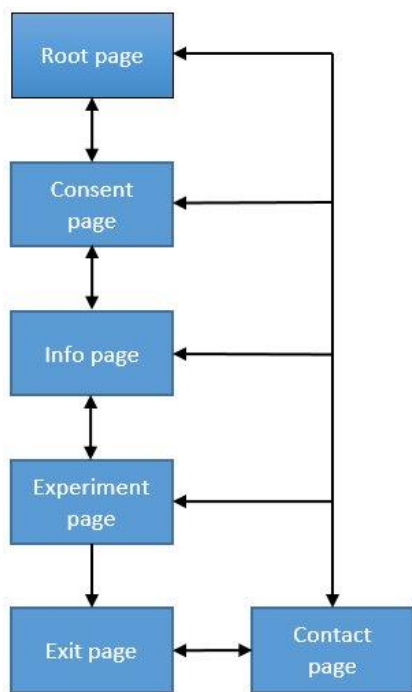
Figure 20: Diagram of web-page structure and diagram of user activities and decision-making steps during an experiment

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- Consent page

On the first web page (top left part of Figure 21), similar to a consent form, subject was presented with information on the study purpose, who is conducting the study, expectation from the participant, risk, benefits, anonymity and confidentiality, freedom to withdraw, and contact info [257]. Participants are also asked to provide consent at the end of this web page. This page is intended to emphasize confidentiality, and to include information that will increase trust in researchers [255, 258]. Self-disclosure has been done using LinkedIn profiles from members of the research team to establish rapport. In addition, it was important to include information on how long the experiment will last, and that participant's contribution will affect the design of technology [259].

- Info page

After providing consent and continuing to the info page (top right part of Figure 21), subject is presented with detailed information about the operation of Priority System, and the input parameters for decision-making in the web experiment.

- Experiment page

On the third page (lower left side of Figure 21), the participant is supposed to interact with the control framework. Participant is expected to select PL based on information about his/her hypothetical trips and $\mathbb{C}$. In addition, optionally, participant can provide information on his/her reasons for decision to select a specific PL. Subject can be involved with the experiment as long as they prefer, and as many times as they prefer. The limit of minimum 10 interactions within one experiment is set to be eligible for raffle. Considering that even the design of PL selection button can affect user's decision-making [255, 258], research team decided to use radio button since it provides the simultaneous visual overview of all PLs. In addition, PL 4 or PL 3 buttons would dynamically disappear, based on the number of available $\mathbb{C}$. The button "Next trip" was used to provide the participant with the information about the next hypothetical trip, and to store previous PL selection and comments. In addition to this button, there is an "Exit" button, used to lead participant to an Exit page. This is preferred option, since participant can be debriefed about the experiment, and prevented from simply closing the browser tab and leaving the experiment [259].

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In addition, trip parameters used in the experiment, along with their distributions and values, is presented on Table 12. Trip purpose distribution has been approximated from National Household Travel Survey for 2009 [260]. Based on the interviews, time obligations are divided into three categories, as without time obligation, with time obligation, and with strict time obligation. In addition, estimates of time delay were also approximated from interviews with users. For web development of experiment mechanism, research team used PHP, general-purpose scripting language [88]. In addition, for generating random numbers, *rand*, a PHP function that generates random integers between certain interval [79]. Finally, every time any user follows the webpage link, new user id is assigned, thus allowing different users to anonymously participate in the experiment several times.

Table 12: The distribution of trip purpose, time obligations, and time delay

Trip purpose	Distribution	Time obligations (uniformly random)			Time delay (uniformly random)				
Shopping	20%	W/o	W/	W/strict	20	10	0	-10	-20
Holiday	8%	W/o	W/	W/strict	40	20	0	-20	-40
Social	17%	W/o	W/	W/strict	20	10	0	-10	-20
Entertainment	5%	W/o	W/	W/strict	15	8	0	-8	-15
Personal	19%	W/o	W/	W/strict	15	8	0	-8	-15
Work/school	29%	W/o	W/	W/strict	15	8	0	-8	-15
Medical	2%	N/A			5	2	0	-2	-5

- Exit page

After experiment page, user can reach exit page (lower right side of Figure 21). Remembering that attracting participant's interest are crucial issue with web-based experiment, experiment design included an option for users to submit their email for a raffle after a certain number of experiment iterations, and to submit their name and approximate location for public announcement of contribution. Research team decided to use online gift-certificates so that subject can redeem their certificate without revealing their identity. In addition, on the final page of the experiment, subject will also have an

option to provide his/her opinion related to Priority System, as a part of debriefing from experiment page.

- Contact page

Finally, from each web page, the user has an option to contact the research team, for questions or to report a problem [259].
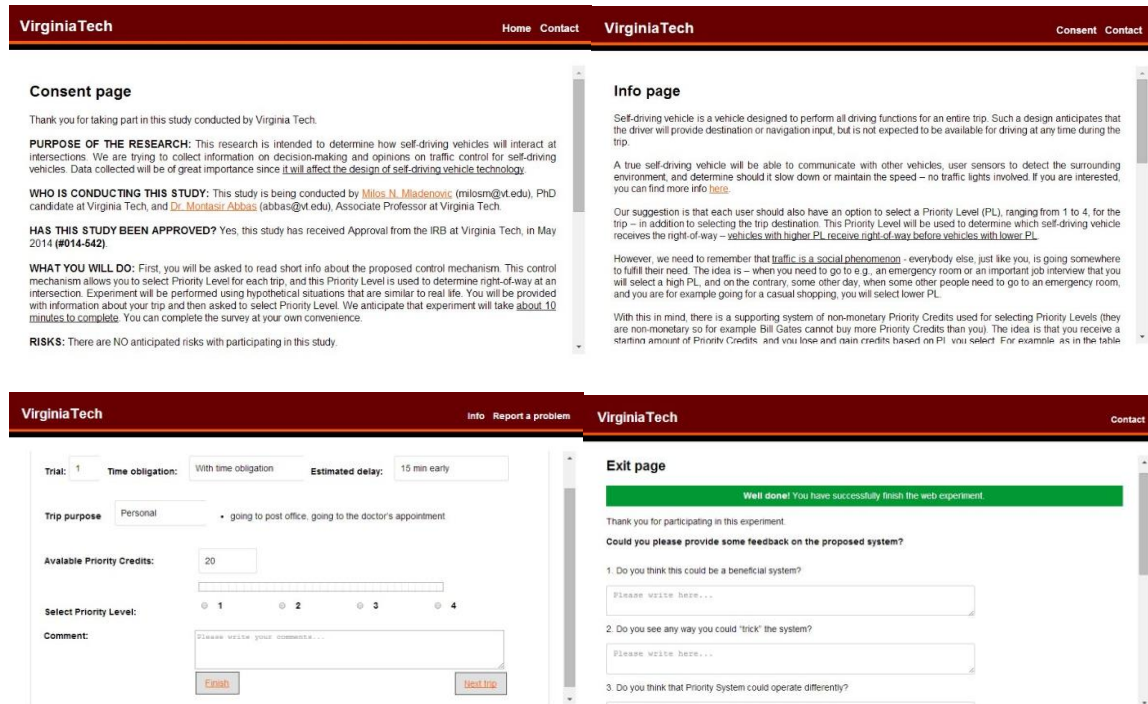
Figure 21: Screen shots from consent, info, experiment, and exit page

Web-based Experiment Results

After closing the web experiment, there has been total of 266 participants. Minority of participants provided less than ten or more than 100 PL selections (maximum is 350 PL selections), with an average of 34.1 PL selections and median of 20 PL selections per participant. In reality, PS is envisioned for long-term interaction, so experiment results present only a part of the potential situations. Consequently, behavior of participants might be primarily short term, and relying on their imagination to consider their decision-

making in specific situations. Considering that experiment results were stored in a database, research team has used SQL queries to extract and group results.

Following several figures (from Figure 22 to Figure 28) show the number of selections of each PL for different trip purpose, and varying by time obligation and expected delay. From these figures we can observe user tendency to select certain PL depending on the trip purpose, time obligation, and expected delay. One can also observe a shift from tendency to select one PL to tendency to select other PL as trip parameters change. First, one can see that user tend to select lower PL for shopping, social, entertainment, vs. holiday, personal business, work/school, and medical trip purpose. Second, one can notice that users tend to select lower PL if the estimated delay is negative vs. when estimated delay is positive. Similarly, for time obligation, users select lower PLs when there is no time obligation, as opposed to trips with time obligation.

Figure 22: Number of selections of PL for shopping trip purpose, varying by time obligation and expected delay
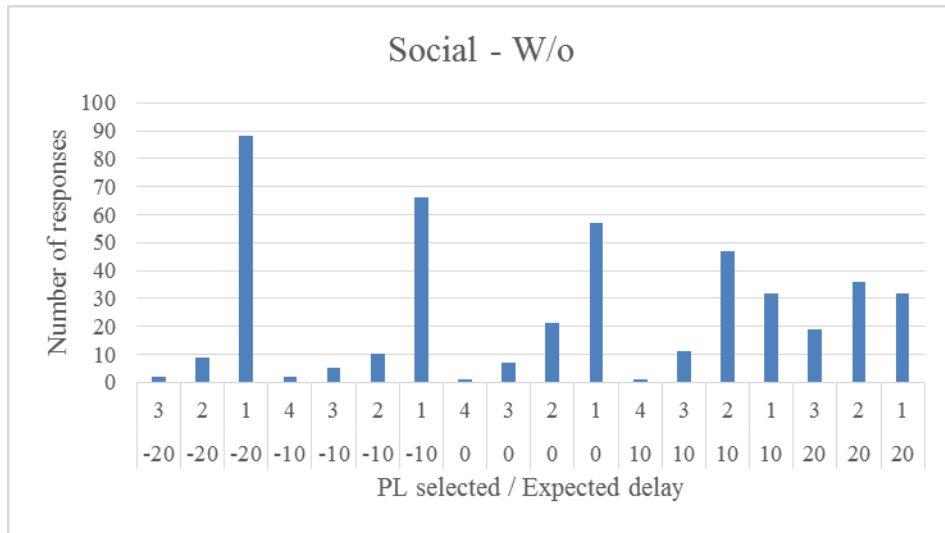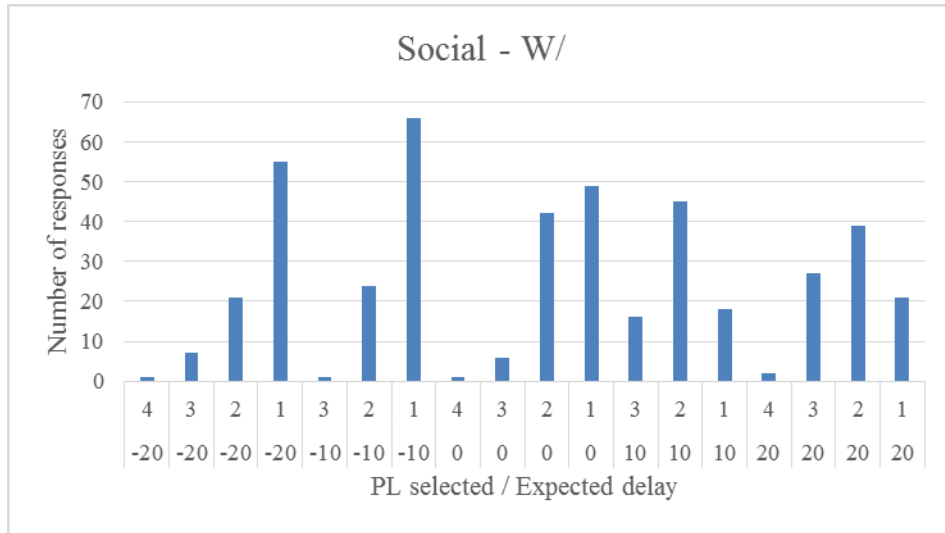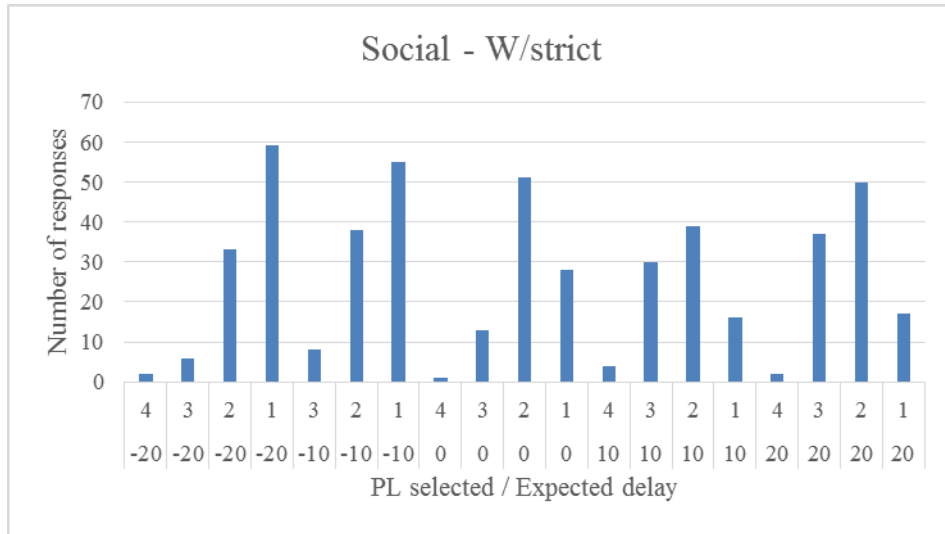
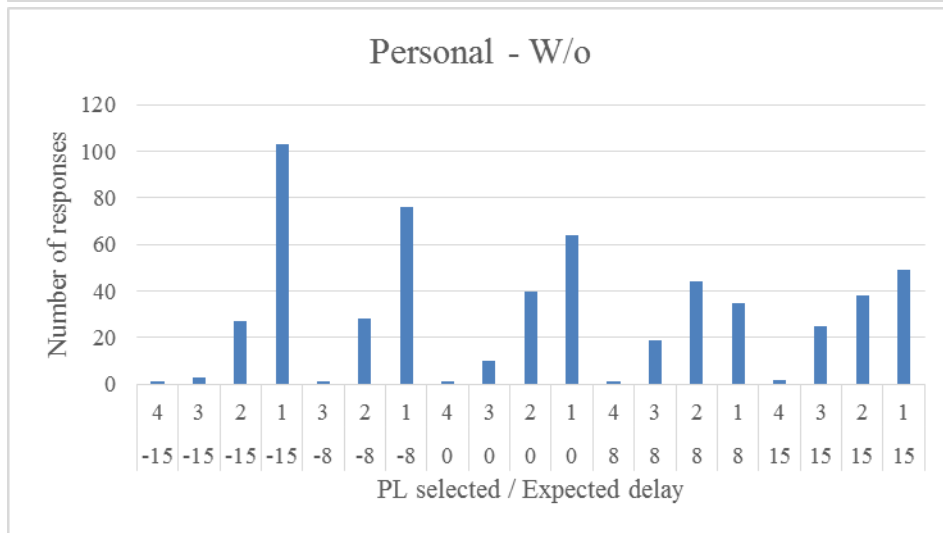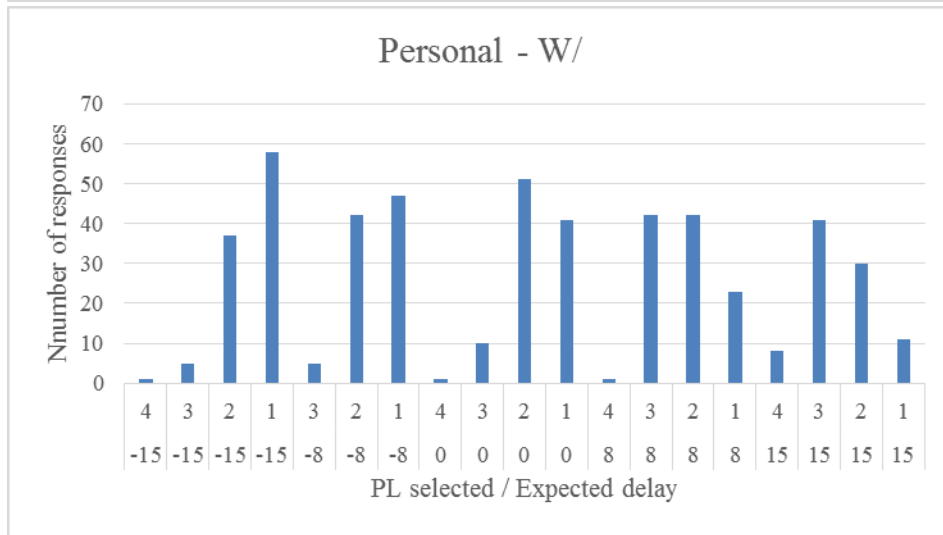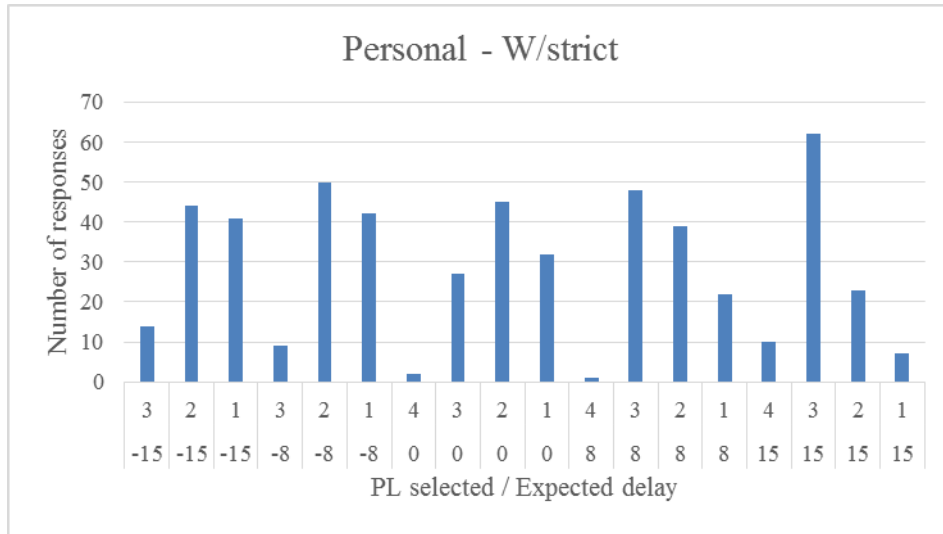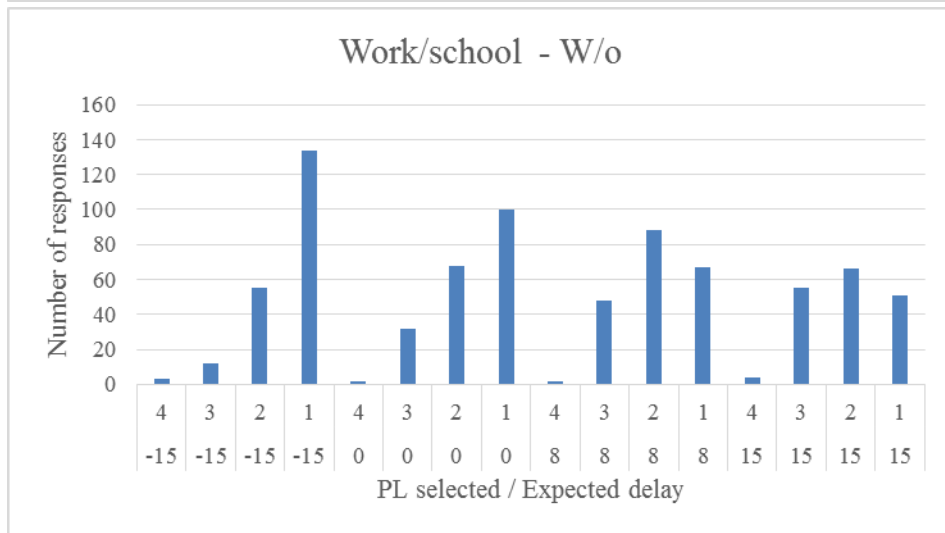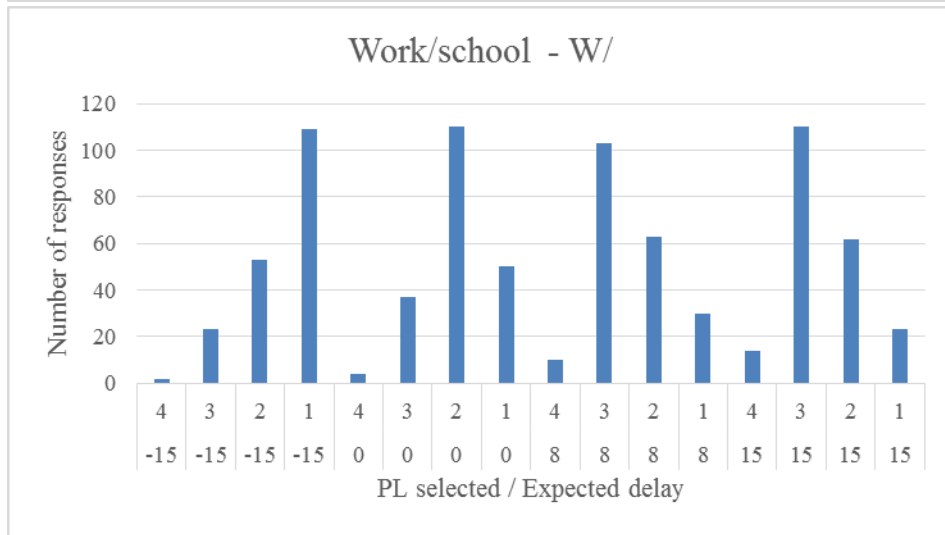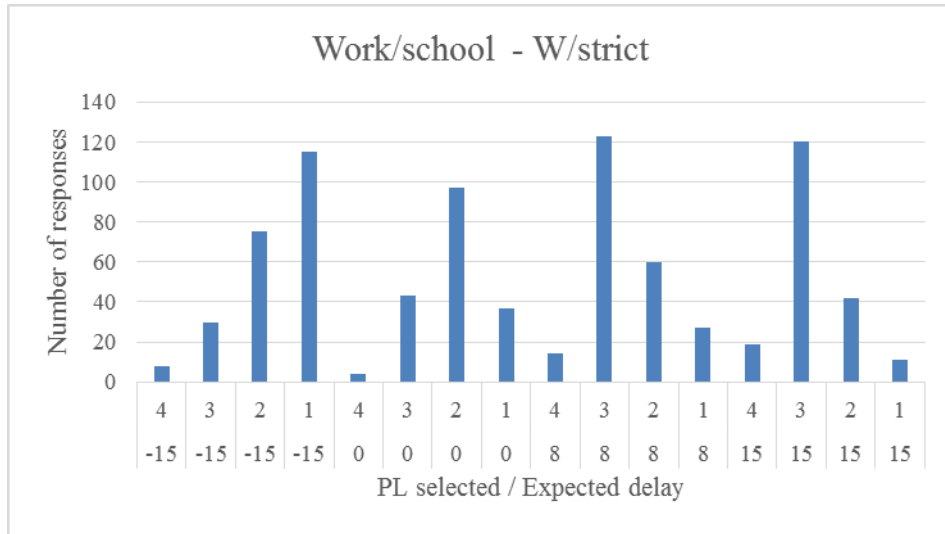**Figure 23: Number of selections of PL for social trip purpose, varying by time obligation and expected delay**

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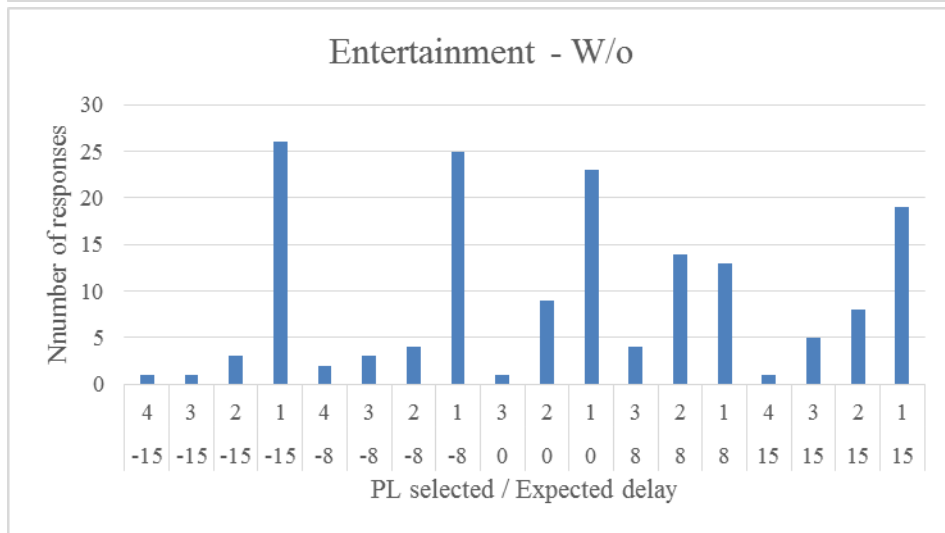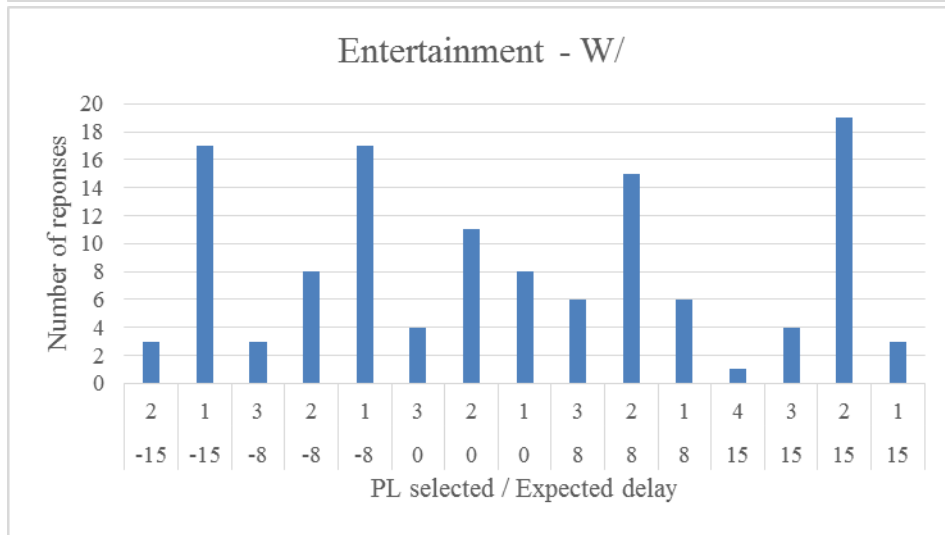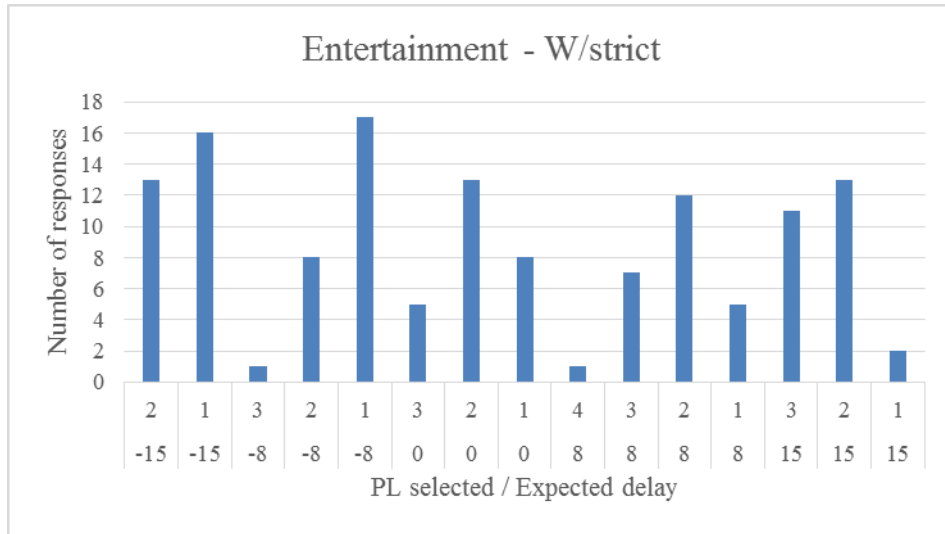
Figure 24: Number of selections of PL for entertainment/sport trip purpose, varying by time obligation and expected delay
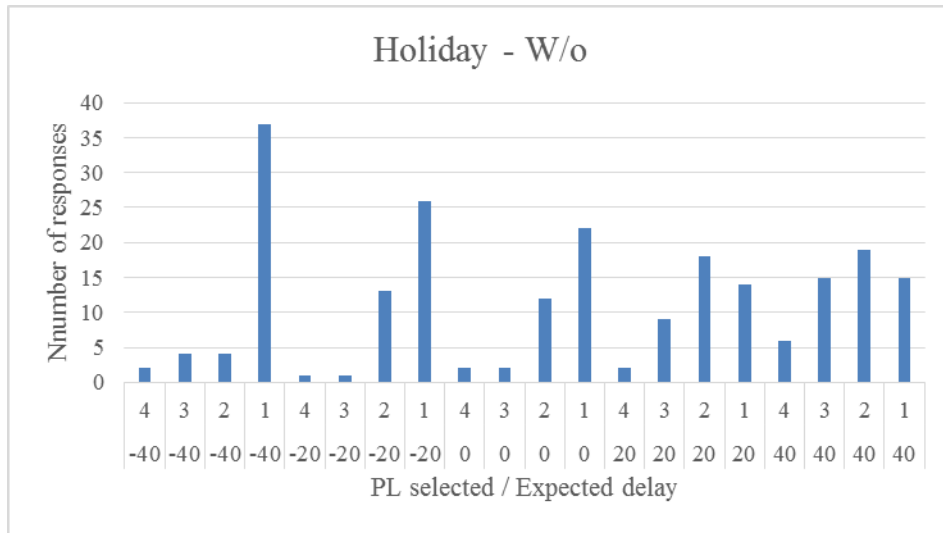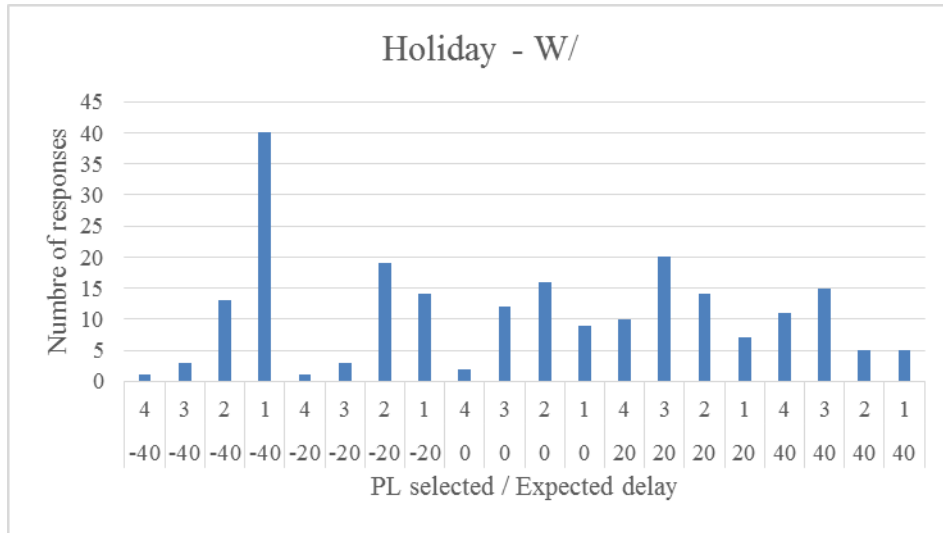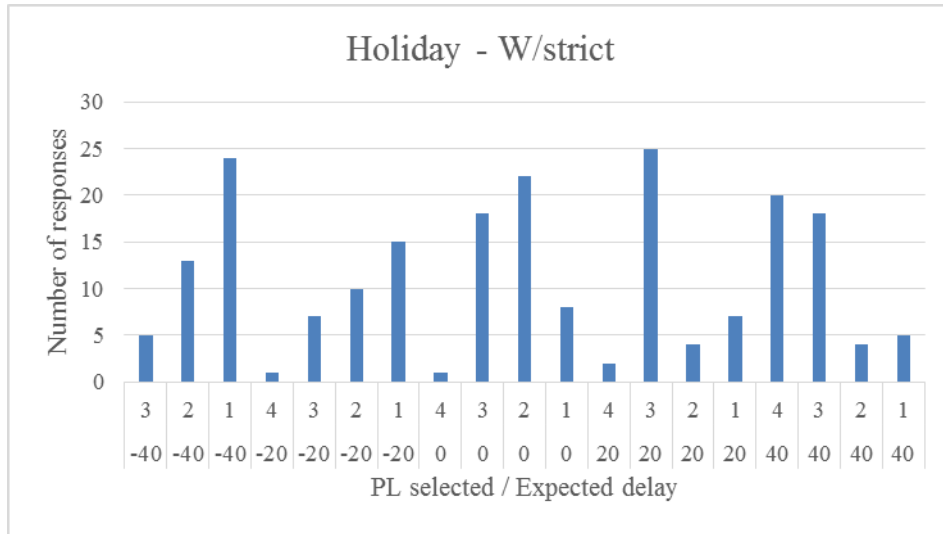
Figure 25: Number of selections of PL for holiday trip purpose, varying by time obligation and expected delay

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Figure 26: Number of selections of PL for personal business trip purpose, varying by time obligation and expected delay

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Figure 27: Number of selections of PL for work/school trip purpose, varying by time obligation and expected delay
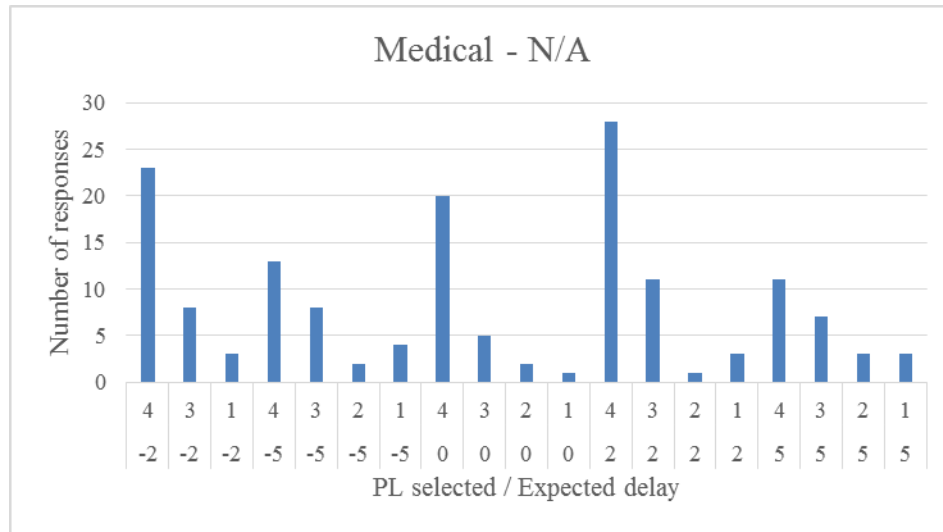
Figure 28: Number of selections of PL for medical trip purpose, varying by expected delay

Figure 29 shows number of PL selections per PL and based on the available $\mathbb{C}$ for the user. One can observe that most of the selections were done at 20, 22, and 24 $\mathbb{C}$, but that users were selecting at all $\mathbb{C}$ values. However, selection of PL 4 does not occur at below 10 $\mathbb{C}$, and selection of PL 3 does not occur at 0 $\mathbb{C}$. In addition, the ratio of PL selected is similar for great majority of available $\mathbb{C}$ values, where the frequency of PL selection is inverse to PL value.
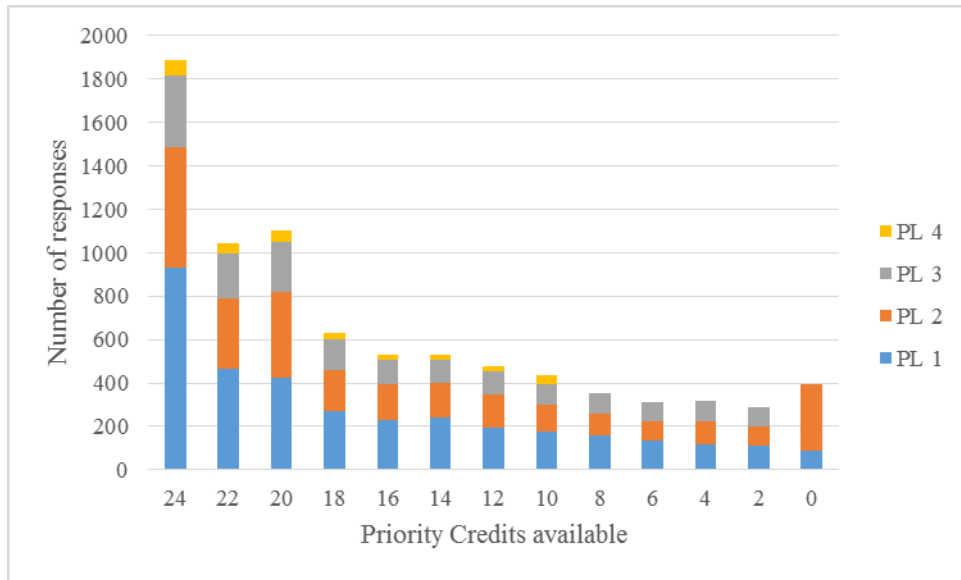
Figure 29: Number of PL selections based on Priority Credits available

Figure 30 shows three types of user behavior in selecting their PL in relation to available $\mathbb{C}$. Participant 64 is an example of risk averse user, always trying to remain around maximum $\mathbb{C}$. Participant 7 is an example of user trying to remain above 10 $\mathbb{C}$, as a critical value for selecting PL 4. Finally, participant 59 is an example of user that covers a wide range of $\mathbb{C}$ values.
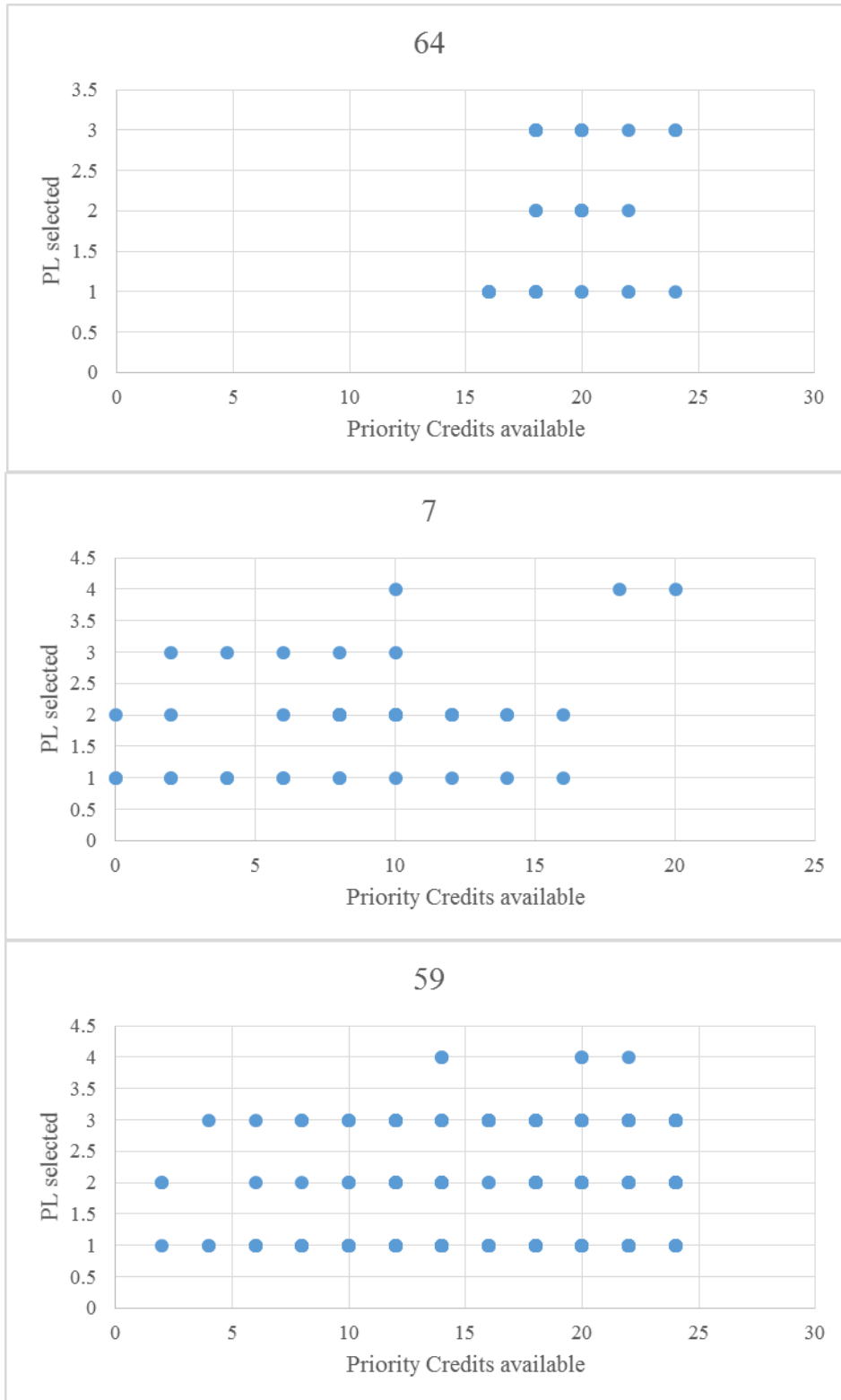
Figure 30: Examples of PL selected in relation to Priority Credits available

Further analysis shows that, from 8311 PL selections, 392 of these selections were at 0 ₵, or 4.7%. Having in mind that at 0 ₵ user cannot select both PL 3 and PL 4, this is not a significant percentage. However, although in long-term system operation, more users might arrive to 0 ₵, there is a learning process involved with long-term interaction, potentially resulting in better ₵ management. In addition, average PL selected was 1.8, while median PL selected was 2, confirming previous observation that participants mostly selected PL 1 and PL 2.

Summary of Respondents Comments

In addition to PL selection, there are comments that participants provided during PL selection, and on the Exit page. They are organized into following 6 groups.

1. Positive features

- Ability for user to prioritize and use highest PL for emergency situations.
- PS is forcing users to think about their choices and to plan ahead their time.
- PS deters abuse (e.g., with the maximum limit for ₵, high ₵ value for PL 4).
- Fair ₵ distribution and ability to save.

2. Potential for system failure

- Concern from self-centered human nature and differences in evaluating different PLs that might lead to inflated sense of urgency and frequent selection of higher PLs.
- Favoring individuals with more education, planning or management skills.
- Remaining without ₵ but facing an emergency situation.
- Using meaningless and short trips to accumulate ₵.
- Alternating between assigning PL 1 and PL 3.
- No incentive to select PL 1 once ₵ are at 24.
- Users that do not drive much could use higher PLs more often.
- If an area simultaneously accommodates many users with medical conditions or appointments, where users assign high PLs all the time.
- Incentive to spend ₵ when a user has them.

3. Further development

- Priority credits should be tied to an individual instead to a vehicle.
- PL should be adjustable during the trip, as the need arises.
- Highest PL should be only activated by external mechanism (e.g., calling police).
- PL should be assigned and ₵ lost/gained based on destination and arrival time needed.
- There should be a mechanism for post-activation verification for highest PL and for spending/gaining ₵ (e.g., medical emergency).
- There should be a separate emergency ₵.
- There should be different mechanism for gaining ₵ (e.g., reporting incidents, using zero emission vehicle, using active or public transportation).
- The importance of PLs should be inverse (PL 1 being the most important).
- PS should be combined with trip information service to reduce system abuse.
- There should be minimum distance or minimum amount of time SDV needs to be stationary for receiving ₵.
- There should be maximum number of ₵ user can gain during certain time.
- Medical emergencies should not cost ₵ or there should be
- Low PL trip with no conflicts at an intersection should not gain ₵.
- PL should be determined by someone who is unbiased (e.g., third party customer representative).
- User should know in advance how long it will take to travel with each PL.
- Route, speed, or road lane for SDV could be determined based selected PL.
- There should be an option for combining several PLs and their ₵ for carpooling.
- There should be three or five PLs, without PL that does not lose or gain ₵, or with higher max ₵ but along with higher ₵ loss for selecting higher PLs.
- Activation of highest PL (or separate emergency PL) should drive SDV to the nearest hospital, with fines for misuse.
- PL 4 should only be available for selection if SDV's destination is on the predefined list (e.g., hospital).
- Gain of ₵ for lowest PL should have higher value.
- PS should be setup differently for delivery vehicles, taxis, or infrastructure support vehicles (e.g., more ₵, less PLs).
- Loosing and gaining ₵ based on the number of ₵ that user has (e.g., as ₵ number increases, gaining less ₵).
- People that need frequent medical care or voluntary firemen should have more starting ₵.
- There should be monetary component related to PLs or ₵ (e.g., either as paying, exchange for bitcoins, or as market).
- Further development will need to take into consideration local culture, values, etc.

4. User factors

- Estimated arrival at destination (e.g., depending on departure time or trip duration)
- Value of time punctuality and consequences
- Culture and habits (e.g., value of time, acceptance for being late to social events vs. doctor's appointment, level of relationship, ability to call ahead, ability to "blame it on traffic", understanding for repeated lateness to social events because of other obligations, acceptable arrival window for activity, dinner reservation, being always late for social events)
- Relative importance of the destination/activity (shopping low, plane important but not as emergency)
- Other people involved or in the vehicle
- Next obligation (e.g., shopping might not be important, but might become based on the next activity)
- Time available in the day
- $\mathbb{C}$ (e.g., being around 10 $\mathbb{C}$ as a critical value for selecting PL 4, intention to save or gain $\mathbb{C}$)

5. General points

- Concern about mechanical failure, hacking, and illegal market for buying/selling priority credits
- Perception of transportation as a service and "selling" arrival on time
- Complexity of trip in time and space and relation to PLs (e.g., higher PL does not mean getting somewhere faster)
- Not losing inherent flexibility in human driving
- Getting used not to have control over the vehicle and the issue that removing a sense of agency from driver that is late can increase stress level
- People do make distinctions between different trips within the same trip purpose – holiday trip to the lake and one that involves taking a plane are not valued equally
- An opinion that an expert system would work better
- Reevaluation of travel time with impact from SDV technology
- Perception that automated vehicles will improve traffic conditions
- Need for real scenario testing and evaluation

6. Other points

- Small number of users would prefer first come, first serve principle instead of priority.
- Participants suggested that there is a need for wider diversity of activities listed in trip purposes, since an activity can significantly influence PL selection.
- There were several cases when participant's decision-making was primarily made from individual perspective, not necessarily taking into consideration other people in traffic. Consequently, there is a need for greater emphasize on cooperation and altruism when presenting PS.
- The arrival time window (i.e., how early or how late one should arrive) highly depend on the activity.
- Low $\mathbb{C}$ number in combination with long estimated travel time and less important activity can influence people to change their departure time.
- Some users expect that other people should plan their daily activities well, and do not support the notion that lack of planning should validate for higher PL.

8.4 Modeling Human Decision-Making within Priority System

Considering that PLs are true categorical outcomes, that are mutually exclusive and collectively exhaustive, the research team decided to use ordinal logistic regression [261]. Ordinal logit model is used when outcomes are inherently ordered, i.e., outcome related to a higher value of the outcome is ranked higher than the outcome related to a lower value of the variable. Basically, this means that the value of each category has meaningful sequential order where one level is actually "higher" than the previous one. However, the ordinal nature of the outcomes does not have implications for differences in the strength of the outcomes. As a result, the ordinal logit model is used to determine the probability of outcome falling in a reference category (i.e., probability of selecting certain PL based on the information about the trip and $\mathbb{C}$). This approach is taking into consideration inherent differences in individual human decision-making, and consequent randomness in human decision-making within the PS.

For example, assume that a probability of selecting PL 1 is P(Y = 1). This value must lie between zero and one, but considering the nature of categorical data, predicted values may be smaller than zero and higher than one. To solve this, probability is replaced with odds that Y = 1. The odds, or Ω(Y = 1), is equal to P(Y = 1)/[1 – P(Y = 1)]. Taking a natural logarithm of the odds is called logit, and represented as Λ(Y). In the case of natural logarithm of the odds, estimated probability of dependent variable cannot exceed maximum or minimum values. Consequently, the equation for the relationship between the dependent and independent variables (X) becomes

$$\Lambda(Y) = \alpha + \beta_1 X_1 + \cdots + \beta_k X_k$$

This relationship can be converted by exponentiation into odds.

$$\Omega(Y = 1) = e^{\alpha + \beta_1 X_1 + \cdots + \beta_k X_k}$$

Finally, we can convert from odds to the probability of selecting PL 1 as

$$P(Y = 1) = \frac{e^{\alpha + \beta_1 X_1 + \cdots + \beta_k X_k}}{1 + e^{\alpha + \beta_1 X_1 + \cdots + \beta_k X_k}} = \frac{1}{1 + e^{-(\alpha + \beta_1 X_1 + \cdots + \beta_k X_k)}}$$

where α is an intercept parameter and $\beta_1, \dots \beta_k$ are coefficients associated with k-th variable. At the end, it is important to emphasize that probability, odds, and logit are three different approaches for expressing exactly the same data relationship. Furthermore, modeling human decision-making using logit regression results in threshold values (θ) of cumulative probabilities, which determine what PL will be selected for specific set of dependent variables. For cumulative logit model, all categories at and below a given threshold value are compared with all the categories above the threshold. In the format that incorporates threshold values, the equation is represented as

$$ln\left[\frac{P(Y \leq i)}{P(Y > i)}\right] = \theta_i - (\beta_1 X_1 + \cdots + \beta_k X_k)$$

where subscripts k = 1, 2, …, K are index predictors, and i = 1, 2, …, I, index categorical values of the dependent variable.

Ordinal logit models were developed using JMP software [90]. Model evaluation is performed using:

1. Whole model test – this test determines if the specified model is significantly better than the reduced model without any effects, not including intercepts, i.e., if all the slope parameters are zero or not.
2. Lack of fit tests – these tests determine if a saturated model is significantly better than the proposed model, i.e., does the model have parameters that should be used in the model.
3. Effect tests – these test determine if the specified model is significantly better than a model without a given effect, i.e., if the model parameters have significant predicting power.

Following several tables (Table 13 to Table 21) show summary of logit models developed, ordinal logistic regression analysis for each of the models, and statistical evaluation parameters. Each of the models had different influencing parameters. This relates to the individual perceptions of relationship between trip purpose, time obligation, time delay, and PS parameters, which was described in the previous section. Clear difference can be observed between trip purposes that are performed more often (e.g work/school, shopping, personal). Decision-making for PL selection in the case of these trip purposes has higher complexity than decision-making for trip purposes that are not as regular (e.g. holiday, entertainment, and social). In the case of medical trip purpose, main influence originates from the number of available $\mathbb{C}$. For medical trip purpose, most of the subjects tend to select PL 4 by default, unless they are restricted by the number of available credits.

Table 13: Summary of logit models' parameters

	Holiday	Shopping	Social	Entertainment	Personal	Work/school	Medical
Intercept 1	-0.6792601	-0.14950425	-0.60689489	-0.46169154	-0.72805837	-0.81674001	-0.38192
Intercept 2	0.89585297	1.70803982	1.54185861	1.70900963	1.26848895	0.98480038	0.21234
Intercept 3	2.86150778	4.18359022	4.34714723	4.26525503	4.2480164	3.9185921	2.06038
Time obligation (w/s)	-0.54556084	-0.6134045	-0.57587799	-0.55040679	-0.65342848	-0.51901311	N/A
Time obligation (w/)	-0.30287747	-0.13044326	-0.02005707	-0.18116382	-0.17618242	-0.17119758	N/A
Time obligation (w/o)	0.84843831	0.74384776	0.59593505	0.73157061	0.8296109	0.69021069	N/A
Estimated delay	-0.03949447	-0.04842235	-0.06219262	-0.07663666	-0.08000233	-0.0782254	-0.02894
Available credits	N/A	0.03627795	0.03300635	0.02470315	0.01359642	N/A	-0.15644
Time obl. (w/s) * Est. delay	N/A	(Delay - 0.242) * -0.00278	N/A	N/A	N/A	(Delay - 1.843) * -0.0128	N/A
Time obl. (w/) * Est. delay	N/A	(Delay - 0.242) * -0.016	N/A	N/A	N/A	(Delay - 1.843) * -0.00822	N/A
Time obl. (w/o) * Est. delay	N/A	(Delay - 0.242) * 0.0144	N/A	N/A	N/A	(Delay - 1.843) * -0.0211	N/A
Time obl. (w/s) * Avail. credits	N/A	(Available - 16.121) * -0.024	N/A	N/A	(Available - 16.369) * -0.0145	N/A	N/A
Time obl. (w/) * Avail. credits	N/A	(Available - 16.121) * 0.00898	N/A	N/A	(Available - 16.369) * -0.0142	N/A	N/A
Time obl. (w/o) * Avail. credits	N/A	(Available - 16.121) * 0.0149	N/A	N/A	(Available - 16.369) * -0.0287	N/A	N/A
Est. delay * Avail. credits	(Delay - 0.153) * (Available - 16.315) * -0.00126	N/A	(Delay - (-0.131)) * (Available - 15.945) * -0.00195	N/A	N/A	N/A	N/A

Table 14: Ordinal logistic regression analysis of selected Priority Levels with a Shopping trip purpose

Term	Estimate	Std. Error	χ^2	Prob > χ^2
Intercept[1]	-0.1495	0.1191	1.57	0.2097
Intercept[2]	1.7080	0.1293	174.43	<.0001*
Intercept[3]	4.1836	0.2398	304.40	<.0001*
Time Obligation - w/strict (STO)	-0.6134	0.0716	73.46	<.0001*
Time Obligation - w/ (MTO)	-0.1304	0.0739	3.12	0.0775
Delay	-0.0484	0.0039	158.12	<.0001*
Available	0.0363	0.0068	28.35	<.0001*
(STO) * (Available-16.3694)	-0.0239	0.0094	6.51	0.0107*
(MTO) * (Available-16.1214)	0.0090	0.0097	0.85	0.3552
(STO) * (Delay-0.2416)	-0.0028	0.0051	0.30	0.586
(MTO) * (Delay-0.2416)	-0.0116	0.0053	4.75	0.0293*

Table 15: Ordinal logistic regression analysis of selected Priority Levels with a Holiday trip purpose

Term	Estimate	Std. Error	χ^2	Prob > χ^2
Intercept[1]	-0.6793	0.0934	52.82	<.0001*
Intercept[2]	0.8958	0.0963	86.54	<.0001*
Intercept[3]	2.8615	0.1539	345.77	<.0001*
Time Obligation - w/strict	-0.5456	0.1076	25.72	<.0001*
Time Obligation - w/	-0.3029	0.1066	8.08	0.0045*
Delay	-0.0395	0.003	173.65	<.0001*
(Delay-0.15314)*(Available-16.3155)	-0.0013	0.0004	12.66	0.0004*

Table 16: Ordinal logistic regression analysis of selected Priority Levels with a Social trip purpose

Term	Estimate	Std. Error	χ^2	Prob > χ^2
Intercept[1]	-0.6069	0.1278	22.58	<.0001*
Intercept[2]	1.5419	0.1364	127.73	<.0001*
Intercept[3]	4.3471	0.2703	258.72	<.0001*
Time Obligation - w/strict	-0.5759	0.0756	58.08	<.0001*
Time Obligation - w/	-0.0201	0.0773	0.07	0.7953
Delay	-0.0622	0.0041	223.19	<.0001*
Available	0.0330	0.0073	20.65	<.0001*
(Delay+0.1308) * (Available-15.9448)	-0.0019	0.0005	14.65	0.0001*

Table 17: Ordinal logistic regression analysis of selected Priority Levels with Entertainment trip purpose

Term	Estimate	Std. Error	χ^2	Prob > χ^2
Intercept[1]	-0.4617	0.2322	3.95	0.0468*
Intercept[2]	1.709	0.249	47.12	<.0001*
Intercept[3]	4.2653	0.4611	85.56	<.0001*
Time Obligation - w/strict	-0.5504	0.1400	15.45	<.0001*
Time Obligation - w/	-0.1812	0.1409	1.65	0.1984
Delay	-0.0766	0.0099	60.25	<.0001*
Available	0.0247	0.0129	3.69	0.0548

Table 18: Ordinal logistic regression analysis of selected Priority Levels with Personal trip purpose

Term	Estimate	Std. Error	χ^2	Prob > χ^2
Intercept[1]	-0.7281	0.1219	35.66	<.0001*
Intercept[2]	1.2685	0.1252	102.69	<.0001*
Intercept[3]	4.2480	0.2201	372.37	<.0001*
Time Obligation - w/strict (STO)	-0.6534	0.0700	87.21	<.0001*
Time Obligation - w/ (MTO)	-0.1762	0.7000	6.34	0.0118*
Delay	-0.0800	0.0050	260.16	<.0001*
Available	0.0136	0.0066	4.26	0.0390*
(STO) * (Available-16.3694)	-0.0145	0.0092	2.48	0.1153
(MTO) * (Available-16.3694)	-0.0142	0.0095	2.24	0.1343

Table 19: Ordinal logistic regression analysis of selected Priority Levels with Work/School trip purpose

Term	Estimate	Std. Error	χ^2	Prob > χ^2
Intercept[1]	-0.8167	0.0482	287.49	<.0001*
Intercept[2]	0.9848	0.0498	390.56	<.0001*
Intercept[3]	3.9186	0.1169	1122.6	<.0001*
Time Obligation - w/strict (STO)	-0.519	0.0553	88.20	<.0001*
Time Obligation - w/ (MTO)	-0.1712	0.0549	9.72	0.0018*
Delay	-0.0782	0.0038	426.16	<.0001*
(STO) * (Delay-1.8427)	-0.0128	0.0049	6.74	0.0094*
(MTO) * (Delay-1.8427)	-0.0082	0.0051	2.64	0.1042

Table 20: Ordinal logistic regression analysis of selected Priority Levels with Medical trip purpose

Term	Estimate	Std. Error	χ^2	Prob > χ^2
Intercept[1]	-0.3819	0.408	0.88	0.3493
Intercept[2]	0.2123	0.3889	0.30	0.5851
Intercept[3]	2.0604	0.4371	22.22	<.0001*
Delay	-0.0289	0.0537	0.29	0.5901
Available	-0.1564	0.0248	39.81	<.0001*

Table 21: Wald and likelihood ratio tests for all trip purposes

Predictor	DF	Holiday Wald χ^2	Holiday L-R χ^2	Shopping Wald χ^2	Shopping L-R χ^2	Social Wald χ^2	Social L-R χ^2	Entertainment Wald χ^2	Entertainment L-R χ^2	Personal Wald χ^2	Personal L-R χ^2	Work/School Wald χ^2	Work/School L-R χ^2	Medical Wald χ^2	Medical L-R χ^2
		Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2	Prob>χ^2
Time Obligation	2	57.78	60.89	105.03	114.11	74.12	76.73	29.01	30.04	146.47	154.33	161.45	167.30	N/A	
		<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*		
Delay	1	173.65	196.37	158.12	170.18	223.19	249.68	60.25	67.04	260.16	285.17	426.15	463.49	0.29	0.29
		<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	0.5901	0.5873
Available	1	N/A		28.35	29.36	20.65	21.36	3.69	3.79	4.26	4.43	N/A		39.81	49.44
				<.0001*	<.0001*	<.0001*	<.0001*	0.0548	0.0516	0.0390*	0.0353*			<.0001*	<.0001*
Delay x Available	1	12.66	13.03	N/A		14.65	14.99	N/A		N/A		N/A		N/A	
		0.0004*	0.0003*			0.0001*	0.0001*								
Time Obligation x Delay	2	N/A		7.31	7.10	N/A		N/A		N/A		17.11	16.65	N/A	
				0.0258*	0.288*							0.0002*	0.0002*		
Time Obligation x Available	2	N/A		6.62	6.93	N/A		N/A		9.63	10.01	N/A		N/A	
				0.0366*	0.0313*					0.0081*	0.0067*				

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8.4 Evaluation using Monte Carlo Simulation Framework

Micro-simulation uses random number generator to determine the time vehicle's time to enter the network. Using Monte Carlo simulation approach, we can use random samples from known populations of simulated data to track a behavior. Consequently, behavior of a variable in random samples can be estimated by the empirical process of drawing many random samples and observing the resulting behavior. Logit models developed as described in the previous section are used to generate PL selected for each specific vehicle in each simulation run. PL generator was developed in MS Excel. Excel's function rand was used to randomly generate trip purpose, time obligation, estimated delay, and available credits for each vehicle agent. Moreover, additional random number was generated, as represented in the Figure 31. Based on the trip information, logit model was used to calculate cumulative probabilities. Additional random number was then compared with these values of cumulative probabilities, and determine the selected PL for specific vehicle, in specific iteration, within specific volume scenario. PL selected per vehicle is converted in text file, which is imported in VISSIM DLL. As a result, each vehicle agent was assigned PL at the time they were created in the simulation.

Volume scenario	Iteration	Vehicle ID	Trip purpose	Time obligation	Estimated delay	Available Credits	RANDOM NUM	Cumulative probabilities from logit models	PL selected
1	1	1	Social	w/o	0	20	0.97716188		3
1	1	2	Holiday	w/	-40	6	0.751337547		2
1	1	3	Holiday	w/strict	0	12	0.135422225		1
1	1	4	Personal	w/	8	12	0.743893574		3
1	1	5	Shopping	w/o	-20	18	0.40855778		1

Figure 31: Example of process for generating PL based on trip and ₡ information using logit models

Volume scenarios (Table 22) are determined based on previous evaluation, considering the thresholds when PS-based operation reaches oversaturation at an isolated intersection. This table shows also a random seeds used in each scenario. At this point, it is important to emphasize that random seeds for conventional and proposed control mechanism were identical. Considering that this is an isolated intersection, inter-arrival times between vehicles generated in a simulation are exponentially distributed.

Table 22: Volume combination for intersection's movement and random seed per testing scenario

Scenario	Volume E+W / T (veh/h/ln)	Volume E+W / L (veh/h/ln)	Volume N+S / T (veh/h/ln)	Volume N+S / L (veh/h/ln)	VISSIM random seed
1	120	30	120	30	1 – 10
2	240	60	240	60	11 – 20
3	360	90	360	90	21 – 30
4	480	120	480	120	31 – 40
5	560	140	560	140	41 – 50
6	120	30	60	15	51 – 60
7	240	60	120	30	61 – 70
8	360	90	180	45	71 – 80
9	480	120	240	60	81 – 90
10	600	150	300	75	91 – 100
11	720	180	360	90	101 – 110

The proposed control mechanism has been comparatively tested with conventional state-of-the-art traffic signal control. Testing was performed on a four-leg isolated intersection. The test VISSIM model has desired speed of 50 km/h for through vehicles, with left-turning velocity set to 25 km/h, as generally accepted value for left turning velocity. Routing and lane change of the vehicles has been under control of static routing and lane change decisions, made upstream from the intersection (approximately 500 m).

Conventional traffic signal control was represented using fully actuated ring-barrier NEMA operation [56], with actuation by 15 m long stop bar detectors. NEMA phase configurations included from two to eight phases. Optimized signal timing parameters were converted into minimum and maximum green for through and left turning traffic in different volume scenarios (Table 4). Signal is operating in Free mode, without fixed cycle length, thus allowing for full signal controller flexibility (e.g., gap out, conditional service, etc.). The upper part of Table 4 shows signal timing for the case of equal traffic on all approaches, while the lower part of Table 4 shows signal timing for volume scenarios based on the premise of minor and major approaches.

The goal of simulation analysis is to compare C1 and C2 for:

1. Average and maximum delay per PL;
2. Average total delay;

A critical comparison is for delay between C1 and C2, for cases when user selects PL 4. The following Table 23 and Figure 32 show the results all simulation runs for conventional (C1) and proposed (C2) control mechanism. Results are shown per simulation scenario. As expected, C2 has lower total average and maximum delay compared to C1 in most of the scenarios. The threshold when C2 becomes less efficient than C1 is when volume is somewhat lower than in scenario 5 and somewhat higher than in scenario 11. This is similar to a threshold that appears for FIFO, that has been proven not to work well for high volume situations [240]. The potential reason for this is that in the cases of higher volume, traffic signal uses queue formation and dissipation for the advantage of forming platoons and reducing gaps between vehicles, thus dissipating queue with a saturation flow rate. In addition, delay for users with PL 4 is always the lowest comparing to other PLs. However, there are cases when two vehicles with PL 4 arrive almost simultaneously at an intersection, so there is always a variation of delay. If there are many of the cases when vehicles with similar PL arrive simultaneously, delay distribution might be skewed to the advantage of lower PLs (e.g., vehicles with PL 2 have lower delay than vehicles with PL 3). However, in average, higher PL has always lower delay value in comparison to lower PL. On the contrary, delay distribution per PL for C1 is not distributed according to PL, since C1 does not take into account the information on PL for operation. Consequently, vehicle with PL 4 and driving a person to the hospital might actually have the highest delay at an intersection.

In comparison to evaluation from Chapter 6, the average delay values from this simulation are little higher in comparison to previously tested PS with 10 PL and uniform PL distribution. This leads us to a conclusion that higher number of PL values provides more control flexibility when vehicles' PLs are compared to determine the right-of-way. In addition, considering that testing was done on isolated intersection, the inherent effects of platoon creation are not utilized. Moreover, this leads a conclusion to the need for further research in developing a coordination mechanism where vehicles could potentially overtake on the link before the intersection points.

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Table 23: Average and maximum delay for conventional and proposed control framework per simulation scenario

		S1		S2		S3		S4		S5		S6		S7		S8		S9		S10		S11	
	PL	Average	Max	Average	Max	Average	Max	Average	Max	Average	Max	Average	Max	Average	Max	Average	Max	Average	Max	Average	Max	Average	Max
C1	PL 1	6.57	27.27	8.29	35.77	23.4	84.5	31.63	108.16	43.01	183.96	5.41	22.88	14.56	77.10	12.97	56.77	15.88	66.87	26.83	91.71	37.10	148.22
	PL 2	6.48	30.87	8.31	37.40	23.1	81.8	31.53	103.86	43.70	164.15	5.43	20.61	14.57	74.89	12.55	50.76	16.18	65.00	26.53	99.36	36.60	154.91
	PL 3	6.56	27.54	8.21	42.36	23.3	79.4	31.02	99.25	43.15	161.22	5.77	18.52	14.05	68.25	12.86	52.22	15.98	67.52	26.93	93.44	37.04	138.01
	PL 4	6.06	21.87	8.19	29.62	22.4	76.4	32.70	97.97	45.41	163.73	6.08	18.92	15.27	66.26	13.09	51.30	15.29	55.35	27.28	88.37	37.92	134.58
	Total	**6.53**	**30.87**	**8.28**	**42.36**	**23.3**	**84.5**	**31.49**	**108.16**	**43.33**	**183.96**	**5.51**	**22.88**	**14.47**	**77.10**	**12.81**	**56.77**	**15.99**	**67.52**	**26.76**	**99.36**	**36.94**	**154.91**
C2	PL 1	1.04	9.94	2.44	14.93	5.13	27.88	12.51	44.63	67.43	140.42	0.62	7.81	1.58	12.31	2.78	17.55	4.79	23.83	8.33	33.98	29.58	77.10
	PL 2	0.59	6.91	1.50	12.08	3.73	24.21	10.60	44.95	66.38	136.87	0.35	6.16	0.95	10.58	1.76	13.72	3.51	23.29	6.66	31.65	28.11	74.10
	PL 3	0.31	4.04	0.94	10.14	2.67	21.15	9.14	41.49	63.72	134.17	0.16	4.64	0.47	6.75	1.11	11.17	2.55	19.71	5.37	27.98	26.52	72.16
	PL 4	0.10	0.40	0.69	4.87	2.20	16.03	8.76	31.20	63.49	123.03	0.12	1.42	0.33	3.41	0.82	6.46	2.00	12.36	4.71	19.13	24.57	63.83
	Total	**0.71**	**9.94**	**1.75**	**15.14**	**4.05**	**27.99**	**11.04**	**46.61**	**66.18**	**140.90**	**0.41**	**8.22**	**1.09**	**12.56**	**2.02**	**17.63**	**3.82**	**24.91**	**7.04**	**34.08**	**28.30**	**77.33**
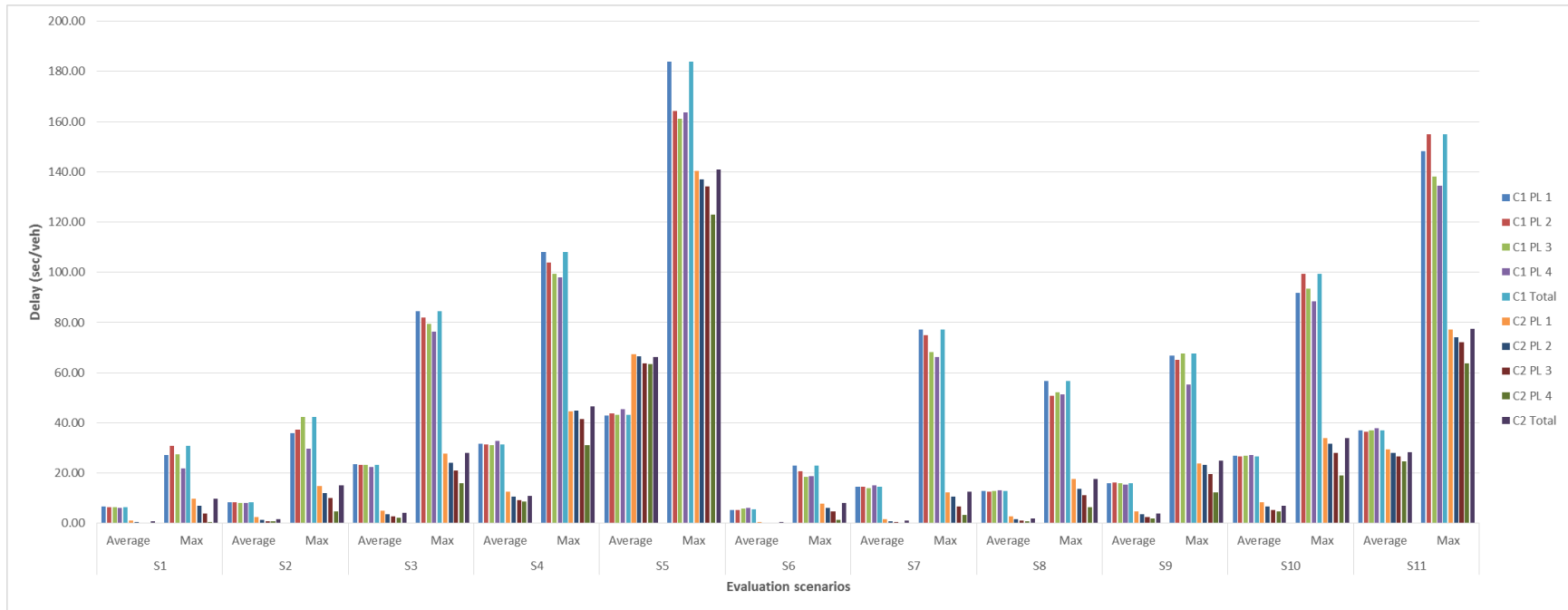
Figure 32: Average and maximum delay for conventional and proposed control framework per simulation scenario

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8.5 Conclusion

In order to evaluate proposed control framework, this chapter has started by implementing a revised Priority System into a web-based experiment. Web-based experiment was developed a series of pages, obtaining consent, providing information, and allowing the subject to interact with PS. Provided with hypothetical trip information and his own ₵, user was supposed to select PL. Results from web-experiment show us that PL selection was altruistic and PL 4 was not selected often for trip purposes different from medical. Consequently, the frequency of PL selection is inverse to PL value, confirming the intended "loss aversion" feature of PS. However, one can notice inevitable randomness in human decision-making, potentially originating from different interpretation individuals have related to trip information or the operation of PS. Moreover, the results were influenced by the short-term interaction perspective that most users had. In addition, web-experiment has provided insights into PS operation, and users have provided a range of comments related to positive features, potential for failure, further development, factors in user decision-making, and general points related to SDV technology.

The information from web-experiment was used to develop logit models of human decision-making within PS. Models were developed per trip purpose, and have consequently included different independent variables. Consequently, these models were capable to include randomness in human decision-making, providing probabilities of selecting specific PL based on trip information and ₵ number. A clear distinction can be made in parameters for more frequent (e.g., work) in comparison to less frequent trip purposes (e.g., holiday). In the last part of this chapter, logit models were integrated within Monte-Carlo simulation framework. They have been used to select PL per user for different simulation scenarios. This information was imported into VISSIM, which could simulate both conventional and proposed control framework. As a result, C2 has showed smaller average delay for scenarios below the saturation points. In addition, delay within C2 is distributed inversely from PL selected, which is not the case in conventional control that does not include information on PL into control process.

9. ENGINEERING SIGNIFICANCE, SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

Transportation technology is an essential element of amenities and social infrastructure that support social sustainability. From a high-level perspective on the stakeholders interested in the traffic signal control development, the author recognizes three main interested parties:

- governmental agencies (state or city Departments of Transportation),
- academic institutions (universities or transportation research institutes),
- companies (organizations providing transportation related services or products)

These three sides are presented on the Figure 33, marked as .gov, .edu, and .com, respectively [262]. All the three parties have a common goal – to affect positively the performance of signal control systems and their effects on safety, efficiency, and environment. These three sides need to be in synergy in order to achieve the global optimum of their common goal.
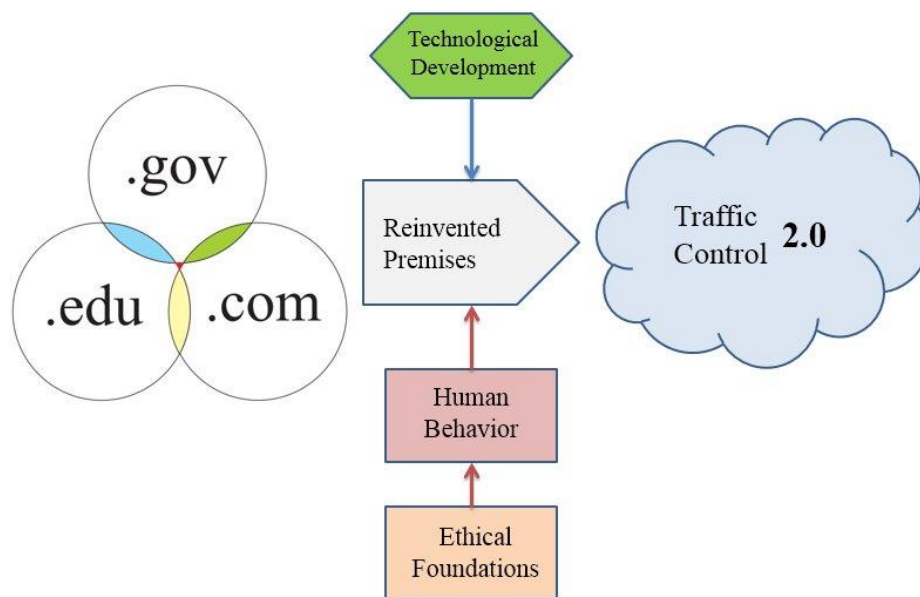
Figure 33: Overview of Development Approach for C2

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This research has started by analyzing the problems in the conventional traffic control systems. We have started this review by identifying the need to understand the dynamical nature of technological development and the way current technological vision for conventional traffic control evolved and became embedded. Historical overview shows us that traffic control technology started developing at the end of 19th century, as an engineering solution to the problem of conflicting flows of users at intersections. Therefore, this technology did not have a long-term vision included in the foundational development. This technological development at the end of 19th and in first part of the 20th century have established conventional traffic control principles as static rules and separation of aggregated conflicting traffic flows using a traffic signal, determining optimality based on minimizing aggregate negative effects, and externalized centralization. Although proving beneficial for several decades, the foundational premises of this solution are currently showing many gaps.

A review has shown that the issues are the result of the discrepancy between local goals that the three main stakeholders have (e.g., economic profit, public satisfaction, etc.). Since these three different parties are also having different constraints, the cooperative overlap is impossible to achieve, and the global optimum is never reached. The original development of traffic control equipment, practice, and theory was based on the engineering solutions for the emerging problem of intersection control. In addition, the conventional approaches in the modern traffic control systems have lost their original focus. Modern traffic signal control systems are becoming increasingly complex and yet can rarely achieve global optimum for all the users. Current approaches to the system control are usually responsive, concerned with local optimums, and cannot successfully accommodate all the requirements for efficiency, safety and reduction of environmental effects. Finally, one of the greatest issues is that the development of theory was superimposed on the already existing device and practice development.

This review concludes that conventional systems have potentially reached their progressive capacity and that there is a need for the reinvention of traffic control systems. Consequently, there is a need for an expansion in the original traffic control perspective established more than a century ago. However, one quote says "you do not invent a light

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bulb with constant small improvements of the candle." The opportunity for reinvention of traffic control principles has become very real, considering the development of in-vehicle computer technology, vehicle sensing, and short-range communication. We, as the community of transportation engineers, have a unique opportunity to reinvent the basic premises of traffic signal control systems while utilizing the capabilities of the distributive computing and sensing power via wireless communications. Considering undergoing foundational development of self-driving vehicle technology, now is the time to shape its long-term vision, considering that already developed technology is hard to change. The community of transportation experts has already recognized the breadth of sustainability requirements for transportation systems. Strategic Plan [30] from Institute of Transportation Engineers points out that public should experience an improved quality of life through an economically, socially and environmentally sustainable transportation system. Consequently, technological decisions stop being only technical decisions, but instead they develop economic, social and environmental implications. Finally, it is important to emphasize that several other communities (e.g., car manufacturers, mobile service providers, etc.) have already recognized the importance of self-driving vehicle technology. However, this introduces a danger that C2 technology will be developed solely with economic purpose. Some authors, e.g., [8], have already pointed out to some of the challenges and open issues. As a result, although we re-emphasize some of those challenges, we also present additional challenges derived from the research presented here.

Theories of social justice provide a framework for distribution of advantages and disadvantages in a society, through a set of rules that distinguish between right and wrong actions [168]. Consequently, a theory of social justice provides a perspective for protecting fundamental human rights. Considering that self-driving vehicle technology is currently under foundational development, the danger arises that, in the absence of an ethical framework, novel traffic-control design might be shaped solely by interests of companies producing the technology. This would result in unjust distribution of the potential benefits of self-driving vehicle technology. As a result, we face a challenge to develop intersection control principles and technology, by utilizing the capabilities of

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self-driving vehicle technology, but attempting to address social aspects, in addition to economic or environmental. Considering that intersections are ubiquitous, the principles of operation for future traffic control technology for self-driving vehicle will impact almost every single individual, throughout their lifetime. If socially sustainable design perspective is not included and addressed through technological development, it will impact not just the human rights of individuals, but the structure and progress of societies as a whole.

This dissertation is proposing a development of novel traffic control framework, with reinvented core premises – named Traffic Signal Control 2.0. The base for development of this system is twofold – philosophical and technological. From the philosophical side, Traffic Signal Control 2.0 (C2) would need to base on the firm ethical principles that would allow the full benefits of the system while constraining any abuse by any of the involved stakeholders. From the technological side, the recent developments of vehicle to vehicle and vehicle to infrastructure communication, along with in-vehicle computing technologies is opening a significant potential for implementation of C2.

In order to develop an expanded vision, we consider that the ethical approach requires anthropocentric perspective. We start from considerations of human needs, represented as fundamental human rights, in a relationship to operating principles for intersections. Human rights are selected as the most fundamental in hierarchy of values, and common to all humanity. In addition, theoretical and empirical investigations have determined the potential for technological development with social considerations included. This developmental approach also has potential for positive influence on public perception of the technology itself. Finally, our starting point for development is envisioning traffic as large-scale, long-term, social phenomenon with a high degree of cooperative automation, functioning as a system for mutually-advantageous cooperative production. The research is inspired by a framework for social justice developed by John Rawls. This framework was used for development and evaluation of C2. Design desiderata are presented, including primarily right to life, and secondary right to equal access to public service and right to the freedom of movement. In addition, a list of technical desiderata are developed.

9.1 Engineering Significance

The significance of this work can be summarized in the following points:

- Providing a holistic review of conventional traffic control technology evolution

- Introducing a new perspective for development of traffic control technology for self-driving vehicles

- Evaluating the capability of conventional control principles to accomplish social justice

- Proposing a traffic control principles within a framework of social justice

- Developing a self-organization control mechanism based on end-user responsibility

- Investigating user's attitudes, behavioral implications, and decision-making in relation to the proposed framework and SDV technology in general

- Evaluating control framework's performance with conclusions and recommendations for further research

9.2 Findings

Chapters 3 and 4 present a long-term vision for the next-generation traffic control systems. The perspective presented here is based upon the premise of mutually-advantageous social cooperation with a priority system, which will guarantee fundamental rights to all the users, but primarily to the least advantaged. Priority System is intended to protect the inviolability of each user. With the shift of the external control component to the user and consequent increase in user's responsibility, there is a potential for user usurpation. The system is suggested to establish a mechanism for preventing user usurpation in the system of long-term cooperation with payoff, reputation building, and sanctioning system.

Chapter 5 and 6 present the development of the control framework. Development of the framework relied upon agent-based modeling approach, where vehicle agents calculate their approach trajectory to the intersection. Vehicle agent performs its actions in a

cooperative framework, interacting with other vehicle agents under realistic constraints, and solving control task for trajectory adjustment. The agent-based model has been programmed using C++, and integrated into VISSIM simulation environment. Test scenarios involved random arrival of vehicles at an isolated four-way intersection. We have validated the developed control mechanism from the safety perspective. In addition, the proposed framework has showed improved benefits in different measurements of social impact. In addition, experimental results showed the potential of agents to adapt and form high performance streams on the link level, even without explicit coordination mechanism.

Chapter 7 presents a survey and interviews conducted to collect feedback on the proposed system design. Survey did not specify complete set of details related to Priority System, but was intended to collect perceptions related to the effects of intersections upon social justice, and elements of moral decision-making related to the intersections as public assets. Survey has showed that user's perceptions are influenced by existing technology but that they perceive the effect traffic control technology has on all life aspects. In addition, survey has shown that there is a potential for development based on social responsibility, despite the respondents concerns and lack of trust in both technology and other citizens. However, the survey has showed us that Priority Level selection cannot exist without a supporting system.

Information from both survey and interviews have showed that PL selection follows a certain global patterns, since people distinguish between low, medium, and high importance trip purposes. Moreover, the results showed us that people can behave altruistically and cooperatively, but that Priority System can also be resilient enough to the fact that people do not follow straightforward rational rules based solely on utility. Moreover, interview participants have provided a set of positive comments, concerns for system failure, a range of factors influencing PL selection, and recommendations for improvement. Finally, we also present some general concerns participants have expressed in relation to SDV technology. All this information is similar to previous findings from social science research, and has provided a basis for further system redesign.

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Chapter 8, in order to evaluate proposed control framework, has started by implementing a revised Priority System into a web-based experiment. Web-based experiment was developed a series of pages, obtaining consent, providing information, and allowing the subject to interact with PS. Provided with hypothetical trip information and his own $\mathbb{C}$, user was supposed to select PL. Results from web-experiment show us that PL selection was altruistic and PL 4 was not selected often for trip purposes different from medical. Consequently, the frequency of PL selection is inverse to PL value, confirming the intended "loss aversion" feature of PS. However, one can notice inevitable randomness in human decision-making, potentially originating from different interpretation individuals have related to trip information or the operation of PS. Moreover, the results were influenced by the short-term interaction perspective that most users had. In addition, web-experiment has provided insights into PS operation, and users have provided a range of comments related to positive features, potential for failure, further development, factors in user decision-making, and general points related to SDV technology.

The information from web-experiment was used to develop logit models of human decision-making within PS. Models were developed per trip purpose, and have consequently included different independent variables. Consequently, these models were capable to include randomness in human decision-making, providing probabilities of selecting specific PL based on trip information and $\mathbb{C}$ number. A clear distinction can be made in parameters for more frequent (e.g., work) in comparison to less frequent trip purposes (e.g., holiday). In the last part of this chapter, logit models were integrated within Monte-Carlo simulation framework. They have been used to select PL per user for different simulation scenarios. This information was imported into VISSIM, which could simulate both conventional and proposed control framework. As a result, C2 has showed smaller average delay for scenarios below the saturation points. In addition, delay within C2 is distributed inversely from PL selected, which is not the case in conventional control that does not include information on PL into control process.

At the end, it is important to emphasize several points. Since the introduction of internal combustion engine and microprocessor technology, transportation has not faced a potential technological impact of this scale. Self-driving vehicle technology is bound to revolutionize transportation, and probably our societies as well. In our research approach, we have tried to aim beyond resolving immediate negative effects, but to take into consideration the long-term impact on society that this technology might have. First, this is specifically related to the notion of common humanity, through our cross-generation responsibility for sustainable development of technology. Moreover, the standpoint for technological development considers that technology is a socio-technical phenomenon. Consequently, decisions related to design of technology seize to be solely technical decisions, but they tend to have direct social implications. In addition, technology is connected with political decision, and can consequently manipulate reality and favor certain social classes [263].

Following this line of thoughts, we cannot lack the conscious reflections on the morals in technology, because it shapes the context of humans as moral agents and consequently it shapes humans themselves. In relation to this, this dissertation proposes an anthropocentric axiom. This perspective places the human being in the center of society and of its ethical values, without ignoring the human responsibility towards other beings, whose lives have a value that is comparable to human, and towards the planet itself. As our intention is, the framework presented here is including one perspective on one framework of social justice, which is again only one of the potential values we can include in the design of SDV technology. This research endeavor was not planned to provide a final solution, but to be used as proof that such an endeavor is possible. The long-term vision for the C2 control systems, will need to achieve a careful balance between the needs of multiple segments of population in the current and future generations. This result, will never be accomplished without a wider discussion, including not just engineers and entrepreneurs, but general public as well. This research has shown the capability of web-based experimentation for redevelopment of PS or development of other approaches for anthropocentric SDV technology.

We have to note that this research does not focus on the issues of privacy, as an important issue in this type of system that relies highly on communication and processing of personal information. In addition, this research only briefly touches upon the important issue of environmental sustainability. Furthermore, this paper does not delve into details regarding the specifics of the technology developed based on the proposed principles (e.g., technology for pedestrians using the intersections) or the questions of feasibility and robustness of the proposed framework.

9.3 Recommendations for Further Research

Following are the points identifying the needs for further research:

- There is a need to establish a common procedure and platform for evaluating a broad range of current and future operational principles.

- There is a need to further investigate potential for the approach where control actions will be the responsibility of individual self-driving vehicles, without centralized control. Examples are already there, with recent developments in decentralized control frameworks and use of model-predictive control approach [37, 120].

- There is a need to investigate potential for varying different control approaches for different traffic situations or network routes.

- There is a need to investigate potential for platoon formation among SDVs [8], especially at the link level. Vehicle speeds could be adjusted ahead of the intersection through multi-hop communication, without waiting for each vehicle to be in the communication range of the intersection. The mechanism could operate based on PL, where vehicles with the same PL create platoons on the network links.

- There is a need to investigate robustness of different system mechanisms to handle nonrecurring events and issues of scalability [8].

- There is a need for investigating optimal trajectory parameters and constraints, which can minimize fuel consumption and emissions.

- There is a need to establish SDV technology development approaches that will include expanded decision-making constituencies. Providing space for reflective vision and critical conversations would provide essential understanding of the relevant values and their function in lives of people and groups.

- There is a need to project and assess all the possible variations in development of SDV technology through constructive technology assessment [177].

- There is a need for greater understanding of human decision-making and planning in relation to the proposed framework but also in relation to trip planning in general. This research has pointed out the difficulties with modeling of human behavior. Consequently, it is important to build robust models that can allow experimentation with different types of behavior. Besides investigation of human behavior, further explorations could rely upon agent-based modelling [264, 265].

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Appendix A – Survey Questions

<u>RELATION BETWEEN SOCIAL JUSTICE AND TRAFFIC CONTROL TECHNOLOGY</u>

Thank you for taking the time to fill out this survey! Your responses are completely anonymous and confidential. The survey should take approximately 7 minutes.

This survey is trying to collect your opinion on the social impact of traffic control technology – for current technology (e.g., traffic light) and for future technology (e.g., self-driving vehicle). This information will be used for research purposes only. The information collected will help us determine social perspectives for designing control technology for self-driving vehicles.

<u>Personal questions:</u>

1. What is your gender?

    a. Male

    b. Female

2. Please tell us the year you are born in. _____

3. Please indicate your ethnicity

    a. American Indian/Native American

    b. Asian/Asian American

    c. Pacific Islander

    d. Black/African American

    e. Hispanic/Latino(a)

    f. White/European American

    g. Other _____ (please specify)

4. What is your highest education?

    a) Some High School

b) High School Diploma

c) Some College

d) Associate's Degree

e) Bachelor's Degree

f) Graduate Degree

g) Professional Degree

h) Vocational Training

i) Other:_____ (please specify)

5. What is your current annual household income?

    a. $< 15,000\$$

    b. $15 - 27$

    c. $27 - 44$

    d. $44 - 73$

    e. $73 - 147$

    f. $147 - 356$

    g. > 356

    h. Prefer not to answer

6. Do you usually drive in:

    a. Urban streets

    b. Suburbs

    c. Rural highways

Social justice and traffic control technology

7. How would you briefly describe your understanding of the term "better intersection control technology"

_____

8. In your opinion, how much does traffic control technology (e.g., traffic signal) impact the fulfilment of your following needs (categories bellow are according to Maslow's hierarchy of needs) (check all that apply):

    a. Physiological needs (e.g., breathing, food, water, sleep, etc.)

    b. Safety (e.g., security of body, security of employment, security of resources, security of health, security of property)

    c. Love/belonging (e.g., friendship, family, etc.)

    d. Esteem (e.g., self-esteem, confidence, respect for others, respect from others, etc.)

    e. Self-actualization (e.g., morality, creativity, problem solving, lack of prejudice, etc.)

9. Driving through a red light at an empty intersection because you are late for work is a wrong action.

    a. Strongly disagree

    b. Slightly disagree

    c. Neutral

    d. Slightly agree

    e. Strongly agree

10. In your opinion, how important is to include principles of social justice into technology design?

    a. Very important

b. Somewhat important

c. Neutral

d. Not very important

e. Not at all important

11. In your opinion, does traffic control technology (e.g., traffic signal) affect (check all that apply):

   a. Your safety while going through the intersection

   b. Your travel time on the way to your destination

   c. The environment through air pollution and noise

   d. Other _____

   e. All of the above

   f. None of the above

12. If you answered in question 11, that traffic control technology affects your travel time, do you think that further affects (check all that apply):

   a. Right to life (e.g., while traveling to the hospital)

   b. Right to work (e.g., while traveling to a job interview)

   c. Right to leisure (e.g., while traveling to entertainment)

   d. Right to standard of living adequate for health (e.g., while traveling to the dentist)

   e. Right to education (e.g., while traveling to school)

   f. Other_____

   g. All of the above

   h. None of the above

13. Would you pay to receive the right-of-way through the intersection before someone else?

  a. Yes – why

  b. No – why

  c. Maybe – why

14. When would you accept waiting at the intersection, considering that the traffic light was set-up to benefit all the users (check all that apply):

  a. While going to the hospital

  b. While going to the funeral

  c. While going to a job interview

  d. While going to the grocery store

  e. While going to the beach

  f. Never

  g. Always

Questions 15 – 17. Imagine the following scenario: You are approaching a four-way stop intersection. At the same time, another vehicle is about to arrive to the intersection from a different street. You have a way to know a trip purpose for the person in that other vehicle. In addition, there is a mechanism for reciprocity – i.e., if you decide to let that other vehicle go through the intersection before you, you will receive the right-of-way next time in the near future.

15. Imagine <u>you are going to a vacation</u>. Would you let that vehicle pass if the person in that vehicle is (check all that apply):

  a. going to the hospital

  b. going to the funeral

  c. going to job interview

  d. going to the grocery store

  e. going to the beach

16. Imagine <u>you are going to an important job interview</u>. Would you let that vehicle pass if the person in that vehicle is (check all that apply):

    a. going to the hospital

    b. going to the funeral

    c. going to job interview

    d. going to the grocery store

    e. going to the beach

17. Imagine <u>you are going to the hospital.</u> Would you let that vehicle pass if the person in that vehicle is (check all that apply):

    a. going to the hospital

    b. going to the funeral

    c. going to job interview

    d. going to the grocery store

    e. going to the beach

Questions 18 – 20. Imagine you could assign a Priority Level from 1 to 10 to your trip, and that number will be compared to Priority Levels of other vehicles to determine when will you receive the-right-of-way (assuming that 10 is the most important, and 1 is the least important). Now, imagine each individual, including you, has a certain number of non-monetary Priority Credits that are used to select Priority Level for the trip.

18. Considering your common trip purposes, could you provide examples of what would the trip purpose be when you would assign Priority Level 1 (extremely unimportant), Priority Level 5 (neutral), and Priority Level 10 (emergency)?

    a. PL 1 _____

    b. PL 5 _____

    c. PL 10 _____

19. Assign your perceived Priority Level (1 – 10) for the following trip purposes

    a. Work/school

    b. Shopping

    c. Personal business

    d. Medical/dental

    e. Social/visit friends

    f. Entertainment/sport

    g. Holiday

    h. Other (please specify) _____

20. How should Priority Credits be initially assigned?

    a. Everybody should have the same number of credits

    b. People with disabilities should have more credits

    c. More productive people should have more credits

    d. Distribute credits to produce the greatest total amount of good in the world

    e. Distribute credits to meet the basic needs of everyone

    f. Other (please specify) _____

    g. Not sure

Considering that self-driving vehicles are an emerging technology. This section tries to obtain your opinion for a hypothetical situation, where the system will operate based on the credit system.

21. Do you think that the mechanism for assigning the right-of-way at the intersection for self-driving vehicles should be publicly decided?

    a. Yes

b. No

c. Maybe

22. Will you be willing to pay higher price for a self-driving vehicle technology that will protect your human rights (e.g., by ensuring you receive the right-of-way in urgent situations)?

    a. Yes

    b. No

    c. Maybe

23. Would you provide support for including social justice into the development of control technology for self-driving vehicles? (check all that apply)

    a. Political (e.g., voting, lobbying)

    b. Financial (e.g., donation, fund-raising)

    c. Social (e.g., volunteering, public discussions)

    d. Not interested in providing support

24. Any other comments or recommendations regarding including social justice into the development of traffic control technology?

_____

Appendix B – Interview Protocol

INTERSECTION CONTROL TECHNOLOGY FOR SELF-DRIVING VEHICLE – INTERVIEW PROTOCOL

STAGE 1

Coded Number: _____

<u>Questions:</u>

1) Do you have a driver's license?

- o Yes

- o No

2) How old are you? _____

3) What is your gender?

- o Male

- o Female

4) What is your highest education?

- o Some High School

- o High School Diploma

- o Some College

- o Associate's Degree

- o Bachelor's Degree

- o Graduate Degree

- o Professional Degree

- o Vocational Training

- o Other:_____ (please specify)

5) Which of the following racial categories best describes you? You may select more than one.

- o American Indian or Alaska Native

- o Asian

- o Black or African American

- o Hispanic or Latino

- o Native Hawaiian or other Pacific Islander

- o White

6) How often do you drive a motor vehicle?

- o Never

- o Almost every day

- o A few days a week

- o A few days a month

- o A few days a year

7) Do you usually drive in?

- o Urban streets

- o Suburbs

- o Rural highways

8) How would you briefly describe your understanding of the term "better intersection control technology"?

_____

9) In your opinion, does traffic control technology (e.g., traffic signal) impact the fulfillment of your following needs? (check all that apply)

- o Physiological needs (e.g., breathing, food, water, sleep, etc.)

- o Safety (e.g., security of body, security of employment, security of resources, security of health, security of property)

- o Love/belonging (e.g., friendship, family, etc.)

- o Esteem (e.g., self-esteem, confidence, respect for others, respect from others, etc.)

- o Self-actualization (e.g., morality, creativity, problem solving, lack of prejudice, etc.)

10) In your opinion, does traffic control technology (e.g., traffic signal) affect (check all that apply):

- o Your safety while going through the intersection

- o Your travel time on the way to your destination

- o The environment (e.g., through air pollution and noise)

- o All of the above

- o None of the above

- o Other _____

STAGE 2

Self-driving vehicle is a vehicle designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip.

With self-driving vehicle, your vehicle, driving itself towards the intersection, will be able to communicate with the other vehicle approaching intersection, and they will be able to agree who will slow down, and who will maintain their speed. However, the decision is up to you.

At this point, it is important to emphasize some key points related to this system. This system is intended to protect your fundamental human rights by allowing you to select higher PL in the more important and urgent trips. However, there are certain points we need to emphasize besides this.

1. An individual is just a part of the overall traffic. Traffic is a social phenomenon. Everybody else, just like you, is going somewhere to fulfill their need.

2. In addition, traffic is large-scale and long-term system. There are many users, most of whom you don't know, but you interact with throughout your lifetime.

3. Finally, you are interconnected with those other users. You all have a need to cross through the intersection, but you cannot all do it at the same time.

In the next fifteen minutes, you will be put in a scenario of approaching an intersection in a self-driving vehicle. You will be assigned a hypothetical trip purpose from the following: **Holiday, Shopping, Social/visit friends, Entertainment/sport, Personal business, Work/school, Medical/dental**. According to this trip purpose, you will pick one Priority Level from one to ten. These Priority Levels are ordered as following:

1. Extremely unimportant	2. Very unimportant	3. Unimportant	4. Slightly unimportant	5. Neutral	6. Slightly important	7. Important	8. Very important	9. Extremely important	10. Emergency

The perspective for operation of this system is: "those who want to share justice, will receive justice". It is based on the premise that, when you need to go to an e.g., emergency room, that other vehicle will slow down, and on the contrary, some other day, when some other vehicle needs to go to an emergency room, and you are for example going shopping, your vehicle will slow down.

You will start with 20 Priority Credits. The trip purpose will be assigned randomly to you. You will then select the PL, and then your new number of Priority Credits will recalculate. In the next round, you will start with that new number of Priority Credits, and will need to select PL again, based on the trip purpose. Please, take PL selection as if this was implemented in the long term, and you would have to use it your whole life.

This is the way you will lose or gain credits based on the PL you select. It will only be possible to accumulate up to 25 credits. When you reach 0 credits, the system will automatically select PL 1 for any trip purpose assigned in that trial. There will be 21 trials total.

Priority Level	1	2	3	4	5	6	7	8	9	10
Credits	4	3	2	1	0	-1	-2	-3	-4	-5

11) Priority Level selection process

Num.	Trip purpose	Traffic Level	Priority Credits	PL selected	Why did you select that PL?	What amount of time delay would make you increase PL?
1			20			
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
Num.	Trip purpose	Traffic Level	Priority Credits	PL selected	Why did you select that PL?	What amount of time delay would make you increase PL?
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						

12) What would be your PL selected for following trip purpose in the case of low and high traffic:

Holiday   LOW_____   HIGH_____

Shopping   LOW_____   HIGH_____

Social/visit friends   LOW_____   HIGH_____

Entertainment/sport   LOW_____   HIGH_____

Personal business   LOW_____   HIGH_____

Work/school   LOW_____   HIGH_____

Medical/dental   LOW_____   HIGH_____

STAGE 3

13) Do you think this could be a beneficial system?

- o Yes (how?)

      _____

- o No (why?)

      _____

14) Do you see any way you could "trick" the system?

- o Yes (how?)

      _____

- o No (why?)

      _____

15) Do you see any potential for failure of the system?

_____

16) Do you think that Priority System could operate differently?

_____

17) Do you think that values for gaining or spending credits could be assigned differently?

_____

18) Any other comments?

_____

Appendix C – Results from Interaction with Priority System during Interview

Results presented here include PL that each interview participant selected for a specific trip purpose in the first trial and in cross-validation. In addition, second graph presents PL selected for available Priority Credits. Each combination of two figures presents results for one participant. Consequently, there are 33 figure pairs.

226

227

S5

S7

233

S11

238

Legend: ■ First trial ■ Cross-validation

S15

PL selected vs Priority Credits available
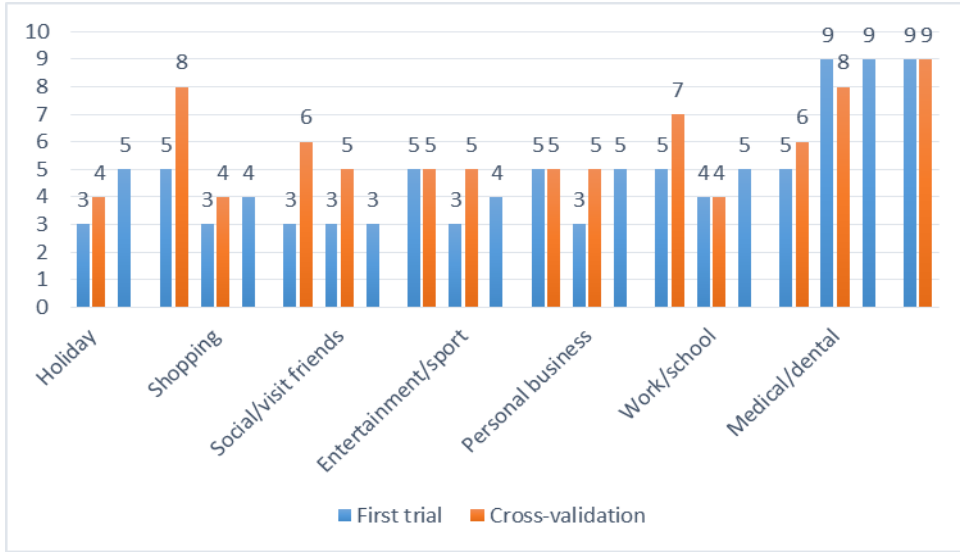
240

S18

S22

S26

S27

251

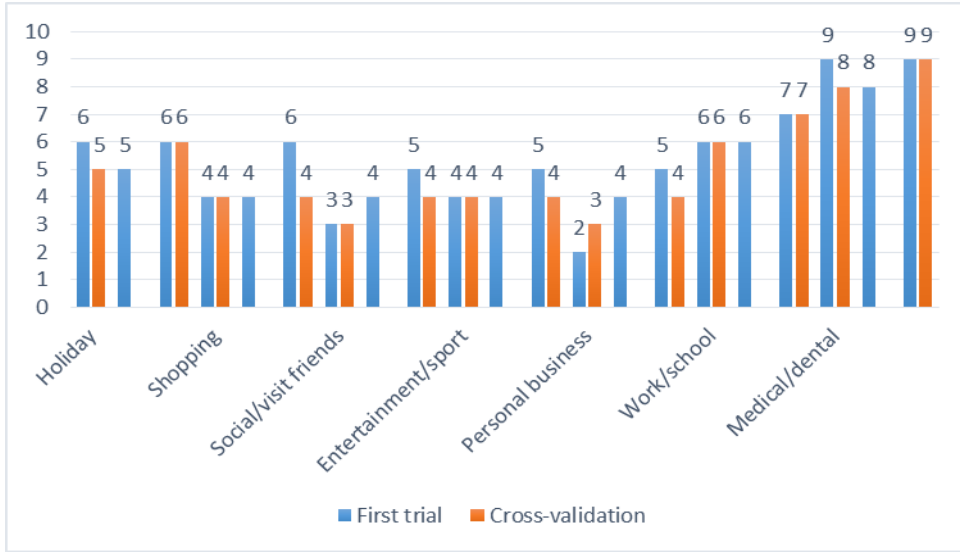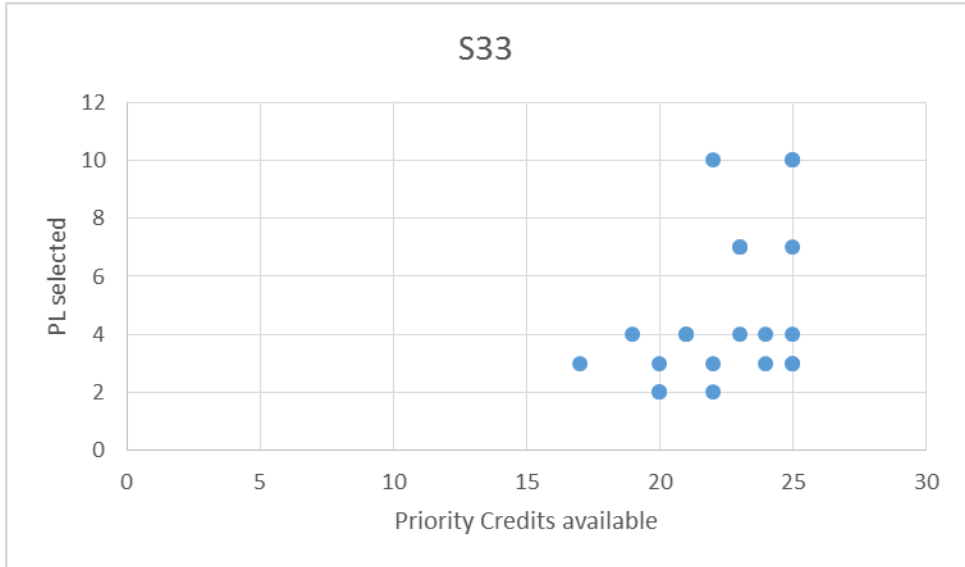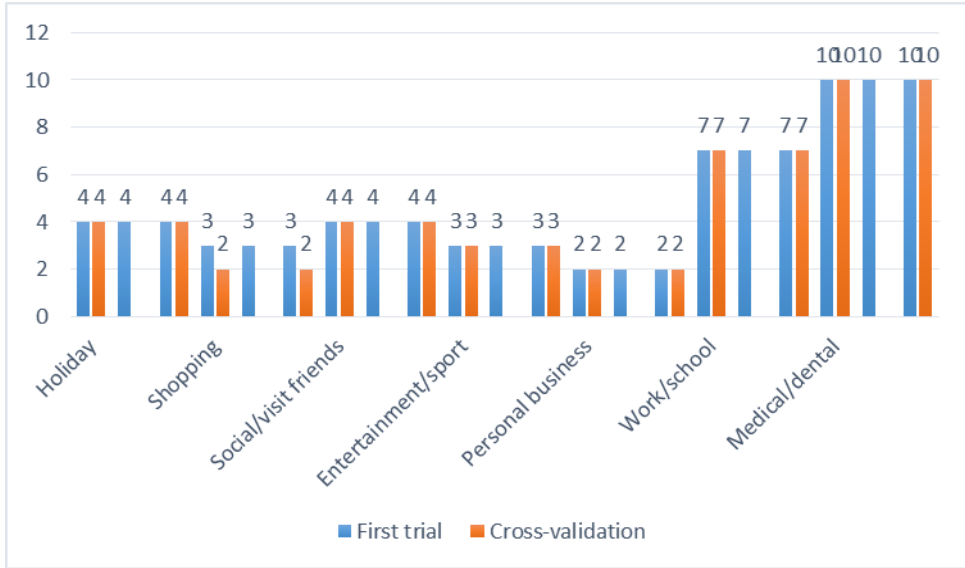S31

257
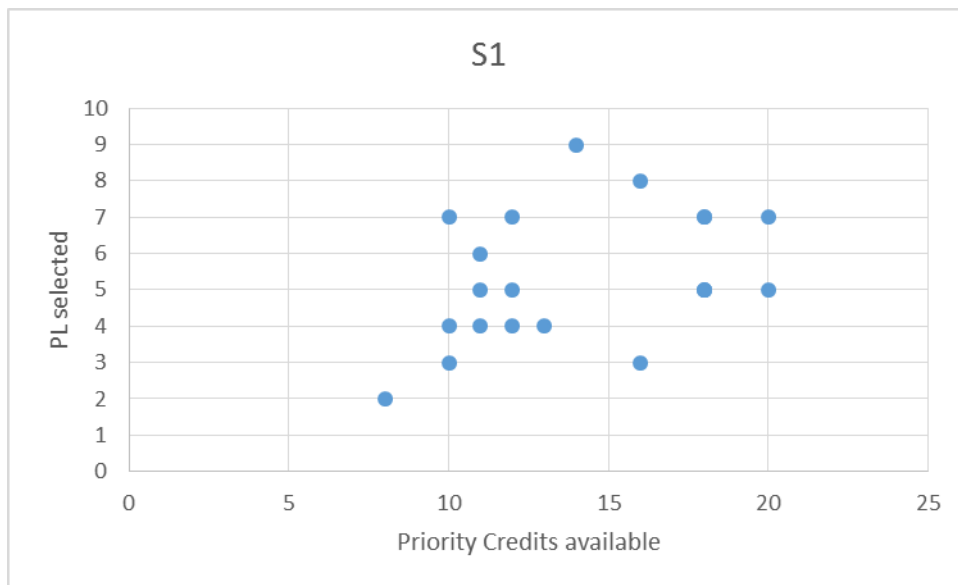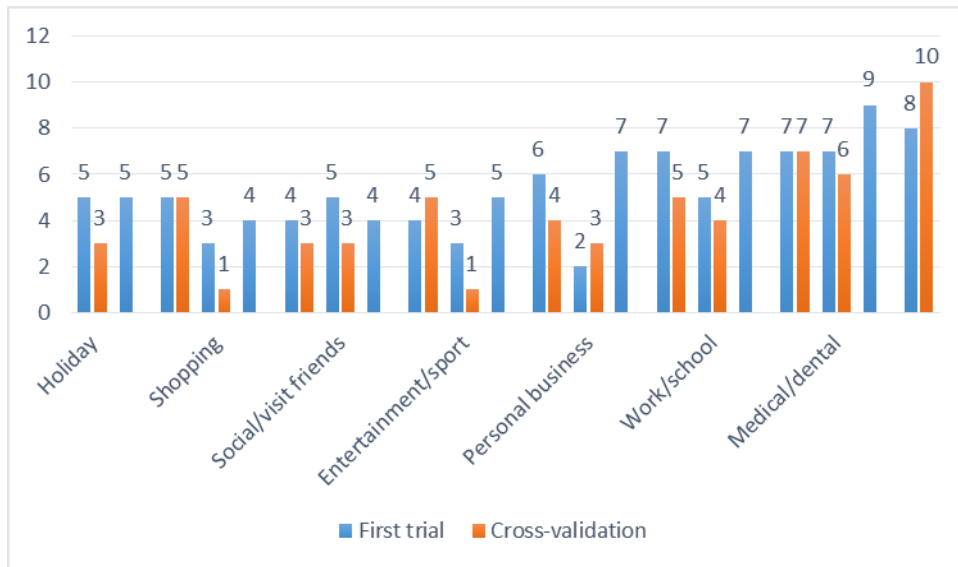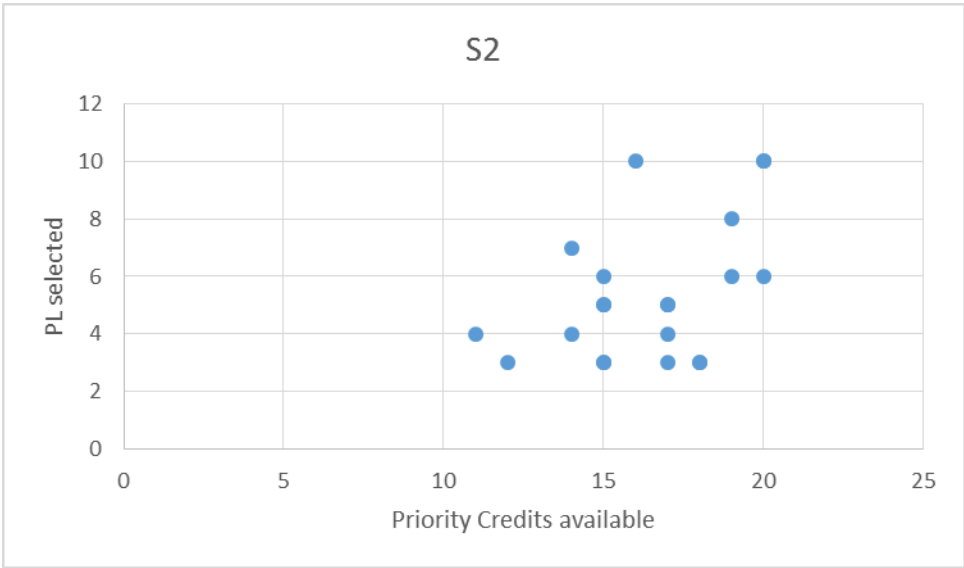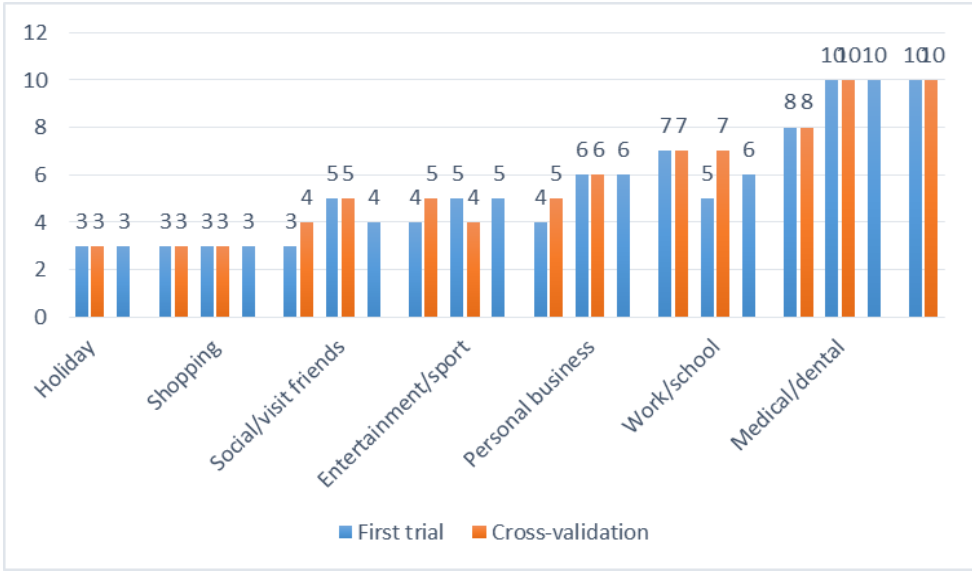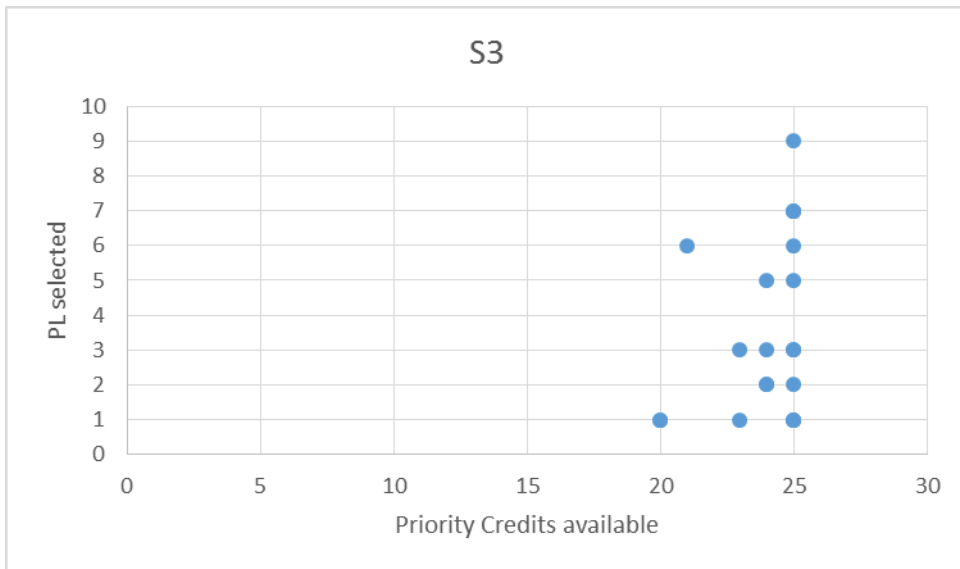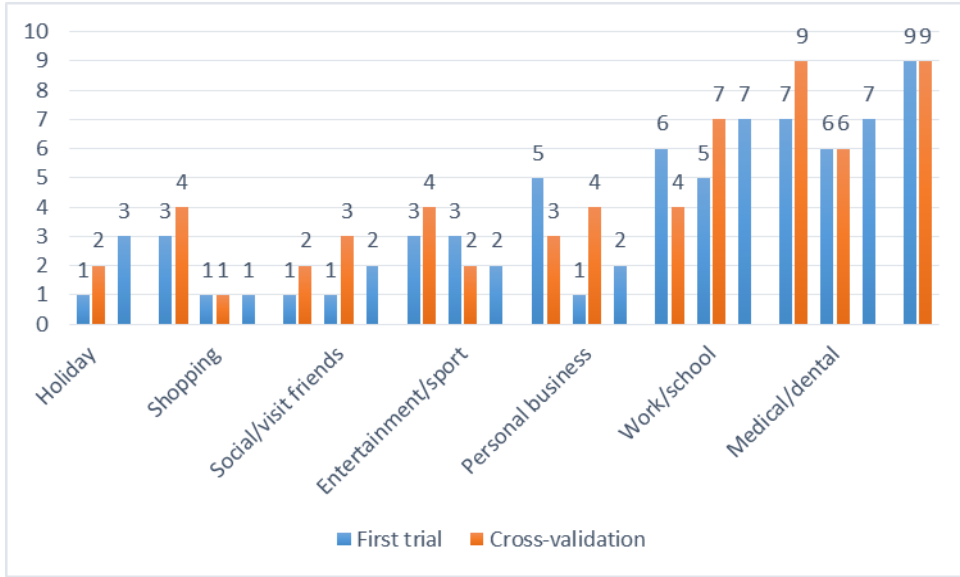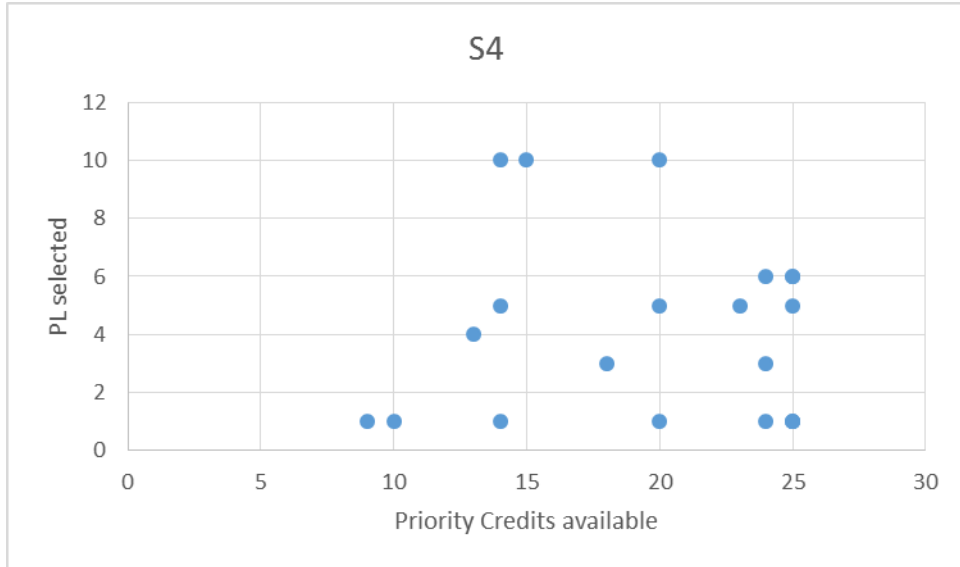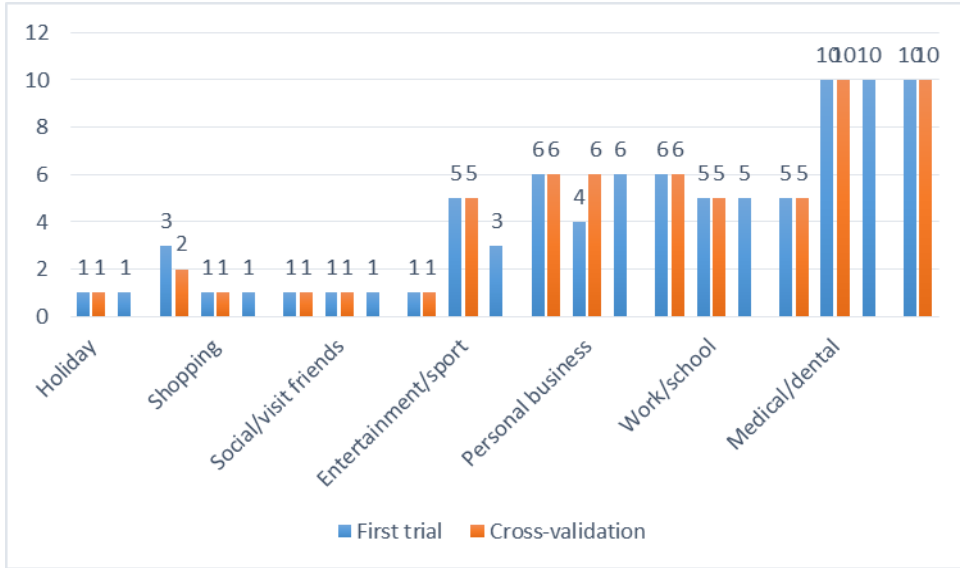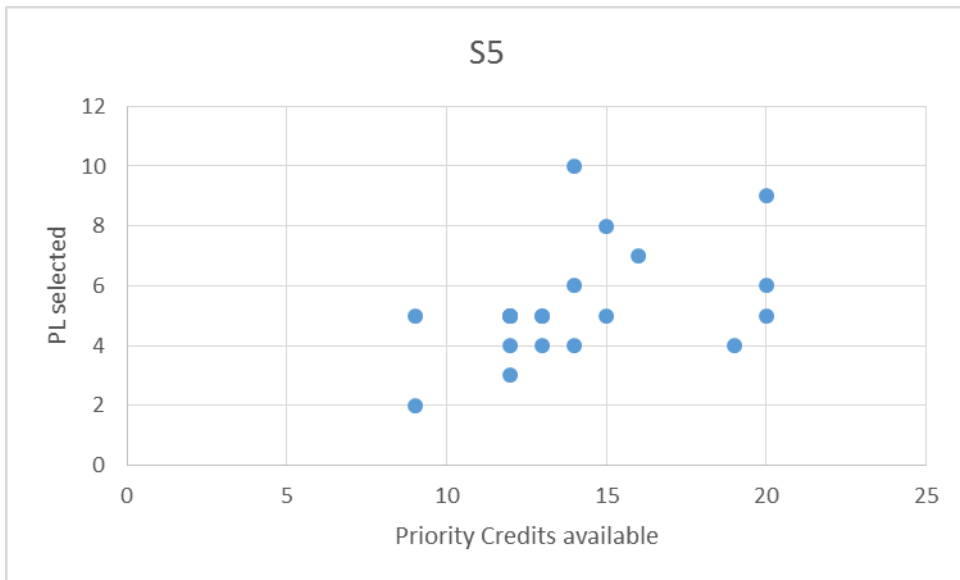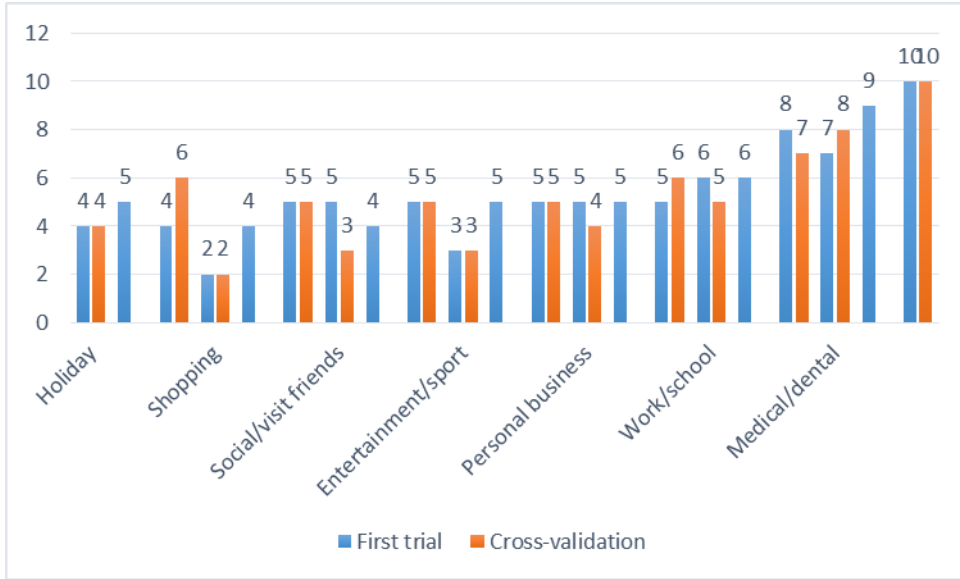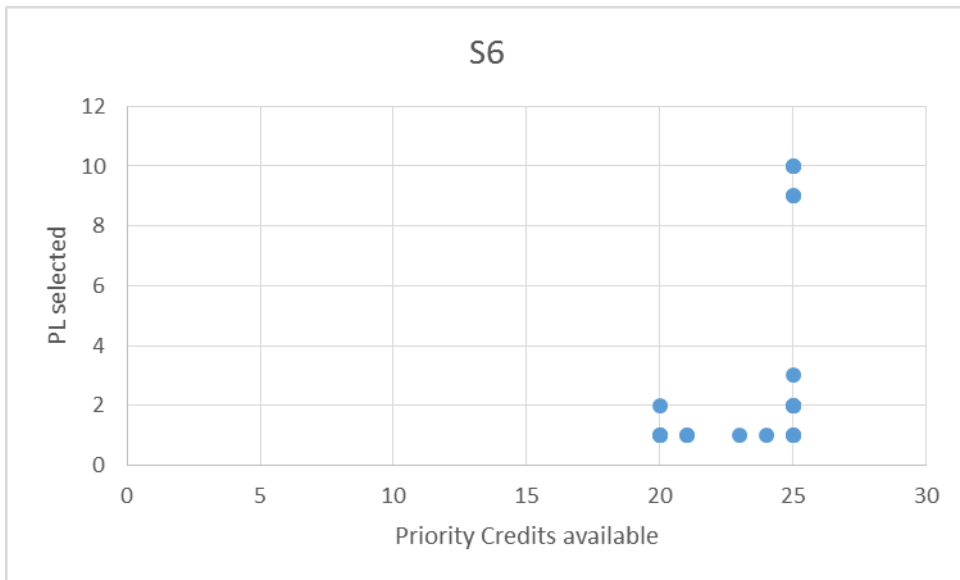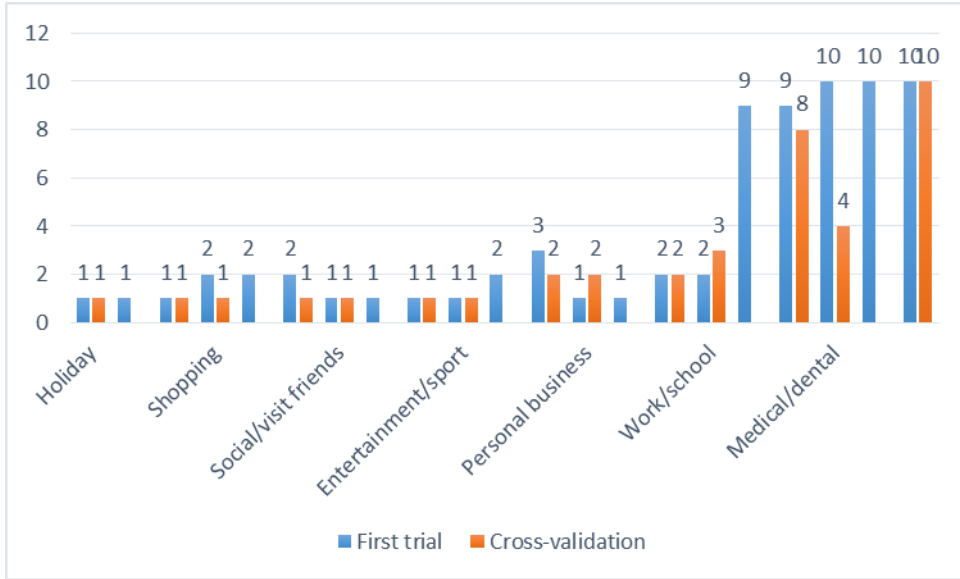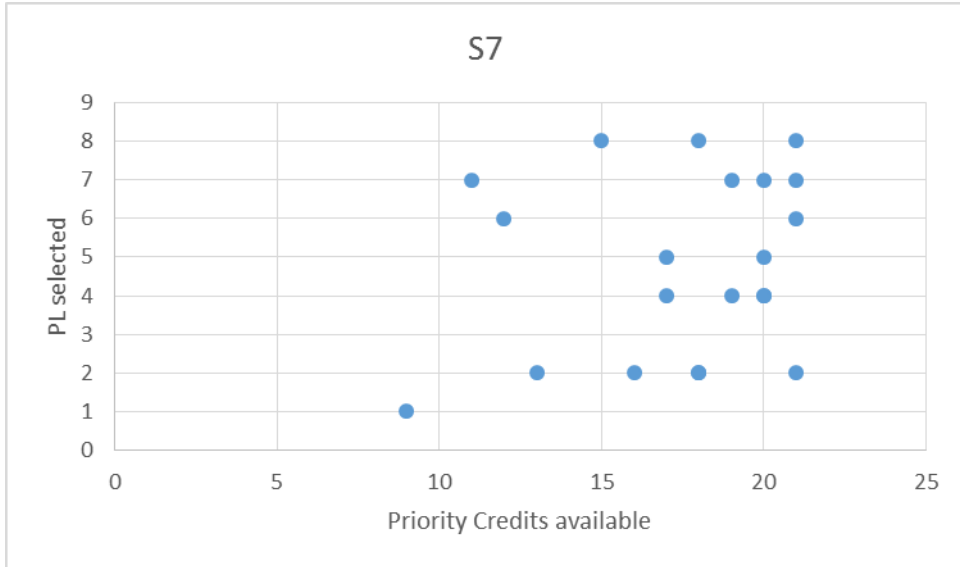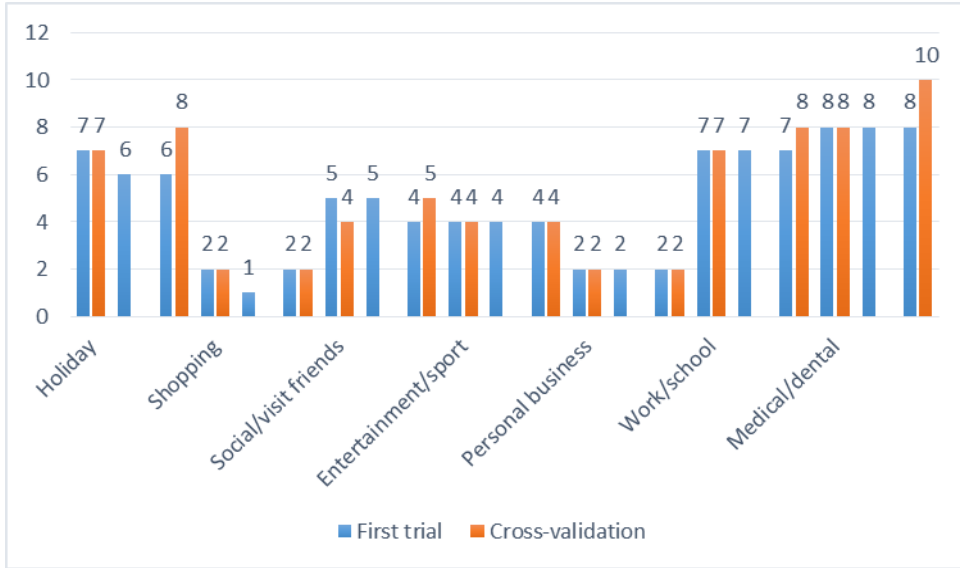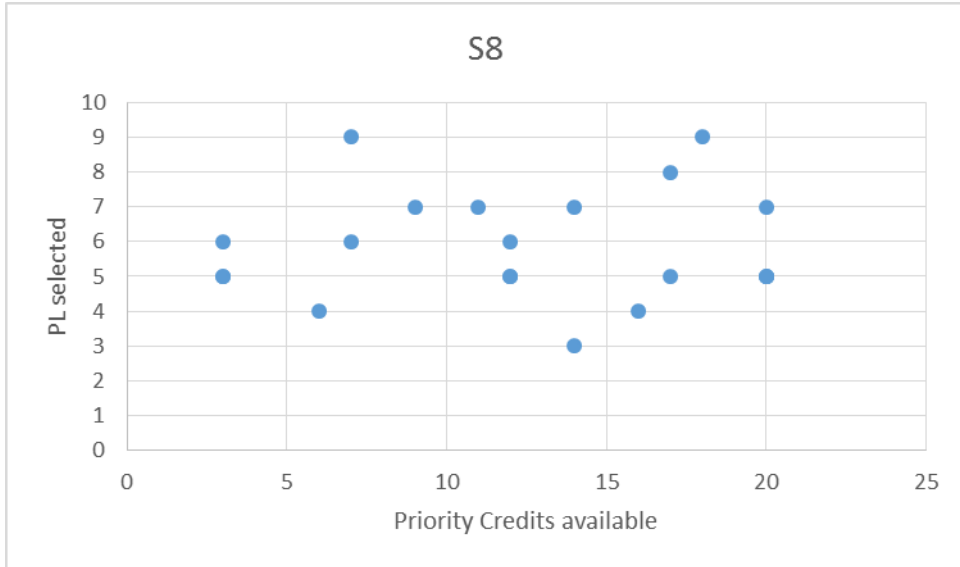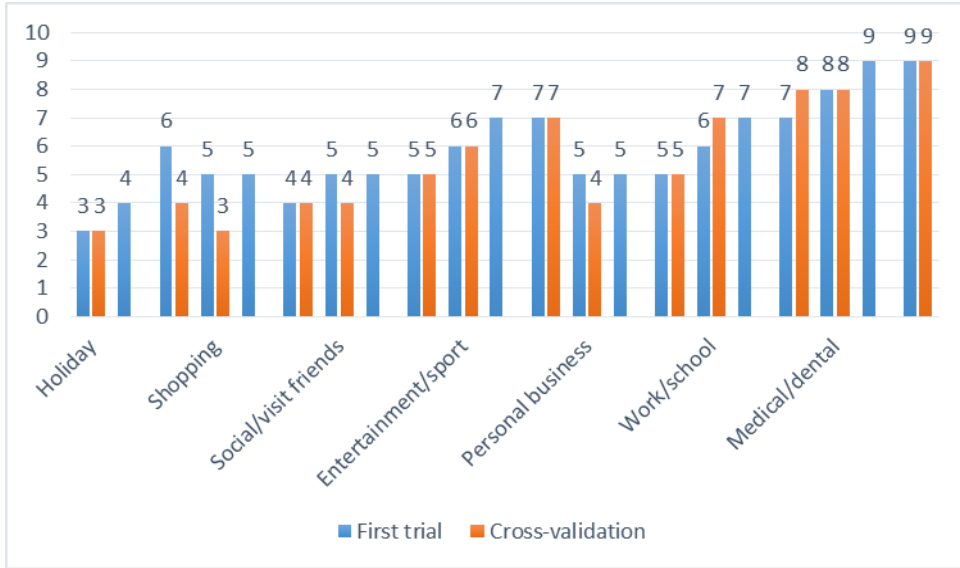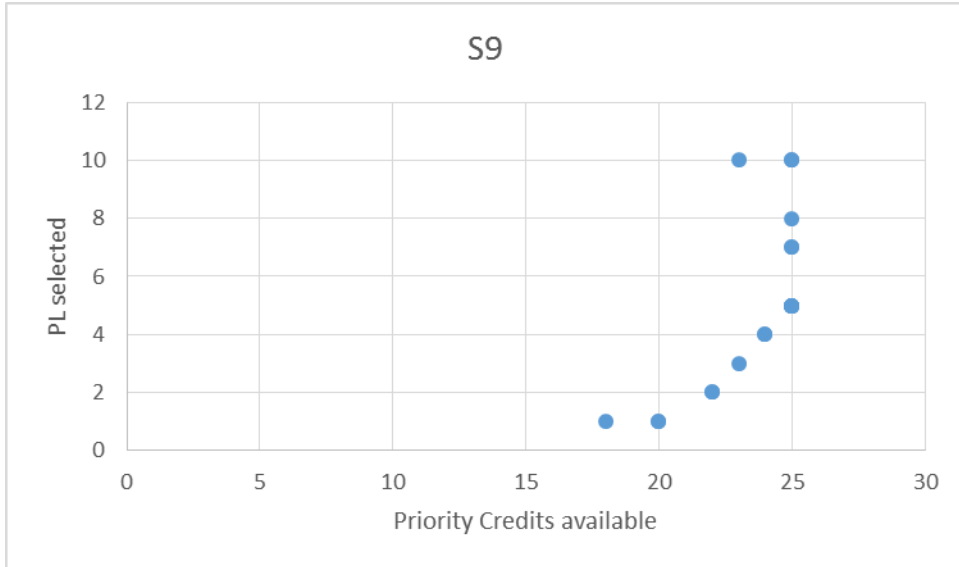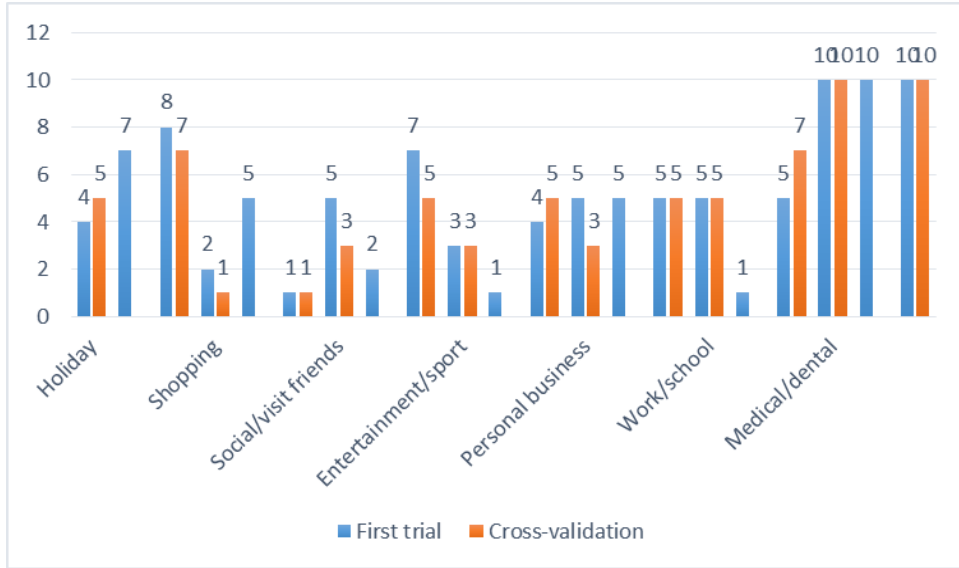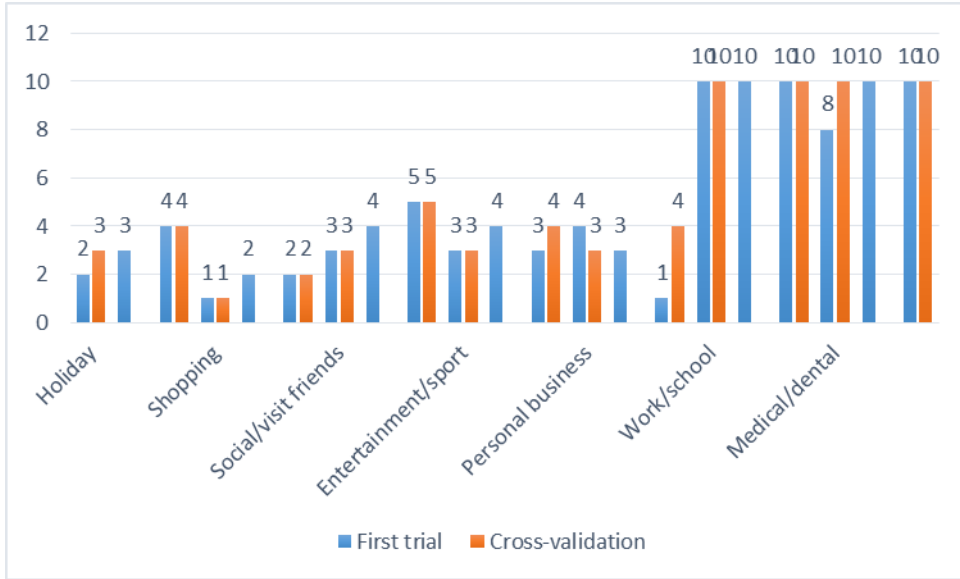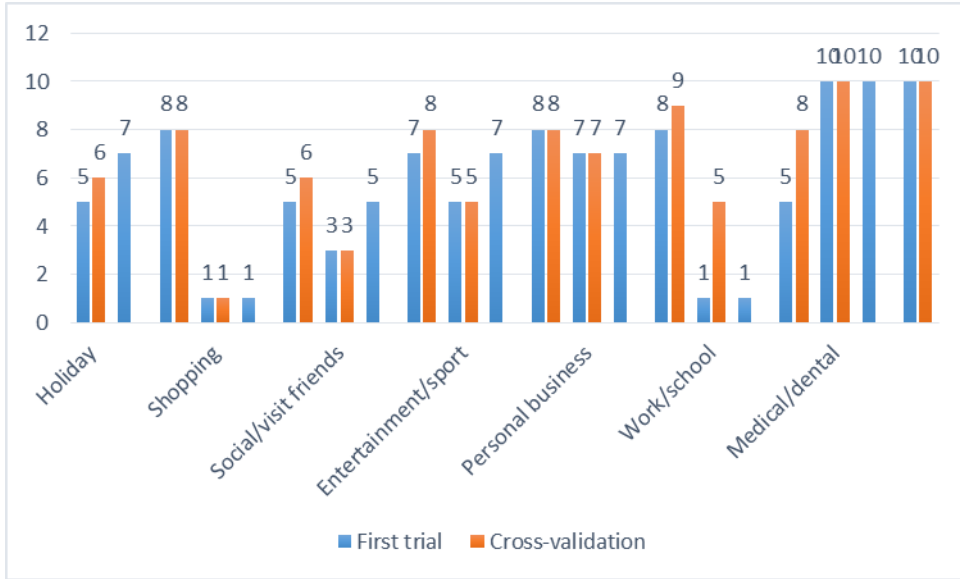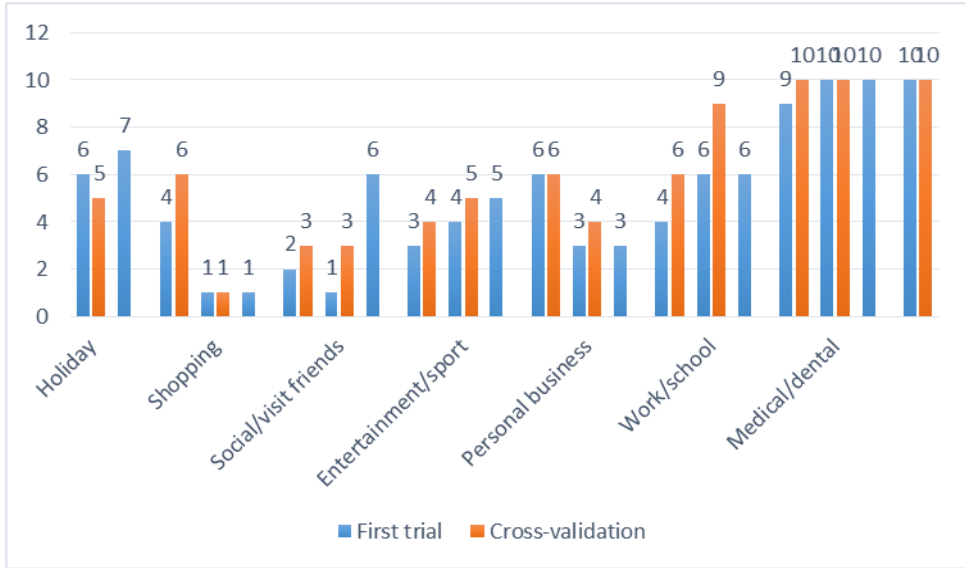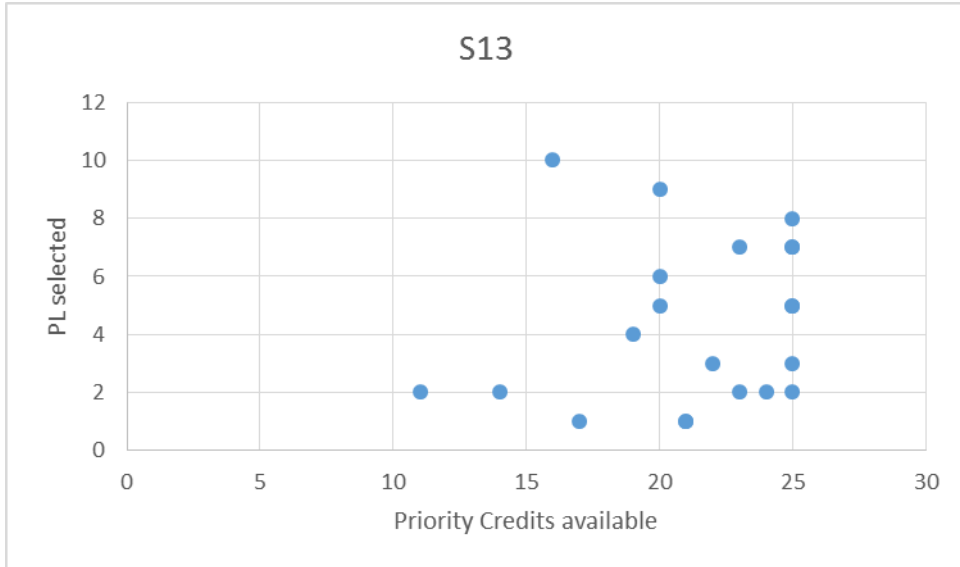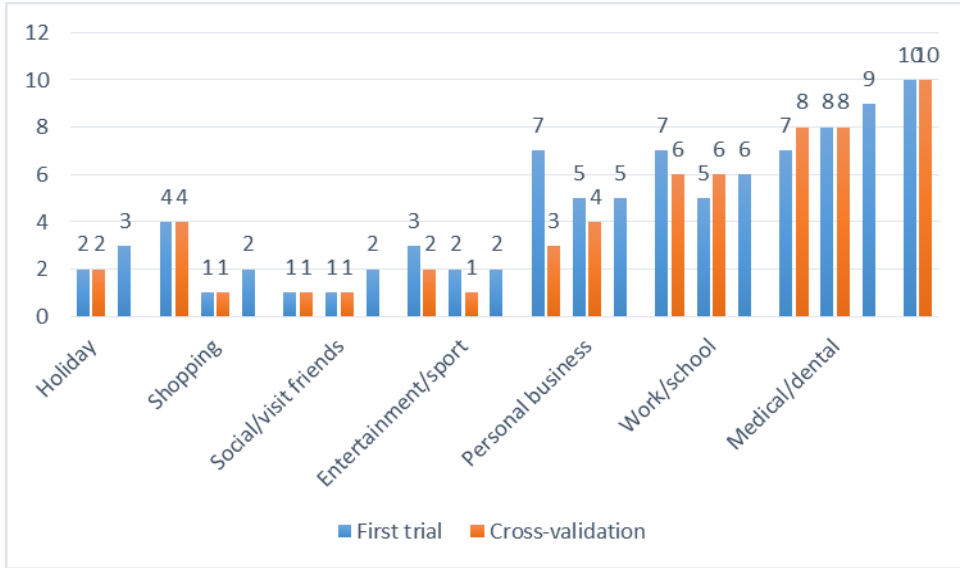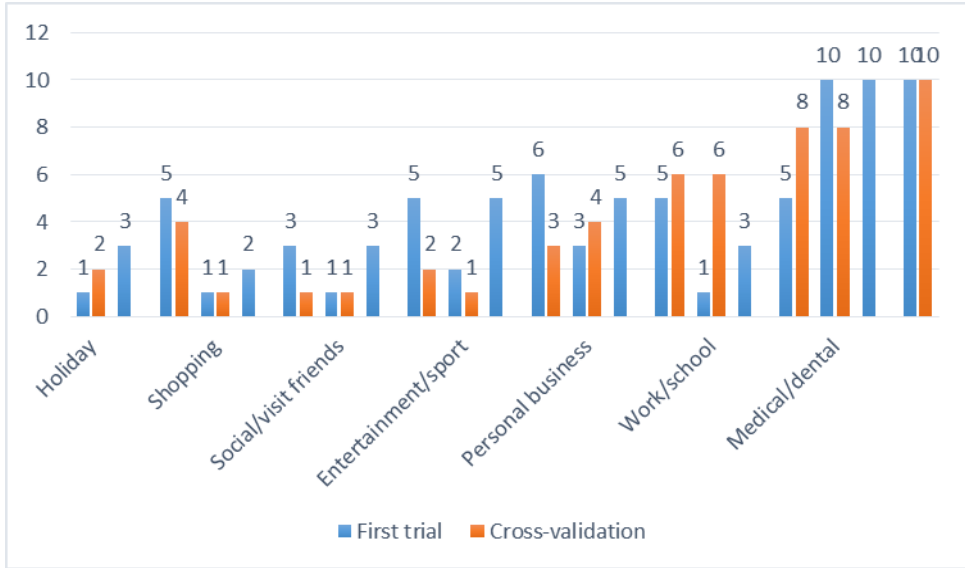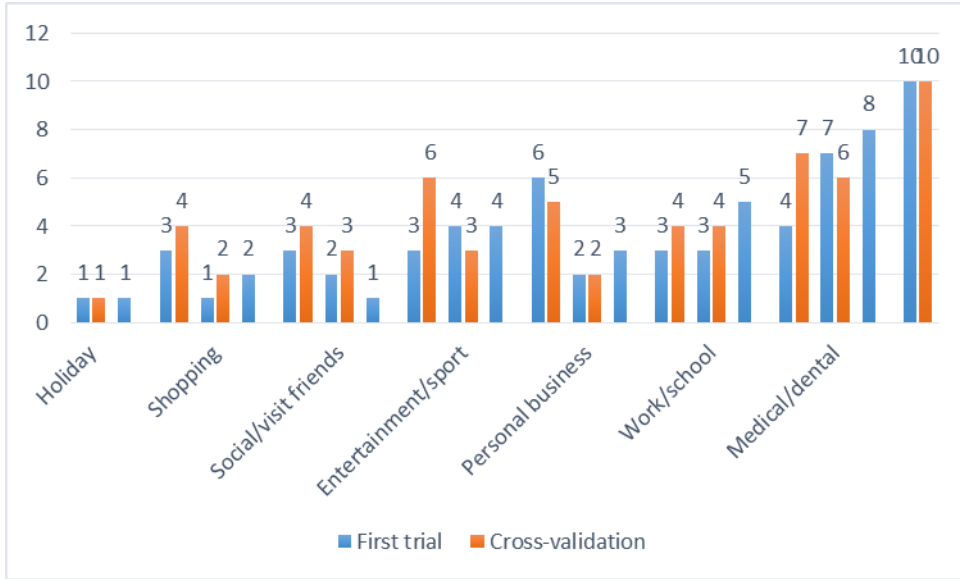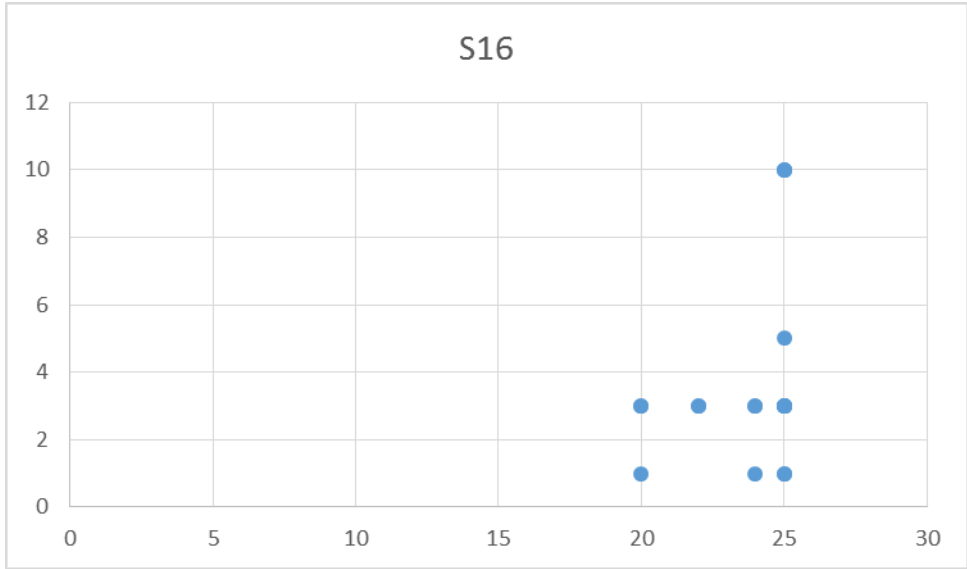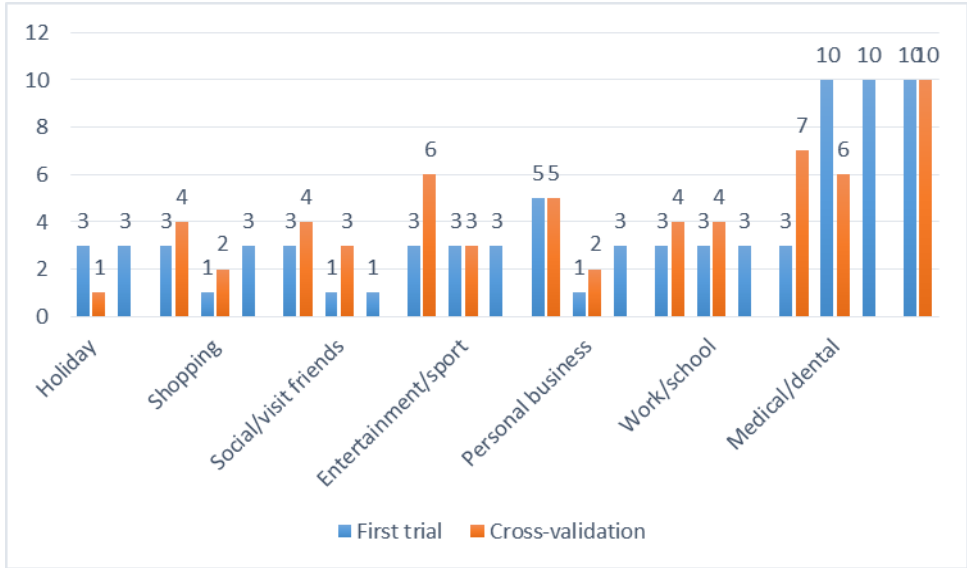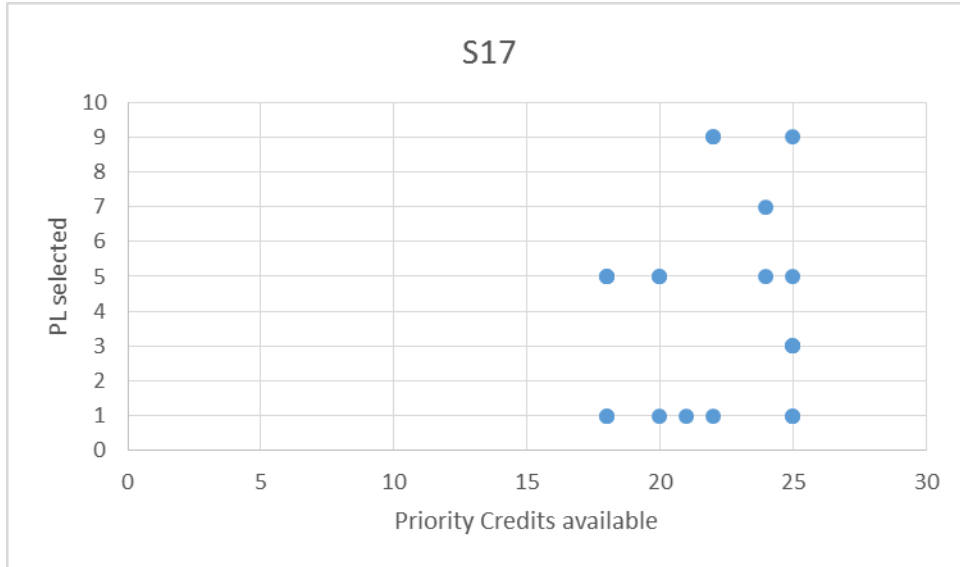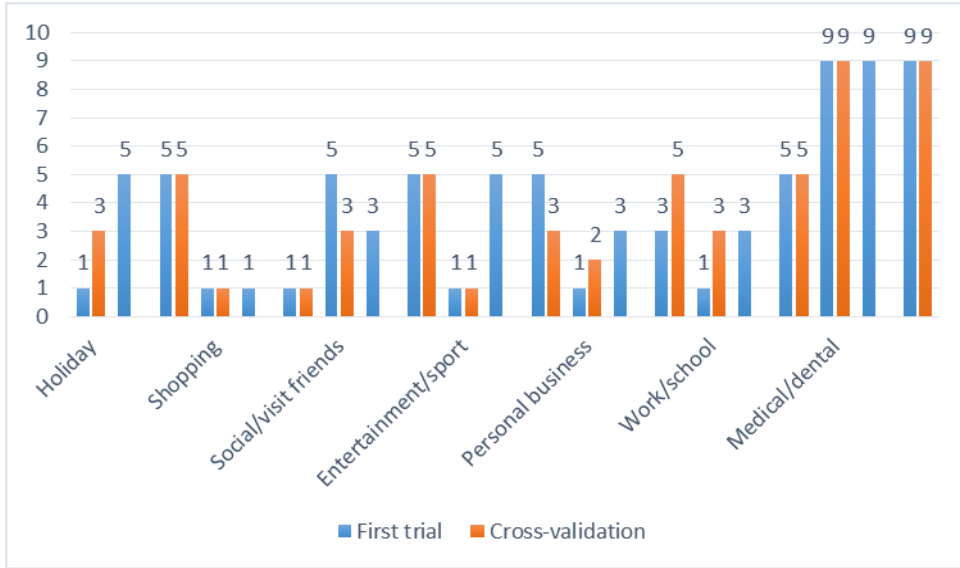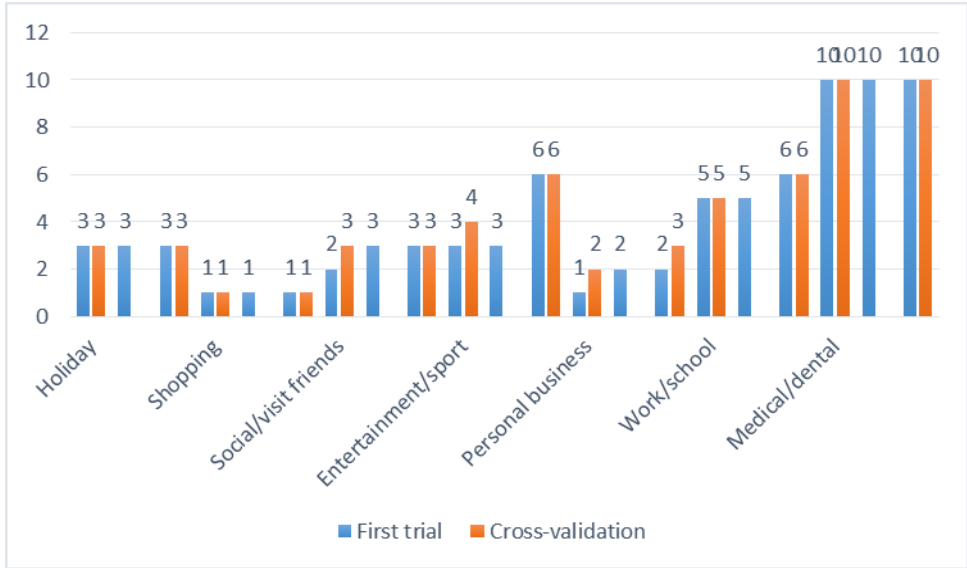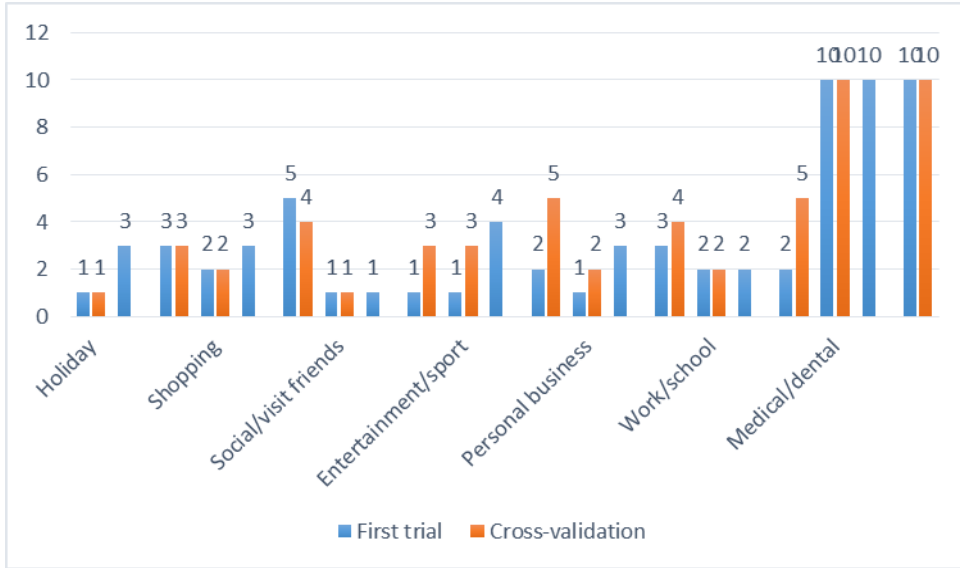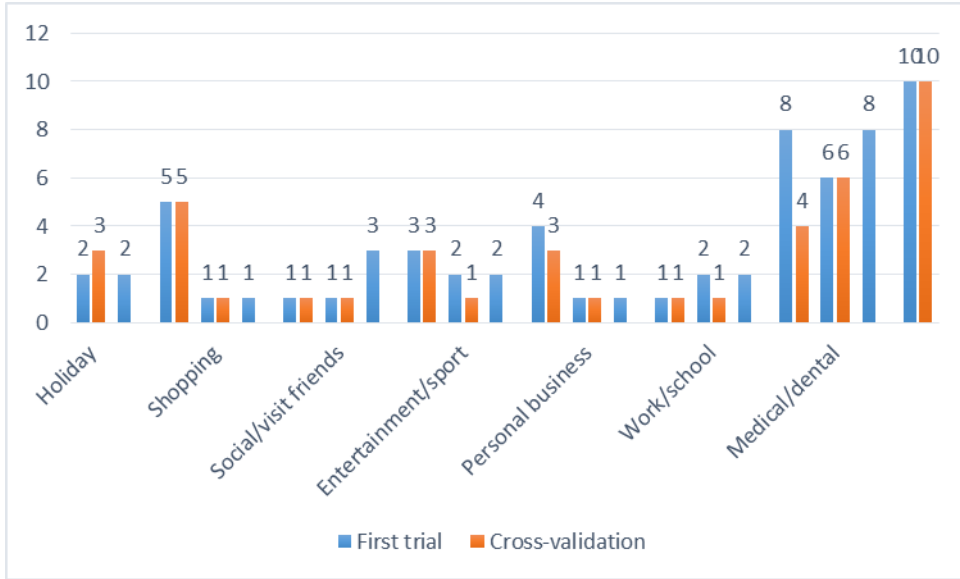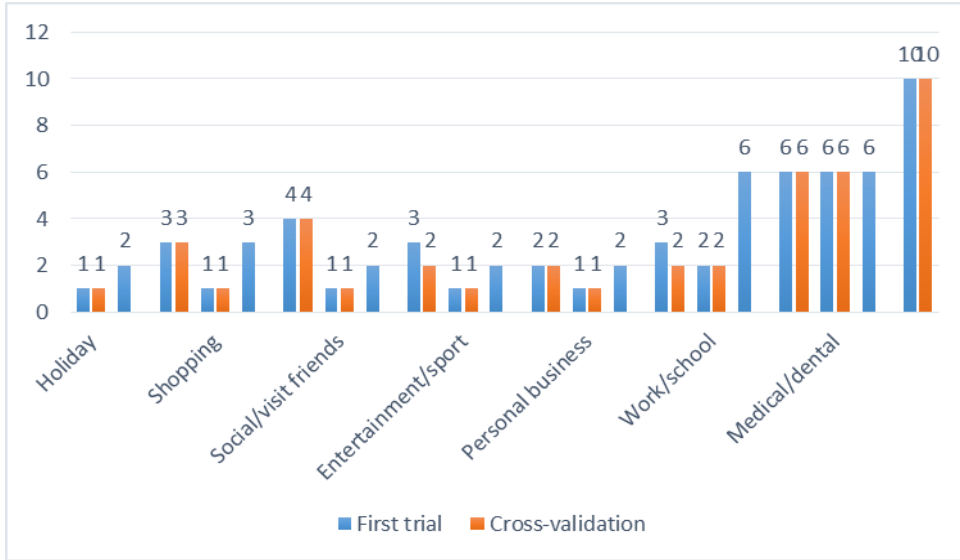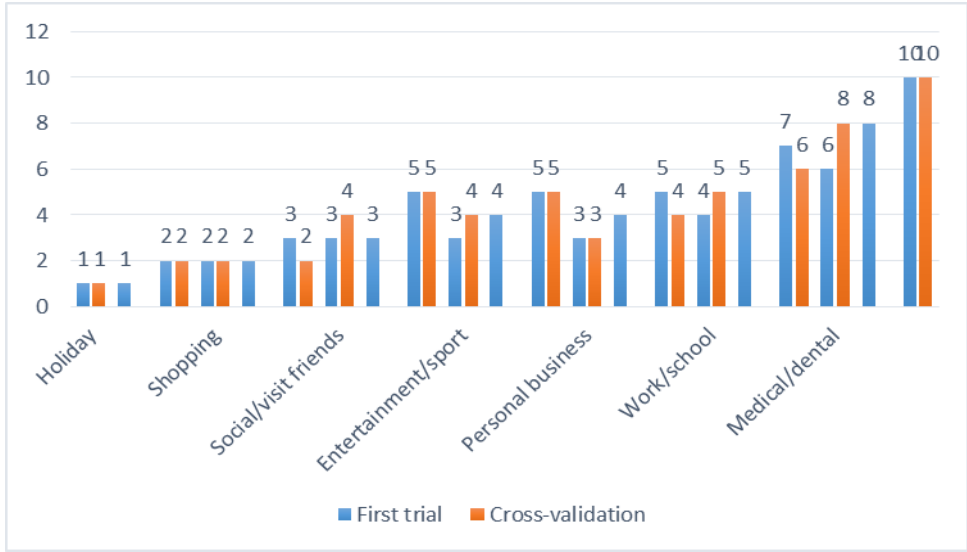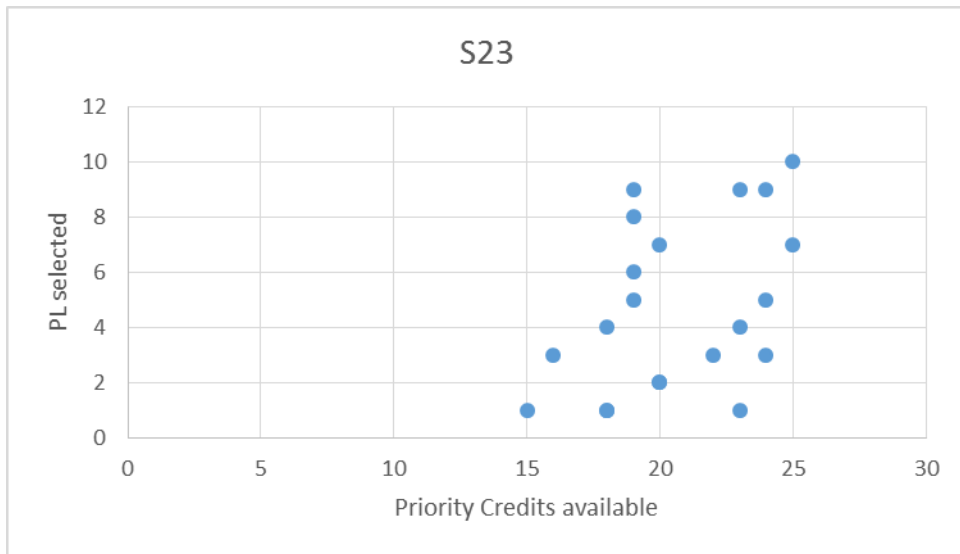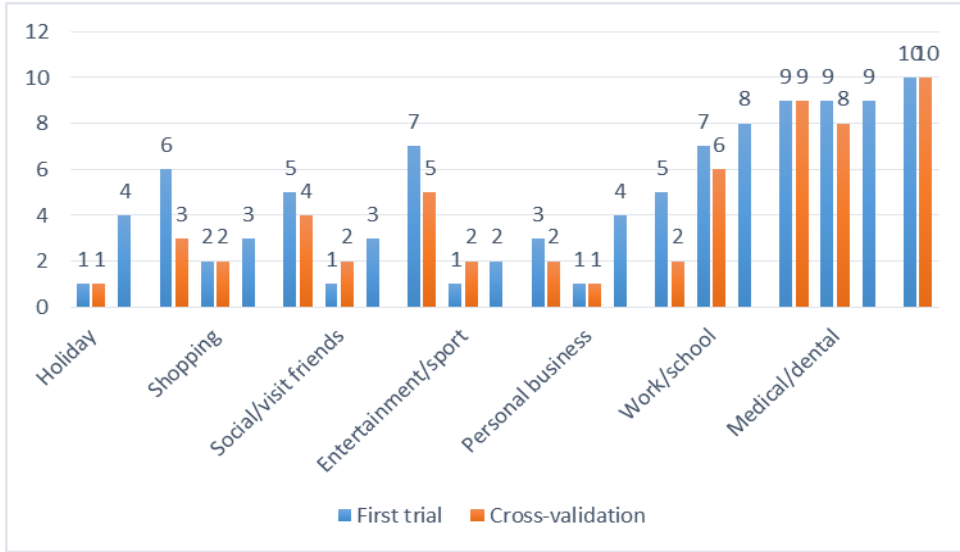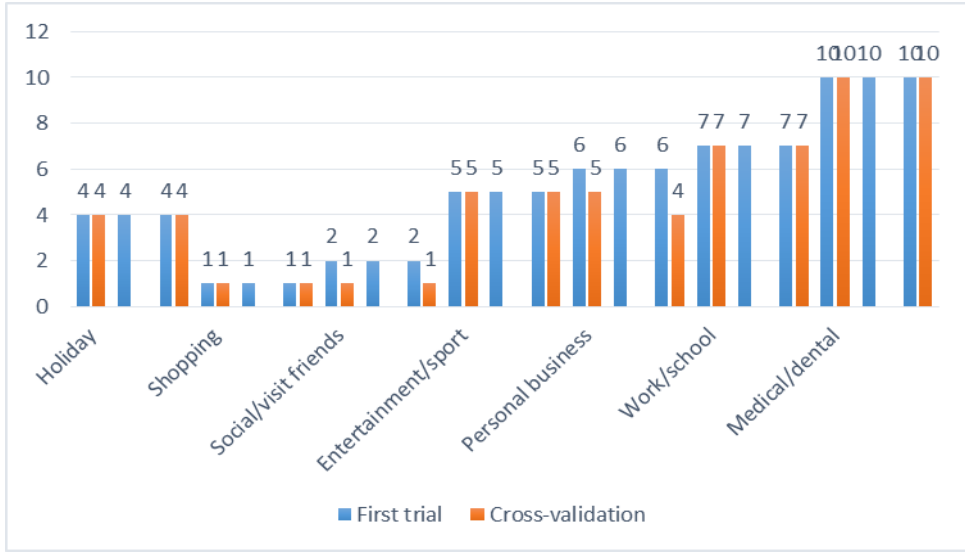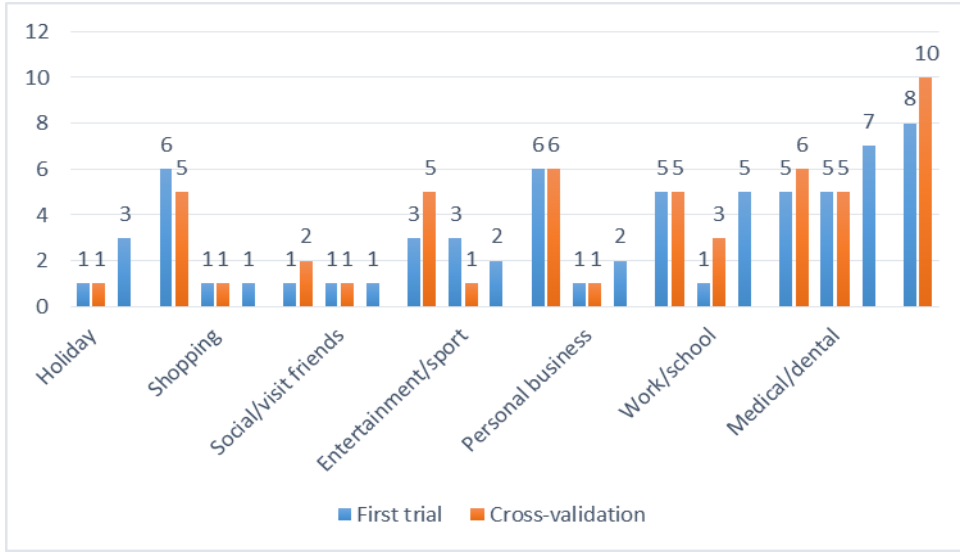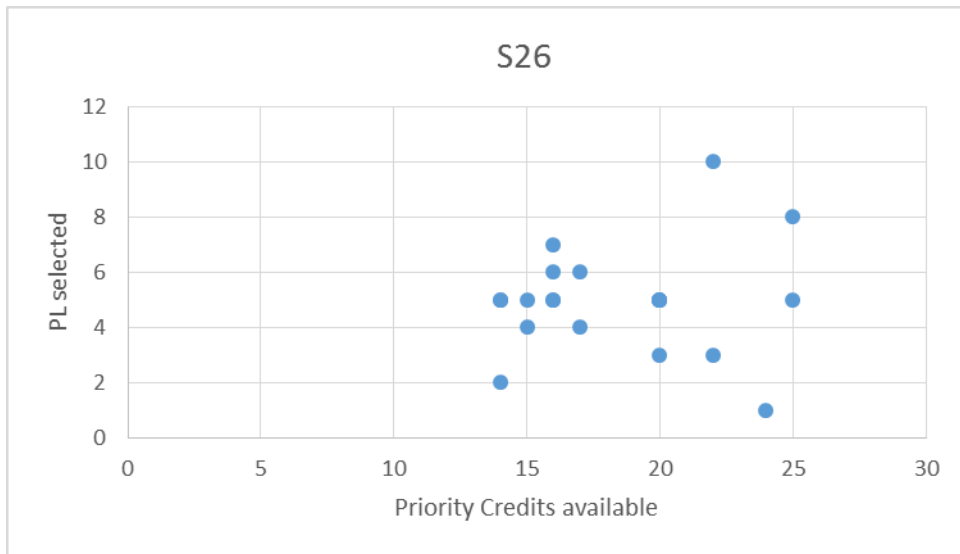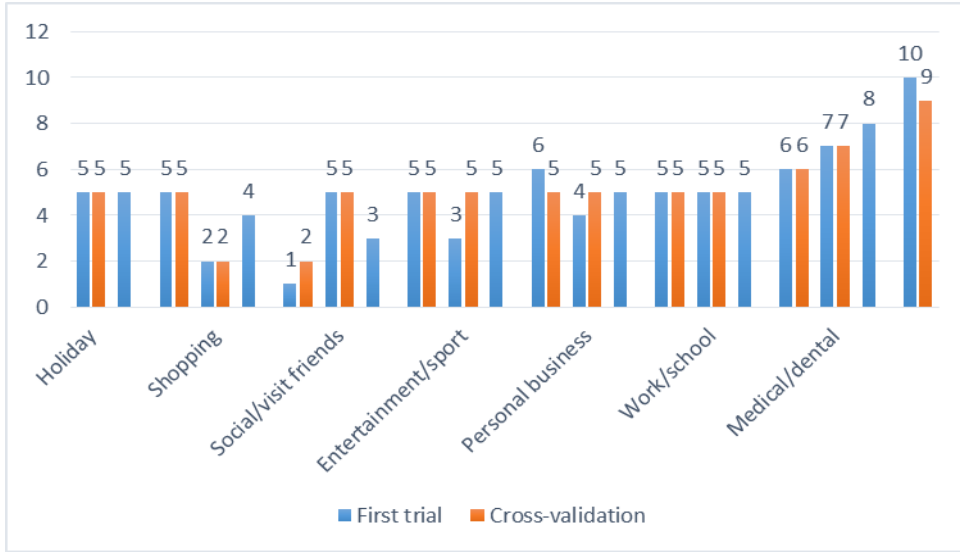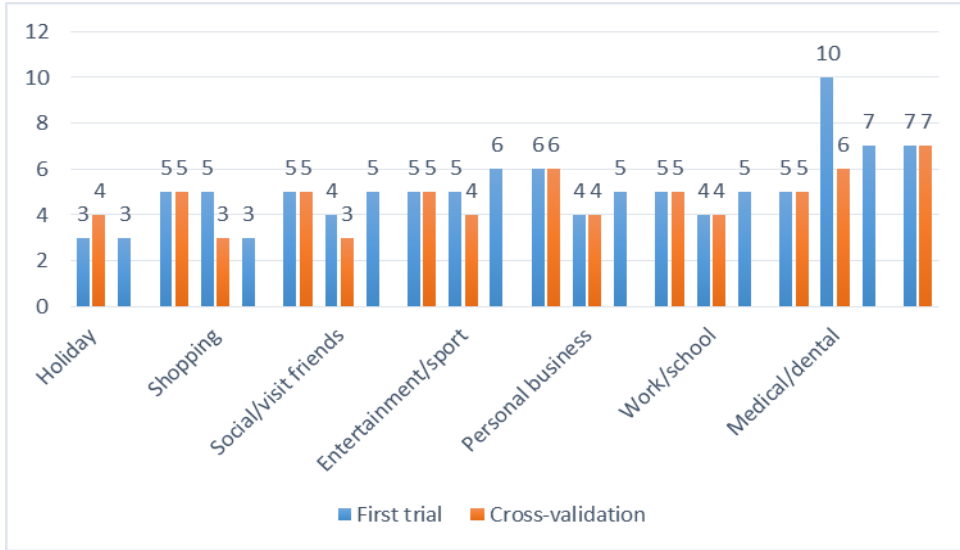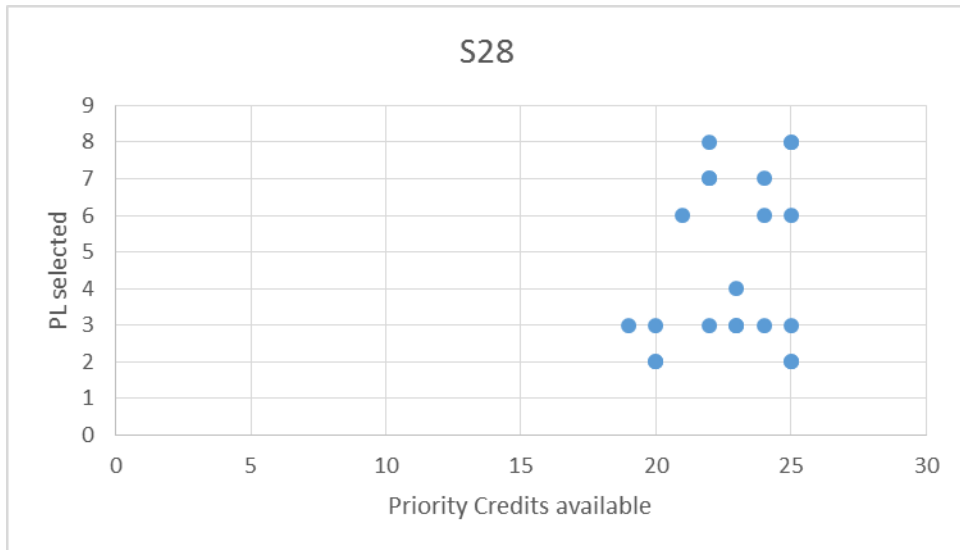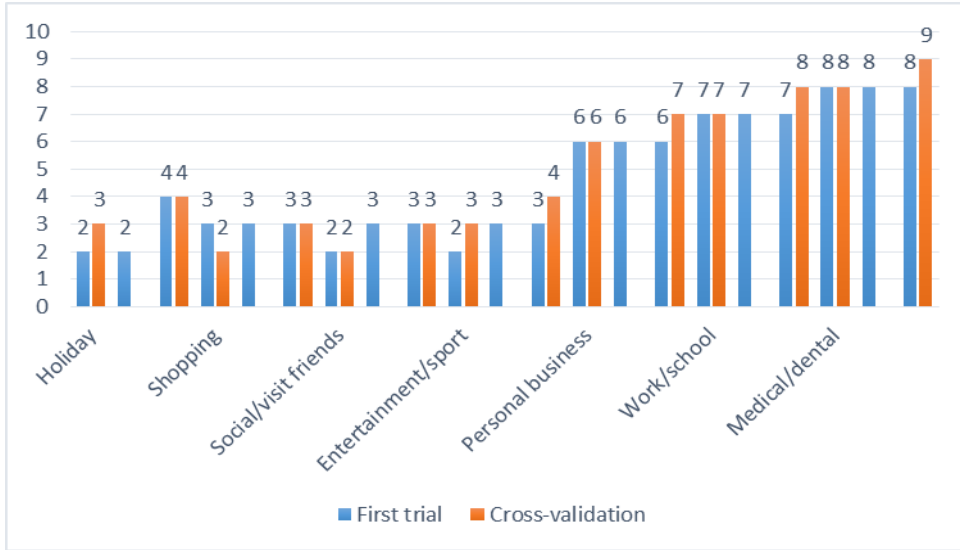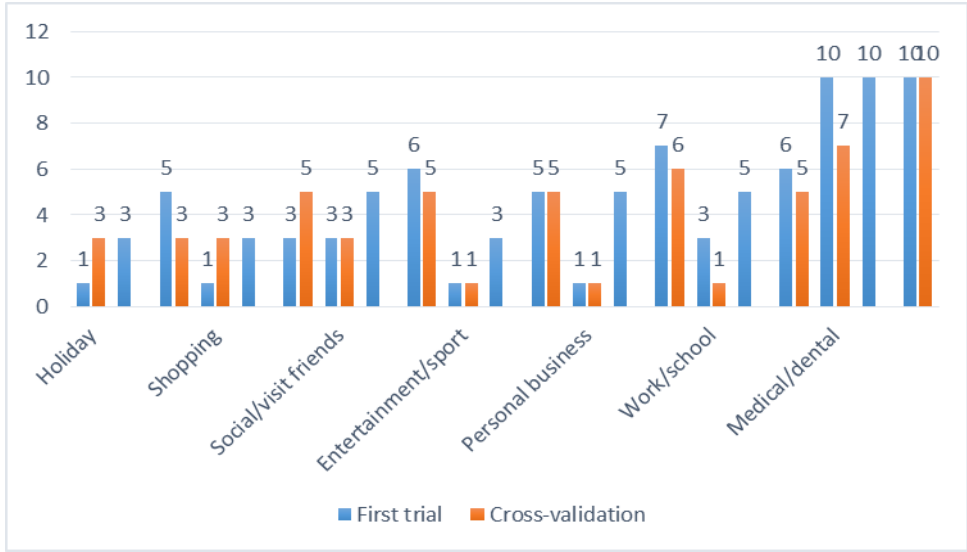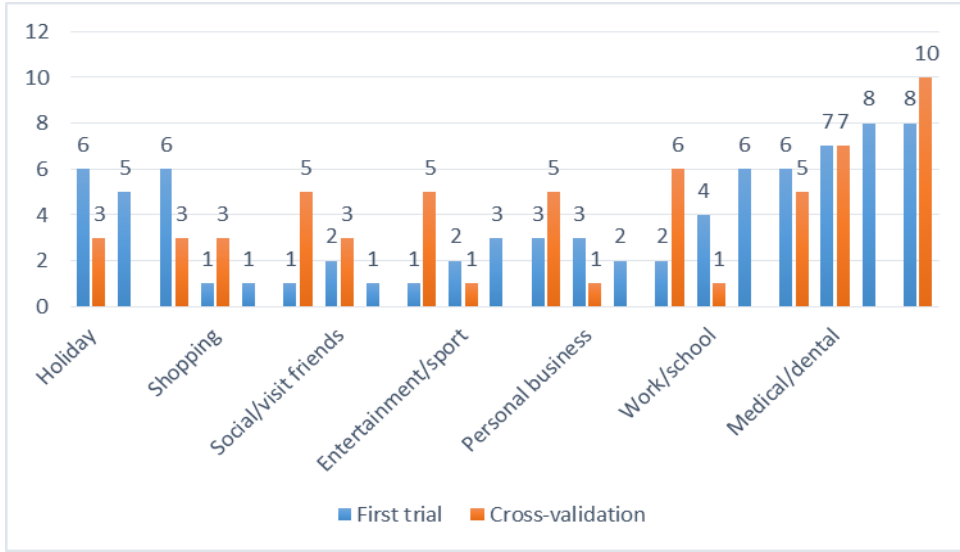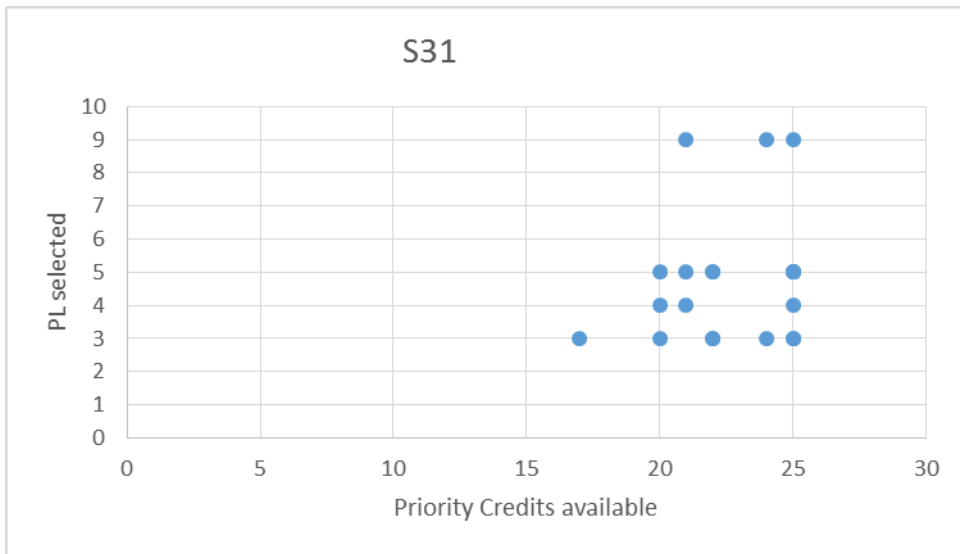
Appendix D – Web-based Experiment Pages

Root Page

VirginiaTech   **Consent   Contact**

Welcome to the Self-Driving Priority Level Web Experiment

Hello! Thank you for visiting our interactive experiment.

This experiment is intended to collect information on the novel traffic control mechanism for self-driving vehicles.

The experiment will take around 10 minutes, and your participation can contribute to the development of novel self-driving vehicle control technology.

If you are interested in participating, please click on the link bellow.

Learn more

Consent Page

Home   Contact

Consent page

Thank you for taking part in this study conducted by Virginia Tech.

PURPOSE OF THE RESEARCH: This research is intended to determine how self-driving vehicles will interact at intersections. We are trying to collect information on decision-making and opinions on traffic control for self-driving vehicles. Data collected will be of great importance since it will affect the design of self-driving vehicle technology.

WHO IS CONDUCTING THIS STUDY: This study is being conducted by Milos N. Mladenovic (milosm@vt.edu), PhD candidate at Virginia Tech, and Dr. Montasir Abbas (abbas@vt.edu), Associate Professor at Virginia Tech.

HAS THIS STUDY BEEN APPROVED? Yes, this study has received Approval from the IRB at Virginia Tech, in May 2014 (**#014-542**).

WHAT YOU WILL DO: First, you will be asked to read short info about the proposed control mechanism. This control mechanism allows you to select Priority Level for each trip, and this Priority Level is used to determine right-of-way at an intersection. Experiment will be performed using hypothetical situations that are similar to real life. You will be provided with information about your trip and then asked to select Priority Level. We anticipate that experiment will take about 10 minutes to complete. You can complete the survey at your own convenience.

RISKS: There are NO anticipated risks with participating in this study.

BENEFITS: After completing at least ten selections of Priority Level, you will have the option to enter your email for a raffle where you can win 50$ Amazon gift-card. Your email id will only be used to enter you into the raffle and will not be associated with your

The odds for winning the raffle is estimated as 1 in 200. In addition, at the end of the experiment, you will have an option to provide your name and approximate location (e.g., town or state), if you desire to be publicly listed on this website as a contributor to the development of self-driving vehicle technology.

ANONYMITY AND CONFIDENTIALITY: Your participation will remain strictly confidential and your responses will not be associated with your identity. In addition, all the data will be securely stored. However, if you decide to submit your name as a contributor, your participation will not longer be confidential.

FREEDOM TO WITHDRAW: You are free to withdraw from the study at any time without penalty. You are free not to answer any questions or respond to experimental situations that you choose without penalty.

CONTACT: If you have any questions, comments or feedback regarding this study, you can contact Milos N. Mladenovic at milosm@vt.edu, or you can use the Contact form in the top right corner of the page. Should you have any additional concerns, please contact the Institutional Review Board at Virginia Tech.

By continuing, you are stating that you are over 18 years of age, and that you consent to participate in the study being conducted.

Back   Continue

Info Page

Info page

Self-driving vehicle is a vehicle designed to perform all driving functions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for driving at any time during the trip.

A true self-driving vehicle will be able to communicate with other vehicles, user sensors to detect the surrounding environment, and determine should it slow down or maintain the speed – no traffic lights involved. If you are interested, you can find more info here.

Our suggestion is that each user should also have an option to select a Priority Level (PL), ranging from 1 to 4, for the trip – in addition to selecting the trip destination. This Priority Level will be used to determine which self-driving vehicle receives the right-of-way – vehicles with higher PL receive right-of-way before vehicles with lower PL.

However, we need to remember that traffic is a social phenomenon - everybody else, just like you, is going somewhere to fulfill their need. The idea is – when you need to go to e.g., an emergency room or an important job interview that you will select a high PL, and on the contrary, some other day, when some other people need to go to an emergency room, and you are for example going for a casual shopping, you will select lower PL.

With this in mind, there is a supporting system of non-monetary Priority Credits used for selecting Priority Levels (they are non-monetary so for example Bill Gates cannot buy more Priority Credits than you). The idea is that you receive a starting amount of Priority Credits, and you lose and gain credits based on PL you select. For example, as in the table below, if you select PL 1 then you gain 2 Priority Credits, and if you select PL 4 than you lose 10 Priority Credits. You will start with 20 Priority Credits, and you can gain up to 24 Priority Credits.

Priority Level	1	2	3	4
Priority Credits	+2	0	-2	-10

In the experiment, your task will be to select PL, taking into consideration several parameters about the trip and Priority Credits (PC). You can also provide comments on the reasons for your PL selection.

Parameters of your trip will be:

1. Trip purpose, which can be:

- Shopping – e.g., going to a grocery store or mall
- Holiday – e.g.,, going to an airport or to the lake/river nearby
- Social – e.g., going for a dinner with friends or to visit friends at their home
- Entertainment/sport – e.g., going to the movies or to play racquetball
- Personal – e.g., going to post office, going to the doctor's appointment
- Work/school – you surely know what this is
- Medical – in the case of this trip purpose, think as if you have an actual medical emergency

2. Time obligation - If you have some time-related obligation, e.g., meeting starting at exactly 10 am, you just need to arrive around 7 pm to your friends house, or you were planning to go shopping in the morning.

- Without time obligation
- With time obligation

2. Time obligation - If you have some time-related obligation, e.g., meeting starting at exactly 10 am, you just need to arrive around 7 pm to your friends house, or you were planning to go shopping in the morning.

- Without time obligation
- With time obligation
- With strict time obligation

3. Expected delay - Value in minutes that can be positive or negative, e.g., -10 you are 10 minutes early or +20 you are 20 minutes late, considering your departure time, traffic, etc.

As simple as that - you take into consideration your hypothetical trip purpose, does that purpose involve exact starting time, and how much late or early you are - and select a PL. Then click Next Trip to receive info on the next hypothetical trip and select PL again. At any point in time, you can exit the experiment by clicking on the Exit button.

For all the trips presented, please consider that these trips are your everyday, local trips, within the immediate area where you live (town, city, county, etc.), with the distance around 2 miles.

You can do as many trials as you want. However, remember that in order to be considered as legible for entering raffle, you need to complete at least 10 trials.

By clicking Continue, you will proceed to Experiment page.

Continue

Experiment Page

Trial: 1   **Time obligation:** With time obligation   **Estimated delay:** 15 min late

Trip purpose Personal   • going to post office, going to the doctor's appointment

Avalable Priority Credits: 20

Select Priority Level: ○ 1   ○ 2   ○ 3   ○ 4

Comment: Please write your comments...

Finish   Next trip

Exit Page

Exit page

Well done! You have successfully finish the web experiment.

Thank you for participating in this experiment.

Could you please provide some feedback on the proposed system?

1. Do you think this could be a beneficial system?

Please write here...

2. Do you see any way you could "trick" the system?

Please write here...

3. Do you think that Priority System could operate differently?

4. Do you think that values for gaining or spending credits could be assigned differently?

Please write here...

5. Any other comments?

Please write here...

If you would like to be listed as a contributor, please submit your name and approximate location (e.g., town or country).

Name and approximate location...

If you would like to submit your email to enter a raffle for a 50$ Amazon gift card.

E-Mail for a 50$ Amazon gift card...

Submit

Appendix E – Summary Results from Web-experiment

Holiday

Shopping

Medical