DRIVER SAFETY AND EMISSIONS AT DIFFERENT PPLT INDICATIONS

by

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Keywords: PPLT, Left-Turn, Driving Simulator, TTC, Emissions, Circular Green, Flashing Circular Red, Flashing Red Arrow, Flashing Circular Yellow, Flashing Yellow Arrow
According to NCHRP Report 493, there are five major left turn signal indications for permitted operations in the United States. They are: Circular Green (CG), Flashing Circular Red (FCR), Flashing Red Arrow (FRA), Flashing Circular Yellow (FCY) and Flashing Yellow Arrow (FYA).

The main goal of this thesis is to study the driver behavior and analyze safety of drivers for different left turn indications using a real-time driving simulator. Different signal indications alter driver behavior which influences velocity and acceleration profiles. These profiles influence vehicular emissions and hence need to be studied as well. For this purpose, different scenarios are implemented in the driving simulator. Data is analyzed using Microsoft Excel, JMP Statistical tool and MATLAB. Safety of drivers is analyzed with respect to the parameter “Time to Collision (TTC)” which is directly obtained from simulator data. Vehicular emissions and fuel consumption are calculated using VT-Micro microscopic emissions model. Graphs are plotted for TTC and total emissions. Results indicate that for a day-time scenario, FCY and FYA are the most suitable left-turning indications whereas FCR and FRA are most suitable for a night-time scenario.
There are five major left-turn indications for permitted operation in the United States. They are: Circular Green (CG), Flashing Circular Red (FCR), Flashing Red Arrow (FRA), Flashing Circular Yellow (FCY) and Flashing Yellow Arrow (FYA). Different states use different left-turn indications throughout the country. The level of driver comprehension for a particular signal indication will have an effect on the driving behavior and this in turn will affect fuel consumption and total emissions. The main goal of this thesis is to study driver behavior for different left-turning operations and to provide guidelines for the selection of signal indications. For this purpose, a real time driving simulator is used and different scenarios are implemented for left-turning operations. Data has been collected from the simulator to analyze driver safety in each scenario. Velocity and acceleration data from the simulator is used to calculate vehicular emissions to analyze environmental impact. The signal indication that best suits a given situation should provide maximum driver safety and minimum environmental impact. Graphs are plotted and results indicate that, during day time FCY and FYA are the most suitable indications whereas FCR and FRA are best suited for a night time scenario.
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Date: 2-1-2017

Duvvuri Sri Rama Bhaskara Kumari
To my parents, Padma and Sarma,

And to my sister Udaya
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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

There are five major left-turn indications for permitted operations in the United States according to NCHRP report 493. They are: Circular Green (CG), Flashing Circular Red (FCR), Flashing Red Arrow (FRA), Flashing Circular Yellow (FCY) and Flashing Yellow Arrow (FYA). The main objective of this thesis is to study the safety impact of different left-turn indications utilizing a real-time driving simulator. Along with signal indication, other factors that affect driver’s behavior include volume at the intersection, speed limit, waiting time at the intersection (which is termed as red duration in this study) and visibility (day time/night time). Change in driver behavior under different conditions will have an impact on velocity and acceleration profiles. This, in turn, will affect vehicular emissions and therefore captured in this study as well. The left-turn indication that best suits a given situation should provide maximum driver safety and minimum emissions. For this purpose, different scenarios are implemented in the driving simulator and data is collected for analysis.

1.2 RESEARCH NEED AND JUSTIFICATION

There are many papers that discuss the safety of drivers for different PPLT operations. Most of these papers are based on crash analysis at intersections, online surveys, surveys from individual drivers, etc. Even though, they provide an insight on driver behavior for different left-turn indications, the study will be more reliable if drivers actually drive through the intersection and data can be obtained for analysis. A driver’s response to a signal in the field differs from their response to online (or static) surveys. Therefore, in order to receive the most realistic response, a
real-time driving simulator is used in this study. In NCHRP report 493, a similar study using a
driving simulator was performed, but only two left-turn indications (FYA and CG) were evaluated.
Many locations in the United States still practice FCR, FCY, and FRA indications and hence, it is
required to study driver behavior to analyze safety of all five left-turning indications.

It is also necessary to study vehicular emissions to analyze the environmental impact due
to change in driver behavior at different situations. Literature indicates that there are many papers
that discuss the effect of various factors on vehicular emissions, such as speed limit, traffic signal
coordination, green split of signal, vehicle’s time headway, average fleet speed, traffic flow,
waiting time near the signal, etc. There is few research that studies the impact of different left-turn
indications on emissions. Hence, in this study, along with analyzing driver safety, vehicular
emissions are also calculated for all scenarios. Graphs are plotted to compare different variables
in order to provide guidelines for the selection of left-turn operations for any given intersection
condition.

1.3 THESIS OBJECTIVE

The main objective of this thesis is to provide guidelines for selection of a left-turn indication at
given intersection conditions. Analyzing both driver safety and vehicular emissions are considered
as objectives for this purpose. An indication that best suits a given situation should offer maximum
driver safety and minimum environmental impact.

1.4 THESIS ORGANIZATION

This thesis is written in manuscript format incorporating two papers that will be submitted soon to
peer-reviewed journals. The thesis is divided into four chapters. Summary of each chapter is
presented below:
Chapter 1 provides a general description of introduction to research work, research need, thesis objectives and thesis organization.

Chapter 2 is co-authored by Dr. Montasir Abbas and will be submitted soon to a peer-reviewed journal. It describes research to study driver behavior and safety of drivers at different Protected-Permitted Left Turning (PPLT) operations.

Chapter 3 is co-authored by Dr. Montasir Abbas and will be submitted soon to a peer-reviewed journal. In this chapter effect of driver behavior on emissions at different PPLT operations is studied.

Chapter 4 summarizes the conclusions along with discussing future work in the field.
CHAPTER 2: STUDY OF DRIVER BEHAVIOR AT DIFFERENT PPLT OPERATIONS
Sri Rama Bhaskara Kumari Duvvuri, Montasir Abbas

2.1 ABSTRACT

The literature indicates that implementation of Protected/Permitted Left-Turn (PPLT) operation is advantageous in improving operational efficiency, reducing traffic delay, reducing air pollution etc. There are mainly five different types of PPLT operations used in different states of the United States. They include Circular Green (CG), Flashing Circular Red (FCR), Flashing Circular Yellow (FCY), Flashing Red Arrow (FRA) and Flashing Yellow Arrow (FYA). It is necessary to study drivers level of understanding for each PPLT operation under different control variables such as traffic volume, time of day, speed limit etc. The main objective of this paper is to use a real-time driving simulator to study driver behavior at different scenarios. The proposed scenarios were implemented in the driving simulator and results were collected for analysis. Driver safety was analyzed under all scenarios with respect to the parameter "Time to Collision" (TTC). Statistical analysis was performed using the JMP Statistical tool to determine the change in TTC in each scenario. Response surface and Prediction Profilers from JMP were analyzed to determine the best suited PPLT operation under different control variables. Graphs were plotted from the results to propose guidelines for different situations. From the results, it was observed that, during the day time, Flashing Circular Yellow and Flashing Yellow Arrow are most suitable displays. During the night time, Flashing Circular Red and Flashing Red Arrow are most suitable.

Key words: PPLT, Time to Collision, Left-turning traffic, Driving Simulator.
2.2 INTRODUCTION

Proper design of traffic signals at any intersection involves studying the crash history of the intersection, intersection geometry, pedestrian considerations, critical crossing gaps, etc. A protected or permitted operation is then determined based on these factors along with the left turning volumes at the intersection. The National Cooperative Highway Research Program (NCHRP) Report 493 [1] summarizes different indications for left turn permitted operations that are used in different states in the U. S. For example, Maryland and Michigan use a Flashing Circular Red for permitted operation; Seattle and Washington State used to operate a Flashing Circular Yellow (which is no longer in operation in Washington State according to the NCHRP report); Delaware and Cupertino, CA use a Flashing Red Arrow, whereas Sparks, NV and Reno, NV use Flashing Yellow Arrow for permitted left turn indication. Different types of indications used in different states cause driver confusion, which in turn will affect safety of road users. It is therefore necessary to study the driver behavior under the five-major left turn permitted operations (Circular Green, Flashing Circular Red, Flashing Red Arrow, Flashing Circular Yellow, and Flashing Yellow Arrow).

2.3 LITERATURE REVIEW

Driver’s perception and safety of driver at different Protected-Permitted Left Turn (PPLT) operations was studied by various researchers using various methods. NCHRP Report 493 discusses the evaluation of traffic signal displays for protected/permissive left-turn control [1]. Photographic driver studies along with field traffic operation studies were performed. Field traffic operation studies include field traffic conflict studies, crash data analysis, driver confirmation studies, etc. Driving simulator studies have also been performed to evaluate the PPLT display and results indicated no statistical difference in the percentage of correct responses for different permissive indications. Also, no significant difference was observed for different PPLT display components in terms of the percentage of incorrect responses.

Qi et al. [2] studied the safety performance of the flashing yellow arrow signal indication by analyzing historical crash data. Crash data was collected from intersections where Flashing Yellow Arrow (FYA) signals were installed. Out of the data collected from 17 intersections, 14 did not
show any increase in crash rate. The analysis was performed using Empirical Bayes method (EB) and results indicated no adverse effect on safety by using FYA.

Another study by Qi et al. [3] dealt with investigating the safety of the flashing yellow arrow indication by surveying traffic engineers and motorists. Results indicated a very good understanding of FYA by a majority of drivers. Field traffic conflict study was also performed to determine safety. It was noticed that at intersections with high left-turn and opposing volumes, FYA might result in higher traffic conflicts compared to the conventional circular green display.

Schattler et al. [4] evaluated the effectiveness of FYA on driver comprehension and traffic operations by conducting an online static survey. 363 drivers from Peoria, Illinois area participated in the survey. The results indicated a higher driver comprehension of both Circular Green and FYA indications. However, misinterpretation of Circular Green permissive left turn display was noticed in some instances. By providing supplemental traffic signs, an increase in driver comprehension was noticed. Before-after field observations were also collected at study approaches and the overall findings indicated that drivers in Illinois area have a high comprehension of FYA message. In addition, no negative impact on traffic operations was observed.

Schattler et al. [5] also tried to analyze the effects of supplemental traffic signs on driver understanding of FYA indication. The authors investigated the impact of supplemental signs on older drivers (age 65 or greater) by conducting a survey. Results indicated a higher understanding of FYA indication when supplemental signs are provided. The authors also performed a crash-based data comparison which showed that crash rates reduced when supplemental signs are provided.

FYA indication is capable of changing from Protected-only (PO) left turn mode to Protected-Permitted (PP) left turn mode, and hence it is considered to offer dynamic left turn control. Chalise et al. [6] analyzed the need of a dynamic left turn control system to address variable traffic demands during the day. Operational impact analysis was performed using micro-simulation. Based on the traffic delay in different operations, the performance of PP and PO signal controls were examined. Results indicated that the dynamic left turn offers both safety and operational control. Therefore, it can be recommended for all left turn operations.

A study on developing an interactive decision support system for predicting the flashing arrow left turn mode by time of day was carried out by Abou-Senna et al. [7]. The authors developed a model to predict the number of left turns during the permitted operation. The model also assesses
the safety and operational impacts of each operation at different intersection conditions. Thus, it helps identify intersections that need to modify their left turn operation.

Appiah and Cottrell [8] analyzed the safety and operational impact of delay in start of FYA when transitioning from protected to permissive operation. Usually, a red arrow signal is used for transitioning considering safety. It was observed by the authors that, a very short red arrow signal (say 1 sec) causes driver confusion. The simulation analysis indicated significant safety benefits by delaying the start of FYA. On account of FYA delay, no negative impacts were observed on average delay, queue length or average stopped delay for both left-turning traffic as well as whole intersection.

Noyce and Kacir [9] evaluated drivers’ understanding of protected/permissive left-turn signal displays using a computer based driver survey. 2,465 drivers participated in the survey and the results indicated a higher driver comprehension of yellow or flashing red permitted indication. Different aspects of driver behavior under various scenarios were studied by Riccardo et al. [10], Arien et al. [11], Chen et al. [12], Shaheed et al. [13] and many others [14-19].

Even though there are many papers that discuss driver behavior at different PPLT operations, most of them are based on surveys from individual drivers or online surveys or crash analyses that determine safety and impact of different operations. Although these studies provide an insight on behavior of drivers under different situations, a study which analyzes data while drivers actually drive through the intersections will be even more reliable. Drivers’ behavior in the field will differ from their online survey responses and hence, the study will be more realistic if a real time driving simulator is used to collect data. A full-scale driving simulator is used in NCHRP report 493 [1] to study drivers’ behavior at different PPLT operations. Circular yellow and Flashing Yellow Arrow were noticed to have same level of driver comprehension and hence, FYA was not included in their study. It was also observed that red indication conveys a message of “stop and yield if a gap is available” instead of “yield if a gap is available” and hence, a Circular Red and Flashing Red Arrow indications were not considered in their study. Though the reasons are valid, these indications (FCY, FCR and FRA) are still in practice in many locations. For example, some locations in Maryland still use a flashing circular red for permitted left-turn operations. Therefore, it is necessary to perform a driving simulator study under all five types of left-turn operations. Also, very few studies have compared driver behavior at all five PPLT operations. Taking all these factors into
consideration, the main objective of this paper is to study driver behavior under five different PPLT operations – CG, FCR, FRA, FCY and FYA – using a real time driving simulator.

2.4 DESIGN OF EXPERIMENTS

The main goal of this paper is to study the driver behavior at different PPLT operations using a real time driving simulator. In order to study the driver behavior in all situations, the control parameters were varied to develop different scenarios. The parameters that are varied include volume at the intersection, waiting time at a red signal near the intersection (which is defined as Red duration in this paper), visibility (day time/night time), speed limit on the road and display of PPLT operation (CG, FCR, FRA, FCY and FYA). The JMP Statistical tool was used to create the design of experiments for this purpose. The input variables for JMP include:

- Volume varying from 200 veh/hr. to 1200 veh/hr.
- Red duration varying from 20sec to 50sec
- Visibility (Day-Time or Night-Time)
- Speed Limit (30mph or 45mph)
- Display of PPLT operation (Circular Green, Flashing Circular Red, Flashing Red Arrow, Flashing Circular Yellow, Flashing Yellow Arrow)

From JMP Design of Experiments (DOE), a total of 39 scenarios were obtained as follows:
<table>
<thead>
<tr>
<th>S. NO</th>
<th>DISPLAY</th>
<th>VOLUME (veh/hr.)</th>
<th>RED DURATION (sec)</th>
<th>VISIBILITY</th>
<th>SPEED LIMIT (mph)</th>
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<td>Day</td>
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</table>

**Table 1: Design of Experiments**
All these 39 scenarios were developed in the driving simulator. Drivers were requested to drive through all the scenarios and data was collected for analysis.

2.5 DEVELOPMENT OF SCENARIO

DriveSafety DS-250 Model driving simulator is used in this study which is shown in Figure 1.

Figure 1: Driving Simulator used in current study

The required scenarios were developed using the HyperDrive component of the driving simulator. It consists of basic database elements such as road tiles, pedestrians, vehicles etc. More complex designing such as speed limits, signal settings and other attributes can be achieved with the help of Tool Command Language (TCL) which is embedded in the simulator software. Each scenario consists of four intersections as shown in Figure 2. Volume, Speed Limit, Red duration and Visibility were adjusted at all intersections to represent the scenarios from the design of experiments.
Figure 2: Design of Intersections in Hyper Drive

Figure 3: Typical speed limit sign in the design environment
The current experiment was implemented in an urban environment. As the driving simulator doesn’t support a horizontal or cluster display type of signal head, a three-vertical display type was used in the design. Figure 3 shows a typical speed limit sign at an intersection. Figure 4 and Figure 5 show a typical day time and night time scenarios in the simulator with a display of Flashing Yellow Arrow.
2.6 METHODOLOGY

The proposed scenarios from the Design of Experiments were developed in the simulator and individual drivers were requested to drive under all 39 scenarios. Fifteen participants volunteered to perform the drive. All participants are licensed drivers from Blacksburg and have considerable driving experience in the state of Virginia. Most of the drivers were experienced with signal indication of Flashing Yellow Arrow or Circular green but were less experienced to Circular Red, Circular Yellow or Flashing Red Arrow displays. The Institution Review Board’s (IRB) informed consent form was provided to the drivers, which consists of general information about the scope of the study along with possible risks and benefits. Before starting the actual drive, the participants performed an adaption drive session. This session basically consists of similar environment as that of experimental scenario so that participants get familiarized with the driving simulator. After they became familiar with driving the simulator, they were asked to drive under the 39 proposed scenarios. After successful completion of the drive, data was automatically collected by the simulator which includes Time, Velocity, Speed Limit, Acceleration, Brake, Vehicle X, Y and Z coordinates, Collision angle, Collision velocity, Vehicle ahead, Headway distance, Time to Collision etc. The total time required by each driver to drive under all the 39 scenarios is approximately 50 to 60 minutes. Data collected from the simulator was then extracted for analysis. Microsoft excel along with JMP Statistical tool and MATLAB was used for analysis of the data.

Data collected from the simulator consists of various parameters that explain driver behavior such as velocity, acceleration, headway distance, time to collision (TTC) etc. Amongst those, since TTC is an effective parameter for studying the severity of traffic conflicts, it was selected as the parameter for analysis. Usually, vehicles change either their trajectory or speed to avoid collision. TTC measures the time to collision between two vehicles if they both continue on their trajectory without changing the speed. It assesses the interaction intensity among vehicles and the potential for collision if drivers do not adapt in time. Lower TTC values correspond to higher conflict severity; and hence lower the value of TTC, higher is the probability of collision

2.7 RESULTS AND ANALYSIS

Statistical analysis was conducted on the simulator data using JMP Statistical tool. The response surface model was used to do the analysis. Data was categorized as follows for analysis:
Visibility [Day/Night] (0-1): 0 denotes day time scenario and 1 denotes night time scenario

Volume: Continuous range varying from 200veh/hr. to 1200veh/hr.

Red Duration: Continuous range varying from 20sec to 50sec

Speed Limit: Lower speed limit of 30mph and higher speed limit of 45mph

Display (1-5): 1 – Circular Green, 2 – Flashing Circular Red, 3 – Flashing Red Arrow, 4 – Flashing Circular Yellow and 5 – Flashing Yellow Arrow

The results from JMP can be observed as follows:

![Analysis of Variance Table]

**Figure 6: Analysis of variance**

Analysis of variance was calculated for TTC values of defined variables as shown in figure 6. Figure 6 shows analysis of variance along with parameter estimates of individual variables. It can be noticed that the analysis is significant with a P value less than 0.0001.
Figure 7: Actual by Predicted Plot from JMP

Figure 8: Prediction Profiler for day time visibility with speed limit 30mph

Figure 9: Prediction Profiler for day time visibility with speed limit 45mph
It can be noticed from Figure 7 that the values predicted by JMP are very close to the actual values with an R-square value of 0.91. Figure 8 to Figure 11 represent prediction profilers for day time and night time scenarios with different speed limits. In each prediction profiler, by changing volume and red duration, the display of PPLT that best suits the given situation can be determined. The higher the value of TTC, the lower the probability of collision. Hence, the display with the highest value of TTC will be most suitable in terms of avoiding collisions at the intersection.

From figure 8, it can be noticed that display 2 and display 4 have higher values of TTC for a day time scenario with volume of 700 veh/hr., red duration of 35sec and speed limit of 30mph. It means that Flashing Circular Red (Display 2) and Flashing Circular Yellow (Display 4) offer lower probability of collision for the defined situation.

From figure 9, it can be noticed that display 4 (Flashing Circular Yellow) with highest TTC, will best suit the given situation. Similar conclusions can be drawn from figure 10 and figure 11 to determine the display of left turn operation that can offer lower probability of collision under defined situations.
While the prediction profiler can provide results for a particular selection of variables, a surface plot will be more beneficial as it provides a graph with wide range of values and is easier to comprehend the results. For that purpose, the predicted values from JMP were exported and surface plots were made in MATLAB. With X-axis representing Red Duration (varying from a value of 20sec to 50sec), Y-axis representing Volume (varying from a value of 200 veh/hr. to 1200 veh/hr.) and Z-axis representing TTC observed in each scenario, surface plots were made from MATLAB which can be observed as follows:

![MATLAB surface plot for Day Time scenario with Speed Limit 30mph](image)

**Figure 12:** MATLAB surface plot for Day Time scenario with Speed Limit 30mph
Figure 13: MATLAB surface plot for Day Time scenario with Speed Limit 45mph

Figure 14: MATLAB surface plot for Night Time scenario with Speed Limit 30mph
As mentioned earlier, the highest value of TTC represents the lowest probability of collision. Therefore, in each of the scenarios presented above, the displays that correspond to higher TTC values (the displays visible at top most layer) represent signal indications that are most likely to avoid collision. The following conclusions can be made from the above plots:

From Figure 12 and Figure 13, it can be observed that:

- Flashing Circular Yellow and Flashing Yellow Arrow should be used for a day time scenario.
- Even when speed limit is high, it can be noticed that FCY and FYA correspond to higher values of TTC and hence, should be used.
- When Red duration at the intersection is less than 30sec, FYA results in higher TTC values whereas if red duration is greater than 30sec, FCY indication results in higher TTC values.

From Figure 14 and Figure 15, it can be observed that:

- Flashing Circular Red and Flashing Red Arrow signal indications reduce the probability of collision during a night time scenario.
- When speed limit is low, FCR has higher driver comprehension and therefore higher TTC.
- When speed limit is high, both FCR and FRA result in high TTC values. Selection of FCR or FRA depends on volume and red duration at the intersection.
2.8 CONCLUSIONS AND RECOMMENDATIONS

From the above analysis, it was observed that for a day time scenario, FCY and FYA signal indications offer better driver understanding and hence, reduce probability of collision. Red duration is the parameter that influences the selection of FCY or FYA during the day time. Volume and speed limit can be observed to be not very influential in this aspect.

For a night time scenario, FCR and FRA indications reduce the probability of collision with highest TTC values. Furthermore, it can be observed that at lower speed limits, FCR has highest TTC values. At higher speed limits, selection of FCR or FRA is influenced by red duration and volume at the intersection.

It can also be concluded from the analysis that drivers’ level of comprehension to a signal indication changes with different parameters. With different intersection conditions, and time of day situation, a driver’s level of perception changes and hence, it is necessary to perform an analysis to understand driver behavior. The above analysis helps give a basic understanding of the type of display that needs to be adopted for different values of visibility, volume, red duration and speed limit.

2.9 FUTURE WORK

This study can be extended for different intersection geometries. Future work should also include implementing design scenarios for different range of speed limits. By increasing the number of participants to drive the simulator well defined boundaries may be obtained for the selection of different signal indications.

REFERENCES

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CHAPTER 3: EFFECT OF DRIVER BEHAVIOR ON EMISSIONS AT DIFFERENT PPLT OPERATIONS

Sri Rama Bhaskara Kumari Duvvuri, Montasir Abbas

3.0 ABSTRACT

There are five major types of Protected-Permitted Left Turn (PPLT) operations used in different states of the United States. They are: Circular Green (CG), Flashing Circular Red (FCR), Flashing Circular Yellow (FCY), Flashing Red Arrow (FRA) and Flashing Yellow Arrow (FYA). Literature indicates that driver behavior is influenced to a certain extent by the type of PPLT operation. This study tries to investigate the impact of resulting driver behavior on vehicular emissions by using a real time driving simulator. For this purpose, different scenarios that correspond to the five PPLT operations are developed in the driving simulator. Using the instantaneous velocity and acceleration data, vehicular emissions are calculated for each scenario using the VT-Micro microscopic emissions model. The data obtained from the simulator is analyzed using JMP Statistical tool. Response surface model and prediction profiler are analyzed to study the effect of PPLT operations on emissions. Emission results are compared with Time to Collision (TTC) values for each scenario. The signal indication that corresponds to maximum TTC and minimum emission will best suit the given situation. Results indicate that during day time, FCY and FYA are most suitable displays whereas during night time it is FCR and FRA.

Key words: PPLT, Emission, VT-Micro, Left-turning traffic, TTC, Driving Simulator, Circular Green, Flashing Circular Red, Flashing Red Arrow, Flashing Circular Yellow and Flashing Yellow Arrow.
3.1 INTRODUCTION

According to NCHRP report 493 [1], different indications for left turn permitted operation are used in different states of the U.S. For example, Flashing Circular Red is used in Maryland and Michigan; Flashing Circular Yellow is used in Seattle and Washington State (It is no longer in operation in Washington State according to the NCHRP report); Flashing Red Arrow is used in Delaware and Cupertino, CA; and Flashing Yellow Arrow is used in Sparks, NV and Reno NV. NCHRP report 493 [1] discusses the safety of drivers under each type of indication by conducting traffic conflict studies, field crash analysis and driving simulation studies. There are many other papers that discuss safety performance of different left turn signal indications. But, in order to evaluate the effectiveness of a particular PPLT operation, along with safety performance it is also necessary to study the resulting vehicular emissions. The literature indicates that a driver’s level of comprehension varies with respect to type of left turn operation [2-7]. Hence, the velocity and acceleration profiles will vary; which in turn will influence emissions. Therefore, the main objective of this paper is to study vehicular emissions under five different types of left-turn permitted operations. The calculated emissions are then compared with TTC values in each scenario to study the effectiveness of a left-turning operation. From the results, most – suitable PPLT operation can be determined for given control variables that can provide driver safety along with minimizing vehicular emissions. In this paper, first the literature review that studies factors affecting vehicular emissions and different models used to calculate vehicular emissions will be discussed. Then, the design of experiments and development of scenarios in the driving simulator will be explained. Finally, analysis of data will be presented. Graphs will be plotted from the results to provide guidelines for selection of a particular PPLT operation under given conditions.

3.2 LITERATURE REVIEW

NCHRP Report 493 [1] discusses different left turning operations used in different states. The major types of PPLT operations analyzed in the report are: Circular Green, Flashing Circular Red, Flashing Circular Yellow, Flashing Red Arrow and Flashing Yellow Arrow. Safety of drivers was evaluated at different PPLT operations using photographic driver studies and field traffic operation studies. The field traffic operation studies include field traffic conflict studies, crash data analysis, driver confirmation studies etc. Along with that, driving simulator studies have been performed to
analyze the statistical results of percentage of correct responses for different indications. Results indicated no significant difference in percentage of incorrect responses for different PPLT operations.

Cortes et al. [8] developed a methodology based on object-oriented model to compute emissions and energy consumption. Different transportation activities were identified and simulated in the model. The developed model was used to determine urban and inter urban transportation activity patterns and to calculate resulting emissions under different scenarios.

Madireddy et al. [9] studied the impact of speed limit reduction and traffic signal coordination on vehicle emissions in the area of Antwerp, Belgium. An integrated model was used in their study that combines the microscopic traffic simulation model with the emissions model to determine the effect of above mentioned traffic management measures on emissions. Results indicated that, a reduction in CO2 and NOx emissions was found by decreasing the speed limit from 50mph to 30mph. By implementing green wave signal coordination on an urban arterial, a reduction of 10% in emissions was observed.

El-Shawarby et al. [10] evaluated the impact of vehicle cruise speed and acceleration level impacts on hot stabilized emissions. Field data under real world driving conditions was collected. An emission measurement device was used to collect emissions of oxides of nitrogen, HC, CO and CO2. It was noticed that as the level of aggressiveness for acceleration increases, fuel-consumption and emission rates decrease. The paper also validated VT-Micro framework for emission calculation and the study demonstrated that further refinement is required to capture non-steady-state behavior of vehicle fuel-consumption and emission behavior.

Rakha et al. [11] developed a framework for microscopic emissions models (VT-Micro version 2.0) for assessing environmental impacts of transportation projects. Data was obtained from 60 light duty vehicles and trucks. Statistical clustering techniques, classification and regression tree algorithms were utilized to classify the vehicles into different categories. The model was validated against laboratory measurements and results indicated a prediction error less than 17%. Rakha et al. [12] also analyzed the requirements of evaluating traffic signal control impacts on energy and emissions based on instantaneous speed and acceleration measurements.

Tang et al. [13] studied the effects of signal light on vehicles’ fuel consumption, CO, HC and NOx under a car-following model. Emissions were calculated using VT-Micro model and results
indicated that a vehicle’s fuel consumption and emissions are influenced by green split of the signal light and the vehicle’s time headway at the origin.

Ahn et al. [14, 15] developed models to estimate vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels. Data has been collected from Oak Ridge National Laboratory (ORNL) for this purpose. The fuel consumption and emission models were found to be accurate with respect to the ORNL data with a coefficient of determination of 0.92-0.99. The models have also been further utilized along with global positioning system to evaluate energy and environmental impacts of operational – level projects in the field.

Pandian et al. [16] evaluated the effects of traffic and vehicular characteristics on vehicular emissions near traffic intersections. The results indicated that vehicular emissions near an intersection are dependent on average fleet speed, deceleration speed, queuing time, waiting time, acceleration speed, queue length and traffic flow rate. It has been mentioned that the existing emission models should be combined with traffic flow models for better estimation of emissions for urban transportation and air quality planning system.

Tielert et al. [17] studied the impact of Traffic Light to Vehicle Communication (TLVC) on fuel consumption and emission. Sensitivity analysis was performed to determine gear choice and distance from traffic light at which vehicles should be informed under connected vehicle environment. Results indicated that TLVC has the potential to reduce environmental impact of vehicular traffic. Also, gear choice was noticed as a significant influencing factor and it can void the positive benefits of TLVC. Therefore, it was suggested that future applications should combine speed advice based on TLVC along with gear-shifting advice. In vehicles with automatic gear transition, both speed and gear choice should be optimized based on TLVC.

Penabaena-Niebles et al. [18] analyzed the impact of transition between signal timing plans on social cost based on delay, fuel consumption and air emissions. A mathematical function was developed to quantify the monetary impacts of transition between signal timing plans on environment. The proposed cost function was evaluated to assess the number of steps required to adjust signal timing that will reduce delay, fuel consumption and gas emissions.

Ericsson et al. [19] estimated the impact of route choice optimization on fuel consumption if optimization is based on lowest total fuel consumption instead of total travel time. The analysis was conducted in city of Lund, Sweden and it was observed that, an average of 8.2% fuel consumption
can be saved by using fuel-optimized navigation system. A methodology was also presented with steps required in performing such an analysis.

Stevanovic et al. [20] proposed an approach of optimizing traffic control to reduce fuel consumption and vehicular emissions. A 14-intersection approach network in Utah was considered for this purpose. VISSIM, CMET and VISGAOST were interlinked to optimize signal timing plans for fuel consumption and CO₂ emissions. It was observed from the results that, the formula used to calculate fuel emissions in traffic simulation tools does not calculate emissions adequately and some of the performance measures used as objective functions in signal optimization tools were proved ineffective.

Ahn and Rakha [21] studied the effects of route-choice decision on vehicle energy consumption and emissions for different vehicle types using microscopic and macroscopic emission estimation tools. Findings indicated that faster route choice results in higher values of emissions. Improvements to air quality can be achieved by slower arterial route even though it might result in extra travel time. Results also indicated that macroscopic emission estimation tools produce erroneous conclusions as they ignore transient vehicle behavior along a route.

Smit et al. [22] validated road vehicle and traffic emission models. An analysis of 50 studies dealing with validation of various types of traffic emission models is presented. Results indicated that less complex models perform better than more complex models. Also, it was identified that most of the models lack guidance on allowable error margins and estimates of prediction error.

As discussed above, there are many papers that study the impact of various factors on emissions and methods of optimizing emissions by changing different parameters. Development and validation of different emission models were also performed in some papers. However, there is very few research that discusses the impact of different type of PPLT operations on emissions. On the other hand, studies that compare different PPLT operations [1-7] are based on driver’s level of understanding, traffic conflict studies and crash data etc. Literature did not reveal any study that compares emissions under different signal indications. In order to evaluate the effectiveness of a particular signal indication, it is important to study vehicular emissions along with evaluating driver safety. Therefore, this paper addresses this issue by comparing emissions with TTC for each signal indication. The main objective of this paper is to study the effect of five different types of PPLT operations on vehicular emissions using a real-time driving simulator. A driver’s response can be most accurately obtained if a real time driving simulator is used and if second-by-second data can
be collected for analysis. The literature indicates that, parameters that affect vehicular emissions are speed limit, traffic signal coordination, green split of signal, vehicle’s time headway, average fleet speed, waiting time near the signal, traffic flow rate etc. Hence, along with the five PPLT indications, different control variables were used to create different scenarios in the driving simulator. The parameters that are selected to vary in this study are volume at the intersection, waiting time near the signal (which is termed as red duration in this paper), speed limit and visibility (Day Time or Night Time).

3.3 DESIGN OF EXPERIMENTS

The main goal of this paper is to study the effect of different PPLT operations on emissions. By varying above mentioned control parameters for different types of PPLT operations, different scenarios were developed in the driving simulator. JMP Statistical tool was used to create Design of Experiments (DOE) for given variables. The inputted variables are as follows:

- Volume at the intersection (200veh/hr. – 1200veh/hr.)
- Speed Limit (30mph or 45mph)
- Red duration (20sec to 50sec)
- Visibility (Day-Time or Night-Time)
- Type of PPLT operation (Circular Green, Flashing Circular Red, Flashing Red Arrow, Flashing Circular Yellow and Flashing Yellow Arrow)

From JMP DOE, a total of 39 scenarios that correspond to different type of control variables are generated. All these 39 scenarios are developed in the simulator using the Hyper-Drive component which will be explained further. Drivers are requested to drive through all the scenarios and data is collected for analysis.

3.4 METHODOLOGY

Drive Safety DS-250 Model driving simulator is used in this study. It consists of three major components: Hyper Drive, Vection and Dashboard. The hyper drive component is used to develop the required scenarios in the simulator. It consists of different database elements such as type of vehicles, intersection layouts, type of roadway, pedestrians, etc. Tool Command Language (TCL)
is embedded in the simulation software that helps develop more complex settings such as signal settings, time triggers, speed limits etc.

Dashboard is the interface between HyperDrive component and Vection. Vection is the software component that runs the simulator. The required scenarios were developed in the simulator as shown in Figure 1. Four intersections were designed for each scenario. Drivers are requested to take a left turn at each intersection so that, they will encounter the PPLT display every time and their behavior can be recorded. The data was automatically collected by the simulator which includes time, velocity, speed limit, acceleration, brake, vehicle X, Y and Z coordinates, vehicle ahead, headway distance, TTC, collision angle, collision velocity, etc. At each intersection, the control variables: volume, speed limit, red duration and visibility were adjusted according to values from JMP Design of Experiments (DOE).

![Image of a four-way intersection with annotations and data recording instruments]

**FIGURE 1: Design scenario in simulator**
FIGURE 2: Day Time Scenario with Flashing Red Arrow Indication

Figure 2 shows typical signal indication at an intersection. As it can be observed from the figure, the scenario was implemented in an urban environment with single lane in both directions. Parking was provided on either side and all intersections are signalized. The driving simulator that is being used does not support a horizontal or cluster display type of signal head and hence, a three-vertical display type was used in all scenarios. Drivers participating in this study experienced the five different types of permitted operation, and they were required to yield to opposing traffic in all scenarios. All 39 scenarios from DOE were developed in the simulator using the Hyper Drive component of the driving simulator.

A total of fifteen participants volunteered to perform the drive. They were invited to participate via email or word of mouth. All participants are above 18 years and are licensed drivers in Virginia. They were requested to sign an informed consent form before they actually start the drive. The consent form consists of the general information of the experiment, total time taken, along with possible risks and benefits. On driver’s consent, they were requested to perform an adaption session before the real data collection session so that they will get familiar with design environment and driving the simulator. Once they got familiar with driving, they were requested to drive in all 39 scenarios. The total time taken by each driver was nearly 50-60 minutes. The data was collected from the simulator for analysis. Microsoft Excel, JMP Statistical tool and MATLAB were used for analysis of the data.
3.5 RESULTS AND ANALYSIS

The Driving Simulator collects data for every 0.1 sec interval. From the data that was collected, velocity and acceleration values were extracted. VT-Micro model [11] is used for calculation of emissions and fuel consumption in all the scenarios. Using the instantaneous speed and acceleration values, fuel consumption, HC, CO and NOx emissions are calculated using (1)

\[ MOE_e = \exp \left( \sum_{i=0}^{3} \sum_{j=0}^{3} C_{i,j}^e \times (Velocity)^i \times (Acceleration)^j \right) \quad (1) \]

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Table 1: Coefficients of VT-Micro Emissions Model [23]

3.5.0 Velocity and Total Emission profiles

Velocity and Total Emission profiles of an individual driver in a low volume scenario are plotted below to get a basic understanding of driver behavior with respect to different left-turning operations.
FIGURE 3: Change in velocity with time for various signal indications (A) Velocity_Circular Green; (B) Velocity_Flashing Circular Red; (C) Velocity_Flashing Red Arrow; (D) Flashing Circular Yellow; (E) Flashing Yellow Arrow

FIGURE 4: Change in emissions with time for various signal indications (A) Total Emissions_Circular Green; (B) Total Emissions_Flashing Circular Red; (C) Total Emissions_Flashing Red Arrow; (D) Total Emissions_Flashing Circular Yellow; (E) Total Emissions_Flashing Yellow Arrow

Figure 3A – Figure 3E are velocity profiles of a driver for different PPLT operations. The above figures are obtained from a scenario with low volume so that, there is no waiting time for drivers near the intersection due to vehicles ahead of it. There are very few opposing vehicles as well and hence, the only factor that affects the driver behavior is the type of left-turn indication. From the above figures, it can be noticed that, for scenario with Circular Green indication, drivers slightly reduce their speed at the intersection before taking a left turn whereas for scenarios with FCY and FYA, the reduction in speed is higher than CG. Drivers are more cautious near a scenario with
flashing yellow and reduce their speed as they approach the intersection and then try to take a left turn accordingly. For scenarios with FCR or FRA, drivers come to a complete stop before they pass through the intersection. They try to “stop and go” instead of “yield and go” thereby increasing number of stops in these scenarios. Due to the increase in number of stops, drivers need to adopt short durations of acceleration and deceleration profiles to achieve desired speed. This in turn, increases emissions for a given situation. Therefore, if total emission profiles in Figure 4 [A-E] are compared, it can be noticed that, FCR leads to higher amount of total emissions followed by FRA.

The above profiles correspond to the behavior of a single driver in day time scenario. In order to evaluate and compare the results further, emissions and TTC graphs were plotted. By comparing the plots, conclusions can be made on selection of type of PPLT operation under given conditions.

3.5.1 Prediction Profiler and Surface Plots:

An effective parameter in analyzing severity of conflicts at an intersection is Time to Collision (TTC). This is directly obtained from simulator as an output along with other data collection elements. TTC values along with calculated emission values using (1) for all proposed scenarios were uploaded to JMP Statistical tool for analysis. Response surface model and prediction profiler were used for analysis. Predicted values in JMP are found to be very close to actual values with an R square value of 0.91 as shown in figure 6. Data has been categorized as follow for analysis in JMP:

- Volume (Continuous range varying from 200veh/hr. to 1200veh/hr.)
- Speed Limit (Lower speed limit of 30mph and Higher speed limit of 45mph)
- Red duration (Continuous range varying from 20sec to 50sec)
- Visibility (Day time indicated by 0 and Night time indicated by 1)
- Left-Turn Display ([1-5]: 1 – Circular Green, 2 – Flashing Circular Red, 3 – Flashing Red Arrow, 4 – Flashing Circular Yellow and 5 – Flashing Yellow Arrow)
FIGURE 5: Analysis of Variance

Figure 5 shows analysis of variance along with parameter estimates of emission values for defined variables. It can be noticed from the figure that the analysis is significant with P value less than 0.0001.

FIGURE 6: Actual by predicted plot for total emission values.
Prediction profiler shows the relationship between different variables and how variation in a control variable will affect total emissions or TTC. Figure 7 represents prediction profiler for day time scenario with a speed limit of 30mph.

**FIGURE 7: Prediction Profiler for Day Time scenario with speed limit 30mph**

From figure 7, it can be noticed that, for a day time scenario with volume of 700 veh/hr., Red duration of 35sec and speed limit of 30mph; highest value of total emissions can be observed for display 3 (Flashing Red Arrow). Lowest TTC value corresponding to same scenario can be observed for display 1 followed by display 3. Figure 7 shows the prediction profiler for one particular selection of control variables. In order to determine the range of values for which a particular display will be most suitable, surface plots are made in MATLAB for both Emissions and TTC values. The predicted values from JMP are extracted and graphs are plotted for four different situations:

1. Day Time Scenario with Lower Speed Limit of 30mph
2. Day Time Scenario with Higher Speed Limit of 45mph
3. Night Time Scenario with Lower Speed Limit of 30mph
4. Night Time Scenario with Higher Speed Limit of 45mph

With X-axis being Volume, Y-axis being Red duration and Z-axis being Total emissions or TTC, graphs are plotted for all four scenarios. For each scenario, surface plots that correspond to different PPLT operation are overlapped so that the different left-turn displays can be compared.
1. Day Time Scenario:

![Figure 8A](image1) ![Figure 8B](image2) ![Figure 9A](image3) ![Figure 9B](image4)

**FIGURE 8:** (A) Emissions for day time scenario with speed limit 30mph; (B) Emissions for day time scenario with speed limit 45mph

**FIGURE 9:** (A) TTC for day time scenario with speed limit 30mph; (B) TTC for day time scenario with speed limit 45mph

Figure 8 [A-B] represent emissions surface plot for a day time scenario with different speed limits. Figure 9 [A-B] represent TTC surface plots for the same scenarios.

The emissions plot shows that, FCR and Circular Green signal indications result in lowest emissions when speed limit is low. When speed limit is high, FCY, FYA and Circular Green can be observed with lowest emissions for the given situation. In addition to speed limit, both opposing volume and red duration also influence the type of signal indication that corresponds to minimum emissions.

As mentioned in Chapter 2, FCY and FYA correspond to higher TTC values during day time. Hence, by comparing TTC and Emission plots, it can be noticed that, FCY and FYA did not result in highest emissions, but did not correspond to lowest emissions as well. Hence, selection of signal indication should result by compromising either emissions or TTC. Considering driver safety as the
main priority, it is recommended to use FCY and FYA signal indications for a day time scenario. Selection of either FCY or FYA should depend on red duration at the intersection as explained in Chapter 2. If red duration is less than 35 sec, FYA is recommended. If it is higher than 35 sec, a FCY is recommended.

2. Night Time Scenario:

![Figure 10A](image1.png) ![Figure 10B](image2.png)

**FIGURE 10:** (A) Emissions for night time scenario with speed limit 30mph; (B) Emissions for night time scenario with speed limit 45mph

![Figure 11A](image3.png) ![Figure 11B](image4.png)

**FIGURE 11:** (A) TTC for night time scenario with speed limit 30mph; (B) TTC for night time scenario with speed limit 45mph

Figure 10A and figure 10B represent emission plots for the night time scenario with speed limit 30mph and 45mph respectively. Figure 11A and figure 11B represent TTC plots for the same scenarios.

-Emissions plot shows that FCR and Circular Green signal indications result in lowest emissions when speed limit is low. When speed limit is high, FCY and Circular Green can be observed to result in lowest emissions.
-Figure 11A and 11B denote that, during night time, FCR and FRA offer better driver understanding and hence, higher values of TTC.

Hence, by comparing both Emissions and TTC values, it can be noticed that, when speed limit is low, a FCR signal indication results in highest TTC and lowest emissions and hence, can be recommended. When speed limit is high, a compromise should be made either with TTC or with emissions in order to make a decision. Considering driver safety as the main priority in this study, it is recommended to use either a FCR or FRA for a night time scenario with higher speed limit. FRA can only be recommended when volume and speed limit are high at an intersection. In all other situations, FCR is recommended.

It can also be noticed from the above analysis that, left turn operations with highest TTC did not correspond to lowest emissions in most of the scenarios. Hence, selection of a signal indication under given situation should be decided by optimizing both TTC and Emissions.

3.5.2 Flow Chart for Determination of Signal Indication:

From above analysis, left-turn signal indications for defined conditions are obtained. Figure 12 represents a flowchart developed in SysML to determine the selection of left-turn indication for a given situation.
Figure 12: Flow chart for determination of signal indication
3.6 CONCLUSIONS AND RECOMMENDATIONS

The design of experiments are categorized into four scenarios, and surface plots are made in each of them with respect to emissions and TTC. The signal indication that offers highest TTC values and lowest emissions is best suited for any given situation. By comparing all the graphs, it can be summarized that:

- For a day time scenario, either a FCY or FYA should be used depending on the average red duration at the intersection.

- For a night time scenario, either a FCR or FRA should be used and decision should be made depending on red duration, volume and speed limit at the intersection.

It can be also be observed that, the recommendations made depending on TTC values, did not correspond to lowest emissions in all situations. They did not correspond to higher emissions as well. Therefore, selection of signal indication should be decided by optimizing both emissions and TTC for a given scenario, and the indication that offers highest TTC and lowest emission should be selected as best-suited indication for given situation.

3.7 FUTURE WORK

Future work should include developing different intersection geometries along with introducing different range of speed limits in the design. More number of participants with different age groups and with driving experience in different states of US should be requested to participate in the study.

REFERENCES


CHAPTER 4: CONCLUSIONS AND FUTURE WORK

4.0 CONCLUSIONS

In this thesis, the results obtained are categorized into four types for analysis. The first two categories represent a day time scenario, one with lower and the other with a higher speed limit. The second two categories represent a night time scenario, one with lower and the other with a higher speed limit. JMP Prediction profilers and MATLAB surface plots were analyzed to study the effect of various parameters on TTC and Emissions. From TTC surface plots, it can be summarized that during day time, either a FCY or FYA indication should be used for driver safety. At night time, either a FCR or a FRA should be used. The selection of a left-turn indication depends on volume and red duration in each scenario. From emission plots, it can be summarized that FCR results in the lowest emissions when the speed limit is low. When the speed limit is high, either a FCY or FYA or CG results in the lowest emissions. Furthermore, the signal indication representing the lowest emissions depends on red duration and opposing volume at the intersection. By comparing these results with TTC, it was noticed that the signal indications corresponding to the highest TTC, did not result in the highest emission values. They did not correspond to the lowest emissions either, and hence, a compromise should be made with respect to emissions or TTC when making a decision. As the results obtained from TTC plots did not correspond to highest emissions, they are comparatively better than other indications with respect to emissions. In this study, considering driver safety as the main objective, results have been summarized.
4.1 FUTURE WORK

Though the results provide a basic understanding of the effect of left-turn signal indication on TTC and emissions, further analysis is required with a larger sample size of participants. Distinct boundaries cannot be defined with a small sample size and hence, more participants are required. Different speed limits should be adopted in the design and more number of scenarios should be developed. Also, current participants belong to an age group of 20-30 years, and the majority are from the same state. Hence, more participants from different states and different age groups should be gathered to drive the simulator.