CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Transportation has always been a crucial aspect of human civilization reflecting the level of general economical and technological advancement of a given society. Transportation means of various kinds have been evolving for centuries leading to faster, further, safer, and more cost efficient trips on roads, rail, on the water, or in the air. It is, however, only in the second half of this century that the phenomenon of traffic congestion becomes predominant due to the rapid increase of the number of vehicles and increases in demand for virtually all modes of transportation. Traffic congestion appears when too many vehicles attempt to use a common transportation infrastructure with limited capacity. In the best case, traffic congestion leads to queuing phenomena (and corresponding delays) while the infrastructure capacity ("the server") is fully utilized. In the worst (and far more typical) case, traffic congestion leads to a degraded use of the available infrastructure (reduced throughput that may even lead to fatal gridlocks) with excess delays, reduced safety, and recently, increase environmental pollution.

The goal of developing the advanced ground transportation systems of the future is worthwhile and thus it should be pursued with enthusiasm and dedication. This research addresses major technical and economic issues associated with this promising transportation technology. The ever-growing base of maglev knowledge and experience is producing benefits today and holds great promise for the future.

2.2 U.S. Maglev Efforts

Pioneering U.S. work on Maglev transportation technology was conducted at Brookhaven National Laboratory in early 1960s. Powell and Danby [10] of the

Laboratory proposed the use of superconducting magnets on a moving vehicle to induce repelling currents in closed aluminum wire loops located on the guideway. They continued to refine their ideas, inventing the low-drag, null flux concept [11], later adopted by Japanese and Canadians for their guidance systems. In 1970, a 500-ft-long test track containing 400 ft if continuous sheet aluminum guideway was built by the Stanford Research Institute (SRI) and later used to elevate an 1,100-lb test vehicle levitated by superconducting magnets. In 1971, the Federal Railroad Administration (FRA) awarded contracts to SRI [12] and the Ford Motor Company [13] for parallel analytical and experimental studies of both electromagnetic suspension (levitation by attractive magnet force) and electrodynamic suspension (levitation by repulsive magnetic force) systems.

The Ford Motor Company was awarded a contract by DOT to develop a baseline vehicle and to build and evaluate a 300-mph test vehicle, but the Federal Government's funding for high-speed maglev was suspended in 1975 and the vehicle was never built. This administrative decision was justified by the belief that the United States could develop air transportation and highway infrastructure to accommodate the anticipated growth in intracity travel at least for the next decade.

2.3 Superconductivity

Superconductors are materials whose resistance to the flow of electric current approaches zero when cooled below a critical transition temperature, thus permitting minimal loss of electric energy in the form of heat. A superconducting magnet is an electromagnet made of superconductive coil. Due to the lack of electric resistance, once the electric current is circulated, it flows persistently. Very strong electromagnetic forces can be obtained from small magnets.

Superconducting magnets require a cooling system to keep the superconductive coil at extremely low temperatures. Conventional superconducting magnets using niobium-titanium or niobium-tin conductors must be cooled to the vicinity of absolute zero (4 K) to achieve superconductivity, requiring the use of liquid helium and the coolant. The cost and complexity of liquid helium refrigeration systems have been the greatest obstacles to their broad application. These conventional superconductors are called low temperature superconductors (LTSC).

The LTSC magnet system for the Japanese MLU002 Projects consists of aluminum outer vessels and stainless steel inner vessels. The vacuum space formed between these two vessels serves as an intermediate thermal insulator. Superconducting magnet coils are placed in the stainless steel inner vessels and cooled down to 4 K (-452.5 °F) with liquid helium. Even though the inner vessels are thermally insulated, heat will intrude into the inner vessel and gasify the liquid helium. The on-board refrigeration system liquifies this helium gas for reuse [14,15].

The bottom line here is that superconductivity is an enhancing not an enabling technology.

2.4 Guideway Considerations

While some design concepts have been developed nearly to commercial application, the attractiveness of maglev systems is expected to be enhanced even further over the next several years by new or improved concepts, improved design and construction methods, and new materials including high-temperature superconductors, high-energy permanent magnets, and advance material for guideways. It is therefore reasonable to expect that maglev systems may indeed be a key transportation mode in the 21^{st} century. For several decades, research and development have been performed in the areas of magnetic levitation, response of maglev vehicles to rough guideways, interaction of variously suspended vehicles with flexible guideways, and optimization of vehicle suspensions. The results of these efforts are useful in providing appropriate criteria for the design of maglev systems [16].

Zicha [17] states that maglev route choice is quite flexible due to unlikeliness of derailment and its independence from adhesion for climbing grades. This flexibility is a common advantage of all maglev systems. Indeed, the limiting factor in specifying line geometry comes from the established level of passenger comfort. However, specifications established for wheel-on-rail systems may be unnecessarily conservative for a maglev, since a high-speed maglev can easily utilize gradients of up to 3.5 percent and a low-speed maglev can afford up to 10 percent.

Chen et al. [18] discuss the structural aspects of guideways as centering around design considerations involving the substructure, superstructure and materials employed. To reduce construction cost, a narrow guideway with widely spaced supports is desirable, while to achieve an acceptable ride quality level and/or to meet constraints on guideway stress, a wide guideway with narrowly spaced supports would be better. To meet ride comfort specifications, guideway stiffness usually becomes the controlling factor. Furthermore, the amount of guideway flexibility and irregularity that can be tolerated depends on the vehicle suspension and other motion controlling systems.

2.5 Status of AHS

A great deal of early research in the area of the automatic control of individual rubber-tired vehicles was conducted on both theoretical and experimental bases, and prototype experimental equipment was developed and operationally tested by General Motors Corporation [19], Ohio State University [20], the Japan Governmental Mechanical Laboratory [21], the U.K. Road Research Laboratory [22], Ford Motor Company [23], and the Japan Automobile Research Institute [24]. This testing was mainly concerned with the automatic control of the longitudinal and lateral movements of the vehicle, and little effort was expended on automated network control.

In 1986, the Federal Railroad Administration initiated the Northeast Corridor Study, one part of which was focused on the automated highway [25] as a mean of relieving congestion in this corridor. Here, TRW System Group considered intercity travel as part of this study and examined a representative AHS that would accommodate rubber-tired passenger vehicles. The application of dual-mode vehicles for intracity and intercity travel has been studied, and several system concepts have been developed [26, 27]. The use of automated pallets has also been frequently suggested [28].

The California Program on Advanced Technology for the Highway (PATH) has emphasized work on automatic vehicle control technology for highway automation to a greater extent than any of other current IVHS programs. The primary reasons for this emphasis is that automatic vehicle control offers the most dramatic potential for solving both traffic congestion and safety problems. Secondary is that a university research program can better emphasize more advanced technologies than those currently being developed by private industry, without finding itself in competition with industry [29].

2.6 Automatic Longitudinal Control

Automatic Longitudinal Control is a primary concern of Advance Vehicle Control Systems, in general, and AHS, in particular. There are two fundamentally different ways of providing automatic longitudinal control for roadway vehicles: vehicle based control and infrastructure based control. The vehicle based control system uses the difference between the state of each vehicle and the state of its predecessor as the error signals for regulation. The infrastructure based control system uses the differences between the position and/or velocity of each vehicle and the corresponding position and/or velocity of a virtual reference point that moves along the roadway as its error signals.

All the current automatic longitudinal control technologies can be categorized as these two types. The most commonly used longitudinal control strategies are Car Following Control (Platoon Control), Autonomous Intelligent Cruise Control, and Point-Following Control. The former two are vehicle-based control while the PFC is infrastructure-based control.

2.6.1 Car-Following Models

Early studies of driver behaviors had been focused on minimum safe following headway. Pipe expressed safe distance headway between vehicles as a function of speed and vehicle length to which Forbes later added the effect of reaction time [30]. At moderate speeds, both models show very close results to those obtained from field studies, but give considerable difference at the high and low speed range.

Recent advances in computer performance have made it possible to simulate the flow of large numbers of vehicles in various traffic situations by describing the motion of each individual vehicle. This has re-awakened an interest in “car-following”, the name given to a class of mathematical models that accomplish this. These car-following models have evolved to predict the dynamic behavior of a line of platooned vehicles by describing how the driver of each vehicle responds to changes in motion of the vehicle immediately ahead by accelerating or braking in a prescribed manner. After extended comprehensive field experiments, General Motor’s researchers, focusing on acceleration of the following vehicle, developed five generations of car following models in the form of responses that is equal to a sensitivity factor times a stimulus. The stimulus in the model refers to relative speed and the response is speed change or acceleration. One of the models was proved to have a mathematical bridge to Greenberg’s macroscopic traffic flow model. The final model was found to be:

$$\ddot{x}_{n+1}(t+\Delta t) = \frac{a_{l,m}\left[\dot{x}_{n+1}(t+\Delta t)\right]^{m}}{\left[x_{n}(t)-x_{n+1}(t)\right]^{l}}\left[\dot{x}_{n}(t)-\dot{x}_{n+1}(t)\right] \tag{2.1}$$

where t is time, Dt is reaction time, x_n and x_{n+1} are positions of leading and following vehicles respectively, and $\dot{x}$ and $\ddot{x}$ represent the first and second derivative of the positions with respect to time, which give vehicle velocities and accelerations.

Using this type of control, a vehicle is warned to brake by a message passed back from vehicle to vehicle within the platoon. When the leading vehicle brakes, each vehicle in a platoon will start to brake as its maximum rate. Vehicles in car-following control can obtain a quick response to an incident or sudden changes in state of the leading vehicle. Spacings between vehicles can be adjusted according to speed changes. By using closely spaced platoons, highway capacity can be increased considerably [31,32]. Nevertheless, traffic instability can easily occur under this type of control.

2.6.2 Autonomous Intelligent Cruise Control (AICC) Concept

In AICC, autonomous control is used by each vehicle to keep a desired distance behind its predecessor, which can be taken as constant for all vehicle at any speed. AICC can operate in the presence of manually controlled vehicles, i.e. mixed flow AICC [33,34,35].

AICC is similar to platoon Control in selection of error signal for the control system. The major difference is that in AICC, the input of the controller of each vehicle only comes from one vehicle ahead of it, so each vehicle needs only detect the state changes of the vehicle directly ahead of it. When it perceives that the vehicle ahead is breaking, it will take the safest response to apply its brake fully, a short period after the preceding one has done so. Another difference is that the focus of AICC is safe braking, not close following, i.e. a vehicle does not necessarily follow a vehicle beyond its desired or design speed.

Since the AICC system does not exchange information with other vehicles, it has fewer oscillations and slinky-effects, and thus can obtain a smoother response than the car following control. However, it may not get as quick a response to the state changes of the leading vehicle as the car following control.

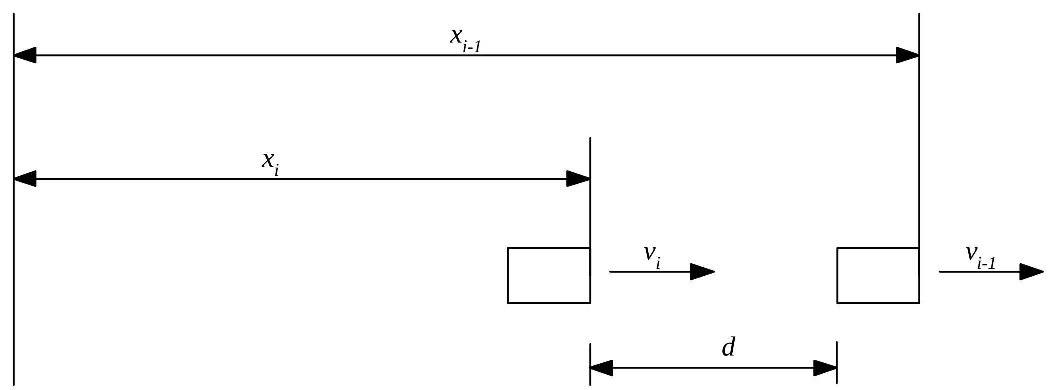


Figure 2.1 Autonomous Intelligent Cruise Control

2.6.3 Point-Following Control (PFC) Concept

The point-following control scheme is infrastructure-based control which requires one-way communication from vehicle to roadway. The main control infrastructure unit assigns a moving slot of length *L* to each vehicle, divided by a spacing of Δ. Attempt is made to maintain the vehicle position within the assigned slot.

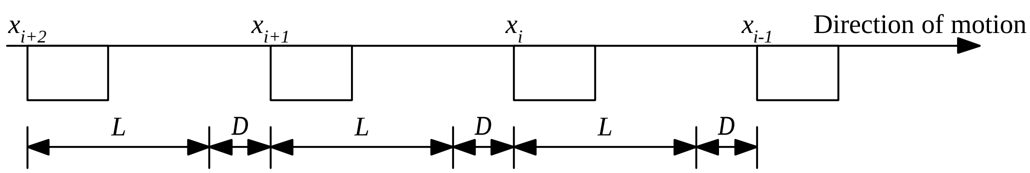


Figure 2.2 Point-Following Control

Point-following control mode can be simpler to implement since each vehicle follows a well-defined target. Under this type of control, merging, routing, and scheduling are simplified by fixed, discrete spacing increments. The disadvantage of point-following control includes lower capacity because of long slots that are usually assigned for the worst case condition. This makes point following control not adaptable to sudden demand changes or high fluctuation traffic. Furthermore, an incident may cause the whole system to shutdown.

2.7 Deterministic Control Systems

Assuming the key factors in the vehicle-roadway system are deterministic, classical control theory and modern control theory have been widely used in modeling vehicle automatic headway control systems. These control models describe the vehicle control process through the vehicle dynamic characteristics. Generally, they take a vehicle as an independent system, or a platoon as an independent system and each vehicle within the platoon as a subsystem. The inputs of the system (or subsystem) are usually the speed and acceleration of the leading vehicle or the vehicle ahead, and the relative distance of a vehicle from the leading vehicle. The outputs of the system could be the speed and acceleration of the vehicle and its distance from the vehicle ahead. These usually form the feedback system, and the information derived from the feedback comes from the deviation of the desired relative distance and speed.

In this type of models, transfer functions are introduced to simulate the information flow from the input to output of the headway control system and PI (proportional and integral relation between input and output) or PID (proportional, integral, and differential relation between input and output) controllers are used to solve the signal following and stability problems. These are usually third or higher order close-loop systems and the stability of the system could be solved by selecting the parameters of the controller to set up or adjust the system pole points. A typical model of this type is developed by the PATH program, which is a vehicle based control system. Assume a platoon consists of *N* vehicles. Each vehicle with in the platoon gets inputs only from the vehicle ahead of it.

2.8 Vehicle Dynamics

In order to simulate a guideway vehicle trajectory, one must understand the importance of resultant forces acting on the vehicle. Recognizing Newton's second law of motion, $F = ma$, acceleration can be expressed in from of $a = \Sigma F_i/m$, where m is vehicle mass and is assumed to be constant. Due to its unique operating characteristics, some forces that are taken into consideration for the conventional modes of transportation may not be relevant to maglev vehicles. Forces that are worth noting include [36]:

2.8.1 Propulsive Force, F_p

This is the force that the guideway exerts onto a vehicle or vice versa. A certain minimum level of the propulsive force is required to overcome other counteracting forces during vehicle motion. It is limited by engine power or drag friction. As a function of speed and gravity force, the propulsive force can be expressed as

$$\frac{F_p}{m} = a_p \leq g\frac{k}{v} \tag{2.2}$$

where k is power to weight ratio, g is gravity, and v refers to vehicle speed.

One can notice from Equation 2.2 that a high acceleration can be developed at low speed and it will proportionally reduce when speed increases.

2.8.2 Braking Resistance, F_b

This is a repulsive force that is intentionally applied to a vehicle to slow down or come to a complete stop. The braking force for rubber-tired vehicles or commuter trains may be expressed as a function of coefficient of friction *f* between the wheels and the contact surfaces as follows:

$$\frac{F_b}{m} = -gf \tag{2.3}$$

Unlike other conventional ground transportation modes, air fleet or maglev vehicle braking maneuver is achieved by increasing drag or reversing the propulsive force so that the force is applied in the negative direction.

2.8.3 Fluid Resistance, F_f

When a vehicle is put in motion, the fluid it moves through (e.g., air) exerts forces against the direction of motion. The fluid resistance is practically taken to be equal to force that is required to move air from the vehicle's path and frictional effect of air along the top, sides, and bottom of vehicle. Air resistance is the type of fluid resistance that would play an important role in determining characteristics of maglev vehicles. A simple form of air resistance can be estimated from

$$F_a = C_D A\frac{rv^2}{2} \tag{2.4}$$

It can be seen that the magnitude of the force, which is frequently referred to as drag force, highly depends on the vehicle's aerodynamic properties, namely frontal crosssectional area A and aerodynamic drag coefficient C_d. Furthermore, the force rapidly increases proportionally to the square of vehicle speeds v. The resistance is also a function of air density r, which varies with altitude and temperature.

2.8.4 Rolling Resistance, F_r

This force will be considered only on a short interval when the vehicle is travelling on the ground. It is approximately a linear function of vehicle speed [37].

2.8.5 Curve Resistance, F_c

This refers to a centripetal force resisting a centrifugal force that acts on a turning vehicle. Usually, a superelevation is employed on a curvature path for the purpose of bisecting the centrifugal force into a smaller component.

2.8.6 Grade Resistance, F_g

When a vehicle travels on a slant path, a contribution of a component of the gravitational force acting on the vehicle is considered. Given a slope G, the gravitational force component can be found from a force diagram to be:

$$\frac{F_g}{m} = g \sin q = \frac{gG}{\left(1+G^2\right)^{1/2}} \tag{2.5a}$$

where m is the vehicle mass and g is the gravitational force.

For the sake of simplicity, for small angles sin q is often taken equal to tan q. Thus, for practical purpose, Equation 2.4a is converted to

$$\frac{F_g}{m} = g \tan q = gG \tag{2.5b}$$

2.9 AHS Schematics

According to Siess [38], a typical highway cross-section of the future may look as shown in Figure 2.3. The magways will run parallel to the existing Interstate Highway System wherever the AHS is implemented. Both the highways and guideways would separate the car traffic from the truck traffic, thus increasing the safety and efficiency of both the highway and the magway. The reason for the connection between the magways and the highways is two-fold. First is the need for a way to load vehicles onto the AHS. The "feeder" would need to have the ability to move large volumes of vehicles at fairly high speeds, and the Interstate Highway System is the best way of implementing this. The AHS could be thought of as the next level above the Interstate Highway System, much like the Highway System is over the arterial network. To accomplish the loading of the AHS from the freeways special Guideway-Freeway Interchanges (Figure 2.4) would be used. At points where two freeways with guideways in the median intersect, Guideway-Guideway Interchanges (Figure 2.5) would be utilized. The second reason for the magway freeway connection is right-of-way. The flexibility of a raised guideway allows for it to be placed in the median of the existing Interstate Highway System and thus utilize the existing right-of-way.

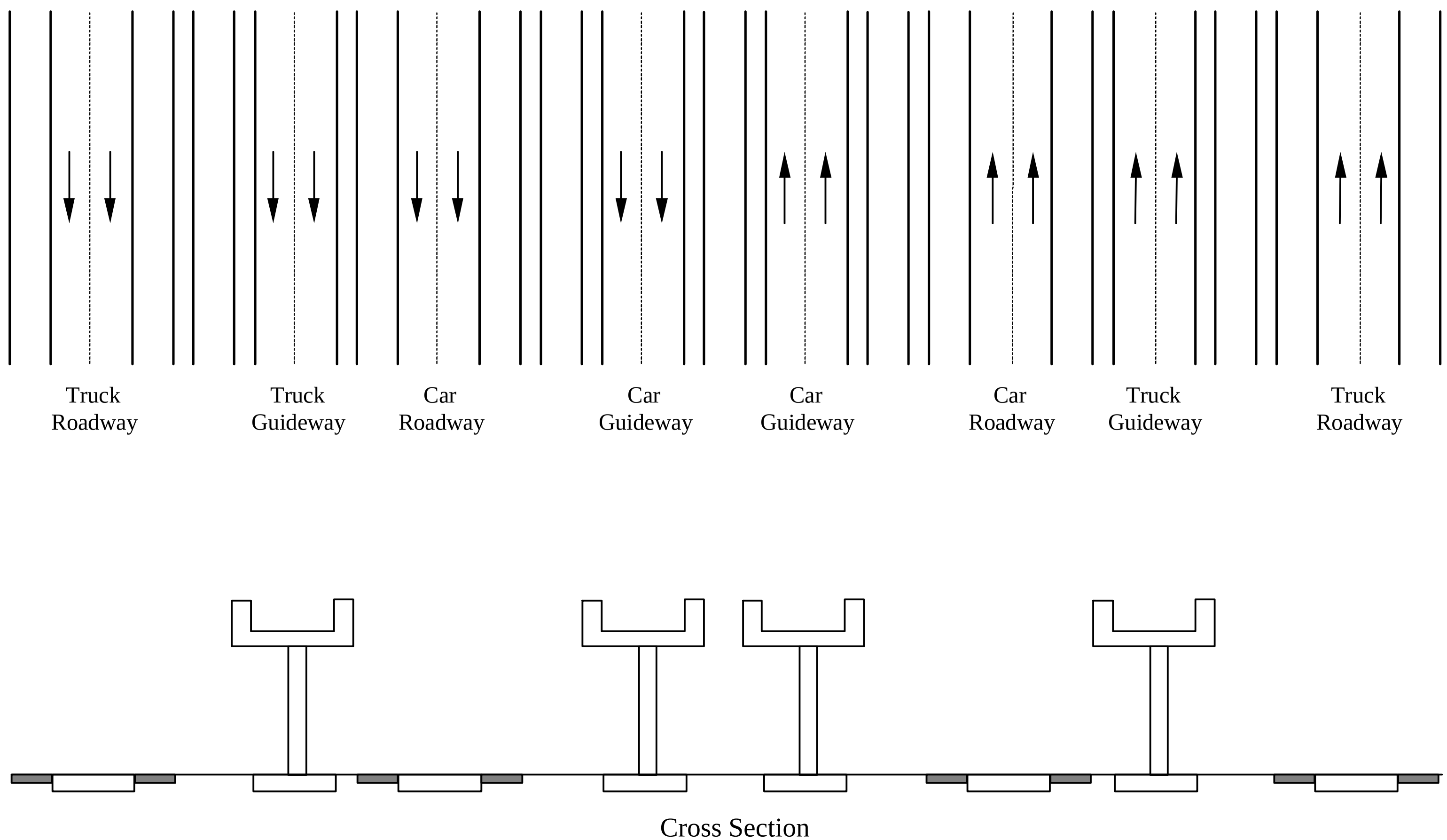


Figure 2.3 AHS Guideway and freeway roadways

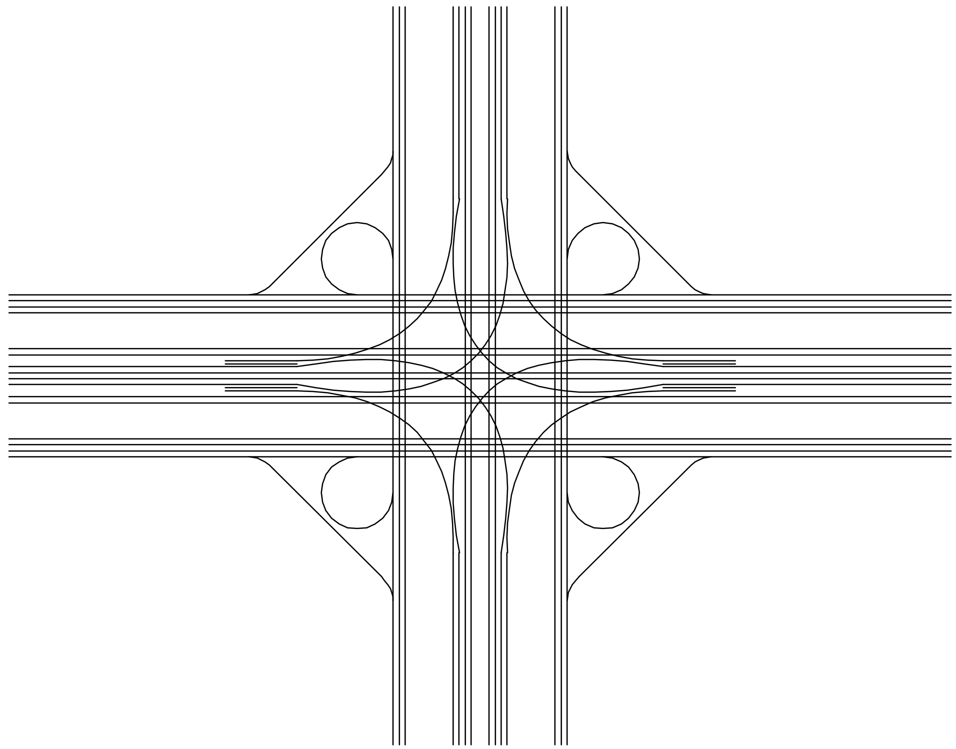


Figure 2.4 Guideway-Freeway Interchange

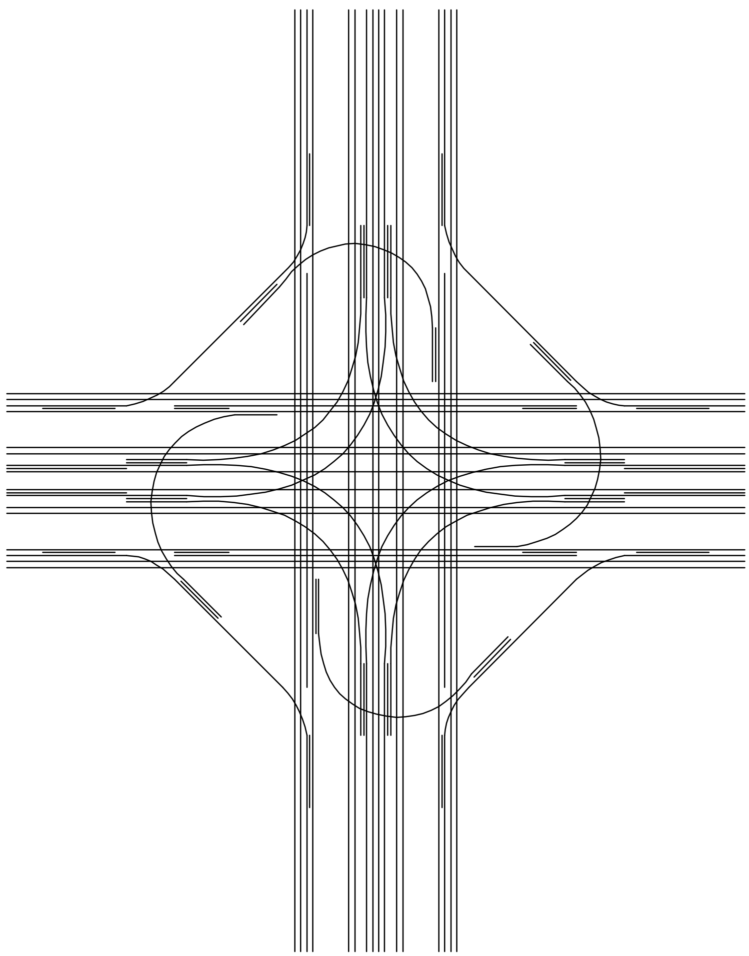
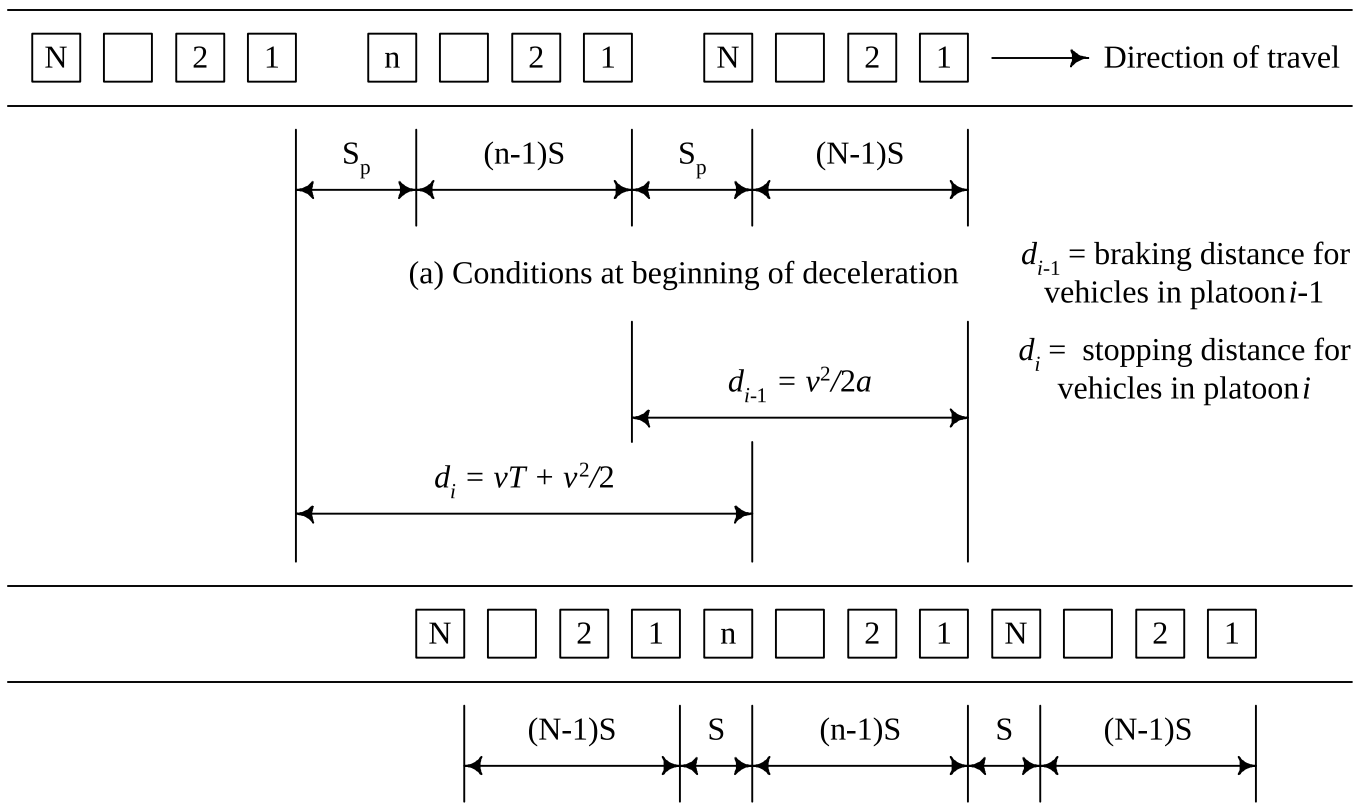


Figure 2.5 Guideway-Guideway Interchange

2.10 Platooning on the AHS

Platooning consists of creating platoons of “linked” vehicles which would travel along the AHS acting as one unit. These vehicles would follow one another with very small headway – vehicle spacing as little as a couple of meters – and be “linked” through headway control mechanism, such as radar-based or magnetic-based systems. The first vehicle in the platoon, the leader, continuously provides the other vehicles, the followers, with information on the AHS conditions, and what maneuvers, if any, the platoon is going to execute.

The safe following distance, *s*, that can be found will essentially become the intraplatoon spacing, or the spacing between vehicles in the same platoon. By examining Figure 2.6, a potential platooning situation can be seen. In Figure 2.6a three platoons are shown with a platoon of n vehicles between two platoons of N vehicles. This would represent normal operations. Figure 2.6b shows what the platoons should look like if they were forced to come to a stop. Siess [38] used this figure as the basis for defining volume-speed relationship for a single lane guideway.



(b) Conditions when vehicles come to a stop

Figure 2.6 Guideway Stream Dynamics