

3. The Automated Highway System

3.1 AHS Architecture

Important to the development of any new technology is the creation of a system-wide architecture. And the need for such an architecture is no different for the creation of an Automated Highway System. Presently there is no such system architecture for the AHS, but the NAHSC has been mandated to select an AHS Concept by March 1999 and to have a preliminary design by June of the same year. By December 2001 a prototype AHS should be demonstrated [9]. Through this process an appropriate architecture will hopefully be developed.

The advantage of quickly developing an architecture can be seen in the successes of many electronic products, including the cellular phone and the personal computer. Defining a system's architecture early on allows for many different companies to develop competing yet compatible products used in the system. This helps the establishment of a new system or technology by lowering prices quicker and promoting further development. This is essential for an AHS to work since consumers will be required to purchase additional equipment for vehicles which are already expensive. Currently the prohibitive cost of the necessary technology is one of the biggest obstacles in the way of deploying a nationwide AHS.

The architectures of potential AHS concepts can be broken into three subsystems – system structural, system operational, and vehicle. The system structural subsystem includes the control and sensing equipment contained within the infrastructure and the characteristics of this equipment, how the decision-making capabilities are split between the vehicle and the infrastructure, and some of the vehicle's structural and equipment considerations. The system operational subsystem concerns itself with such policies as lane separation requirements, platooning, vehicle fleet mixture (if any), and network make-up and control. The vehicle subsystem consists of components of the smart vehicle such as the power plant, body and chassis, and the lateral and longitudinal control systems.

America's attachment to the automobile in any form is one of the greatest hindrances in realizing the automated highway's total potential. The consumers' demand for the high performance that requires the internal combustion engine will always create the problem of the higher the capacity of the AHS, the more pollution that is generated. It is this pollution problem which has fueled the search for an adequate replacement in the electric car. But limitations in power plant size and battery technology has led to low performance - low speed vehicles which would have very little success competing against today's automobiles.

In response to the void left due to problems with internal combustion engines and electric power trains, the use of magnetic levitation ("Maglev") will be explored as a potential alternative which would allow the automated highway reach its optimal performance potential. Maglev provides an opportunity to overcome both the pollution and performance problems. Pollution due to travel could actually be reduced from today's levels, even with the increase in throughput, since Maglev uses magnetic forces to levitate and propel the vehicles. There would be no emissions from the vehicle at all. And the technology has also shown the ability to provide speeds well in excess of what today's vehicles could possibly obtain.

Maglev was born in the United States in 1912 when Emile Bachelet used magnetic forces to levitate and propel a model vehicle. Later, in 1966, the concept of levitating a vehicle above a guideway using superconducting magnets and propelling it with magnetic forces was invented by James Powell and Gordon Danley. Unfortunately development efforts were prematurely ended within a decade.

Since then the German and Japanese governments have dedicated substantial amounts of resources to explore the applications of Maglev, especially to high-speed commuter rail travel. Both efforts have been met with much success, with the Japanese pursuing an EDS (Electro-Dynamic) Repulsion System while the Germans have used an EMS (Electro-Magnetic) Attraction System in their "Transrapid" System. The System, which is due to enter service in 2005, has the potential to reach 300 kilometers per hour in under five kilometers, climb grades

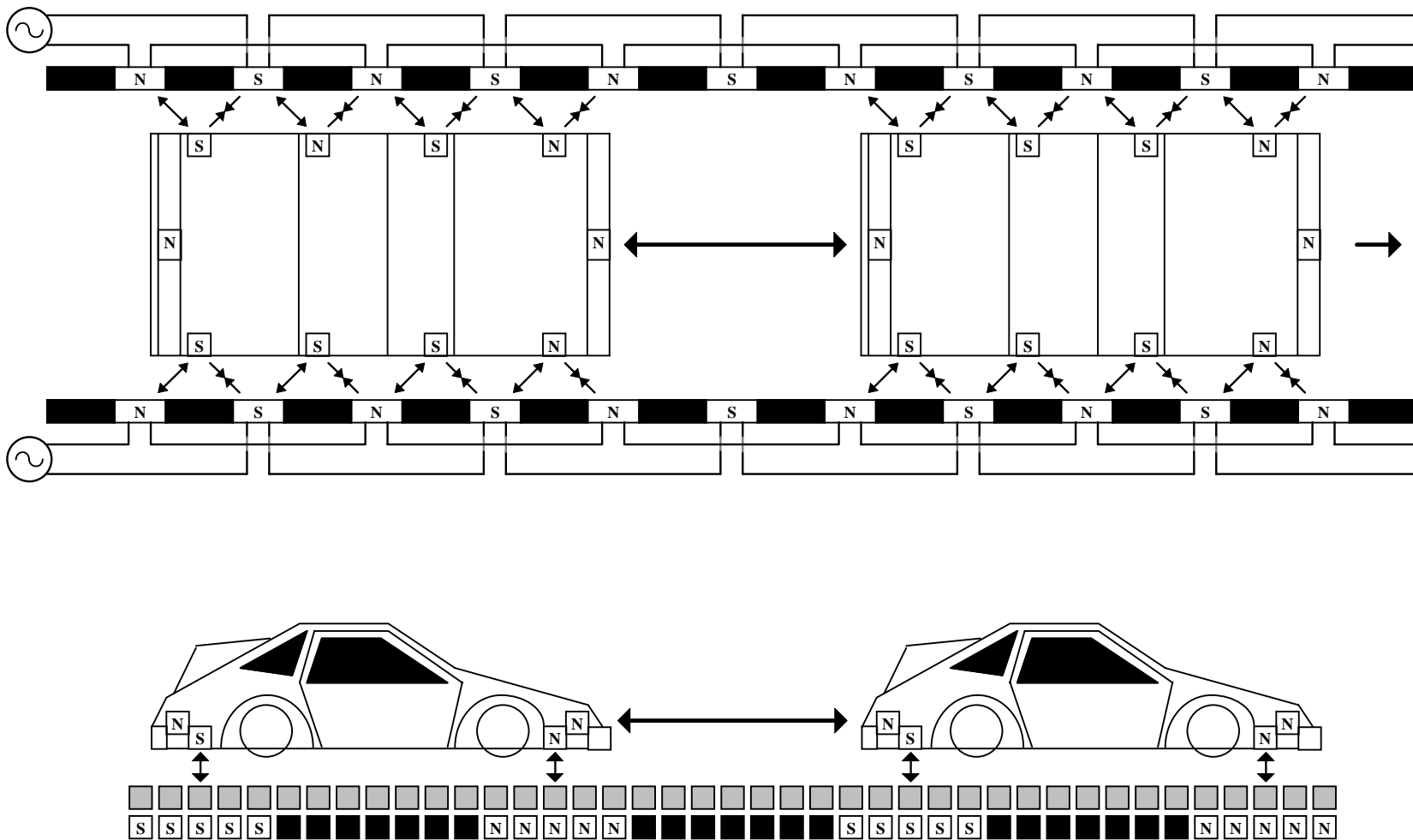
as steep as ten percent, and negotiate turns as tight as 2825 meters at speeds of 400 kilometers per hour. This kind of performance was never even dreamed of with conventional railways.

Another application of the Transrapid technology is to be implemented in Switzerland, with a pilot section starting in 2002, and the entire \$21 billion system in place by 2020 [26]. The unique aspect of this system, called SWISSMETRO, is that it would be entirely underground with its stations located below existing rail and bus terminals. The small-bore tunnels being designed would be partially vacated of air to reduce resistance and air blockage problems. The Swiss envision running 200 meter vehicles, with seating for up to 800 passengers, with 15 minute headways and three minute stops, with a 12 minute between station travel time. The system would tie into all of Switzerland's major population centers and make the cross-country trip in a little less than an hour. Currently the train takes three hours to complete the same trip.

When applying Maglev technologies to roadways, the goal is to get the same kind of enhanced performance compared to traditional highway travel while retaining the personal vehicle that Americans are so reliant on. Referring to Figure 3-1, each individual vehicle would be equipped with superconducting magnets. The repulsion of like poles allows the vehicle to "ride," or hover, above the guideway. Other magnets propel the vehicle along the guideway through the use of repulsive and attractive forces between the vehicle's magnets and the guideway's magnets. The guideway electromagnets will alternate between north and south poles based on the electric current supplied by a substation. Spacing between vehicles is maintained through the placement of magnets on the vehicles. While not utilizing the Maglev technology on the AHS, the vehicle would revert to an electric power plant and operate as do today's vehicles, but without the pollution.

3.2 AHS Schematics

One of the keys to the AHS Maglev is the guideway, or magway. It would be this new

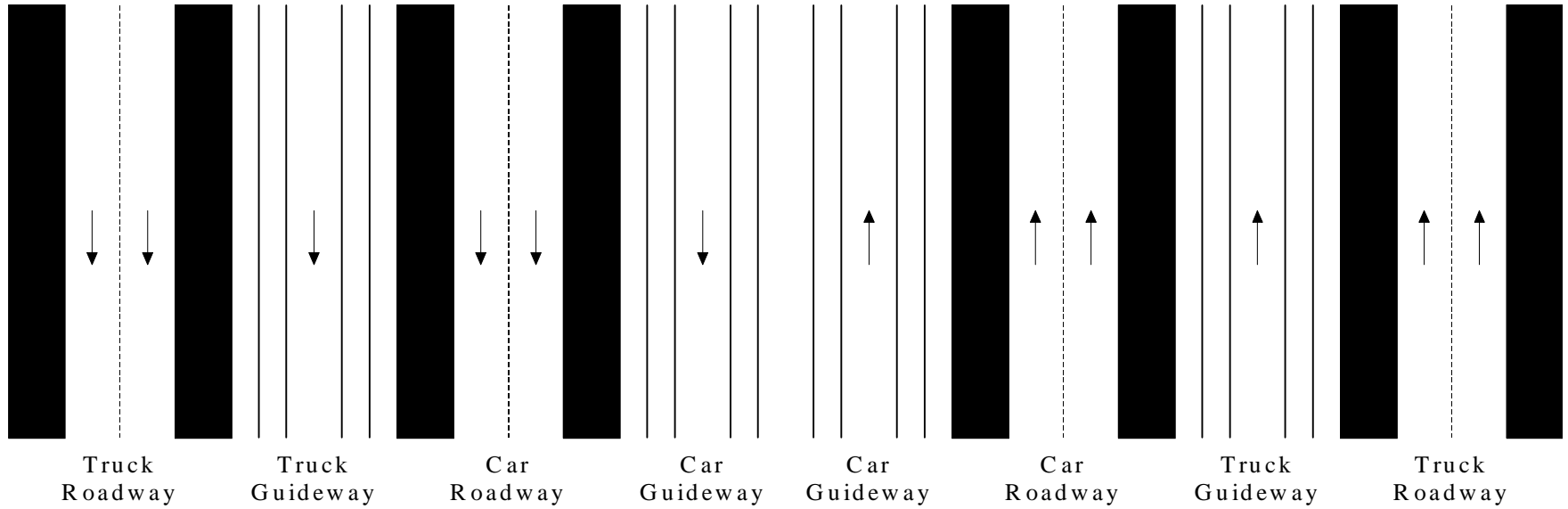


AHS Maglev Levitation, Propulsion and Guidance

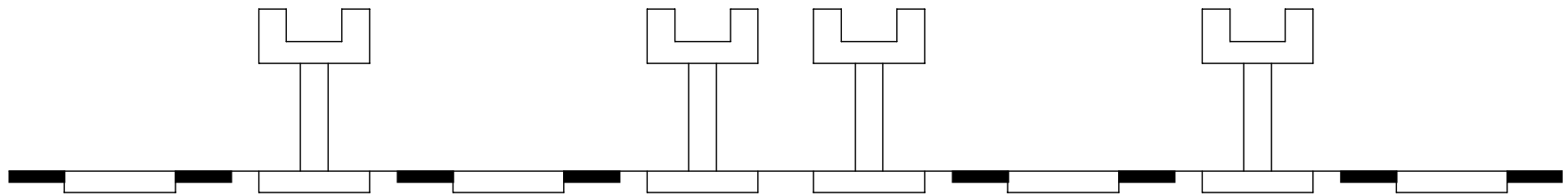
Figure 3-1

infrastructure, as opposed to retrofitting existing highways, that would allow an enormous increase in capacity and speed. To allow the magways to perform as intended, they will have to be tied into the current highway network in some way. The other factor in AHS design is the hybrid vehicles, namely cars and trucks, which will be utilizing the magways. Due to vastly different performance abilities, it would be the most beneficial to segregate the two forms of traffic. While this may sound drastic, this separation of traffic has been contemplated by many State DOT's as they add more and more lanes to the existing highway network.

A typical highway cross-section of the future may look something like what is shown in Figure 3-2. 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 "feeders" 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 3-3) would be used. At points where two freeways with guideways in the median intersect, Guideway-Guideway Interchanges (Figure 3-4) 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. While it is clear that placing the guideways parallel to the Interstate Highway System poses no problems when considering tangent sections, the issue becomes more complicated when regarding curves. This is due to the difference in design speeds. Figure 3-5 shows the conditions for an AHS Maglev vehicle negotiating a curve. For the vehicle to remain centered on the guideway through the turn the forces parallel to the guideway surface must be in equilibrium. Slemon [16], referring to the conditions shown in Figure 3-5, reports that an electrostatically suspended maglev system can provide a guidance force which is equivalent



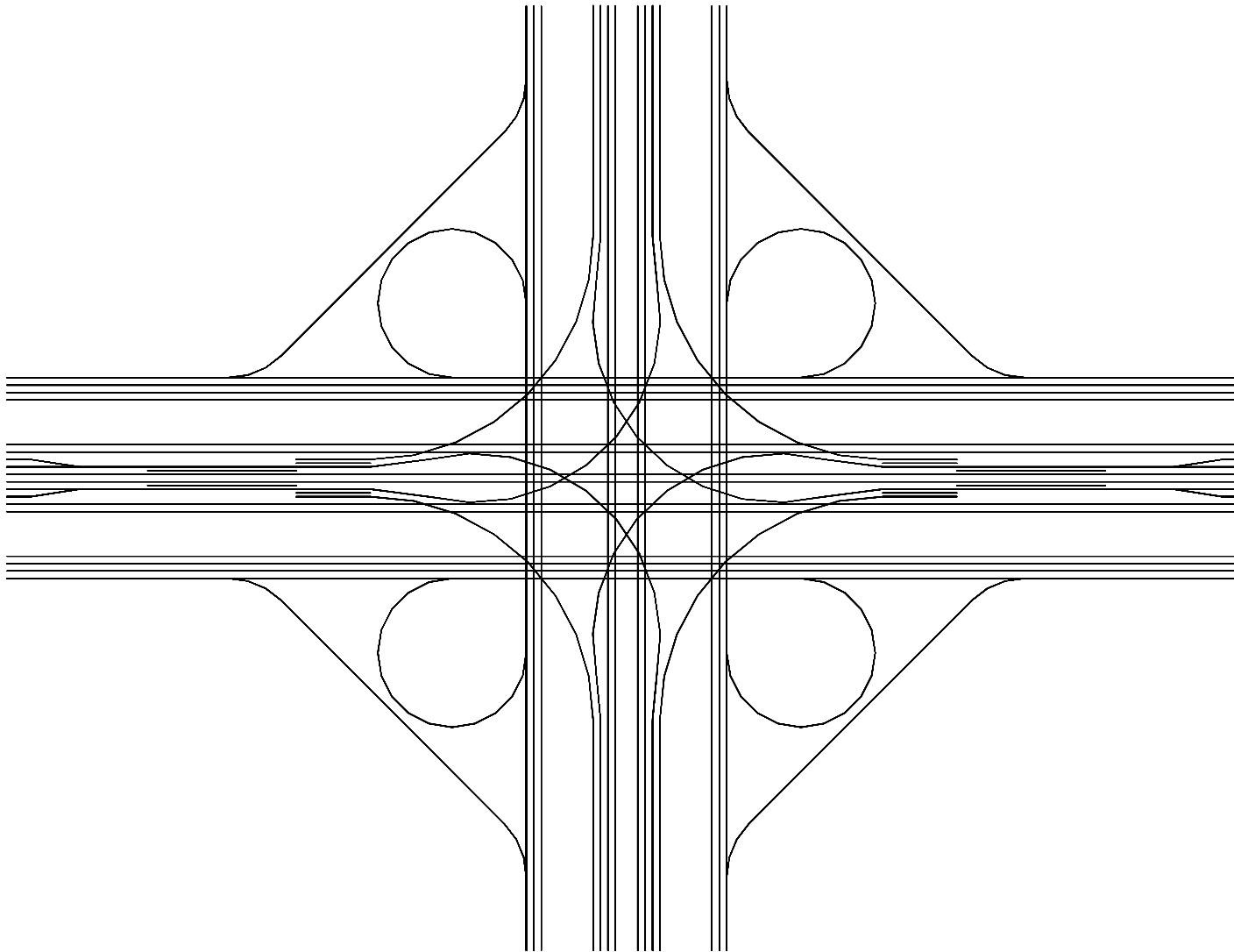
Plan View



Cross-Section

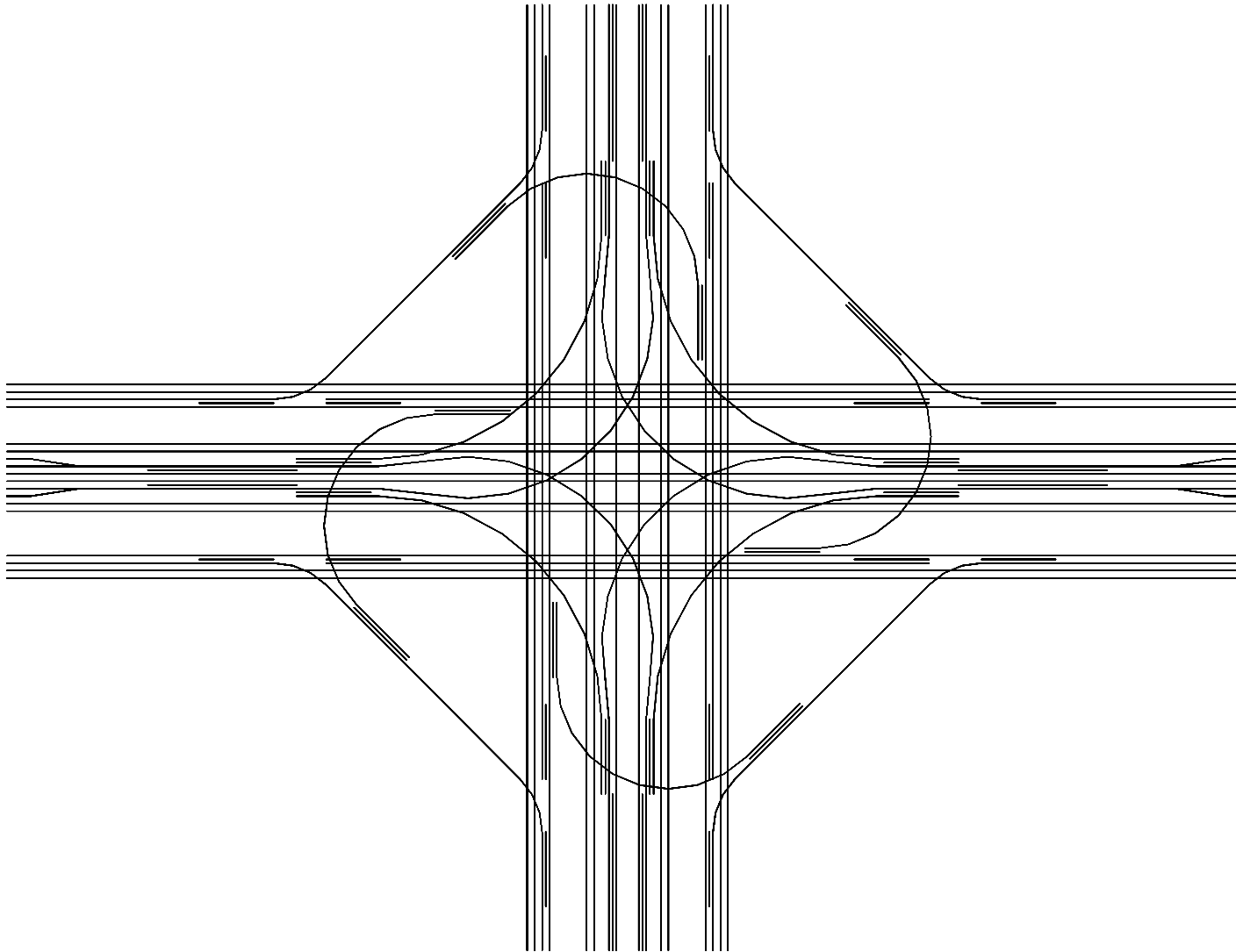
AHS Guideways and Freeway Roadways

Figure 3-2



Guideway – Freeway Interchange

Figure 3-3



Guideway-Guideway Interchange

Figure 3-4

to the total weight of the vehicle. In other words, $S \leq W$. Let $S = kN$ where N is the normal component of the weight and k is the incline weight factor. Summing the forces parallel to the guideway

$$C \cos \theta = W \sin \theta + S \quad (3.1)$$

where $S = kN = kW \cos \theta$. Realizing that the centrifugal force, C , is

$$C = m \frac{v^2}{R} \quad (3.2)$$

where m is the mass of the vehicle and equal to W/g , Equation (3.1) becomes

$$\frac{W v^2}{gR} \cos \theta = W \sin \theta + kW \cos \theta \quad (3.3)$$

Dividing through by $W \cos \theta$,

$$\frac{v^2}{gR} = \tan \theta + k \quad (3.4)$$

Note from Figure 3-5 that $\tan \theta = e$, thus giving

$$\frac{v^2}{gR} = e + k \quad (3.5)$$

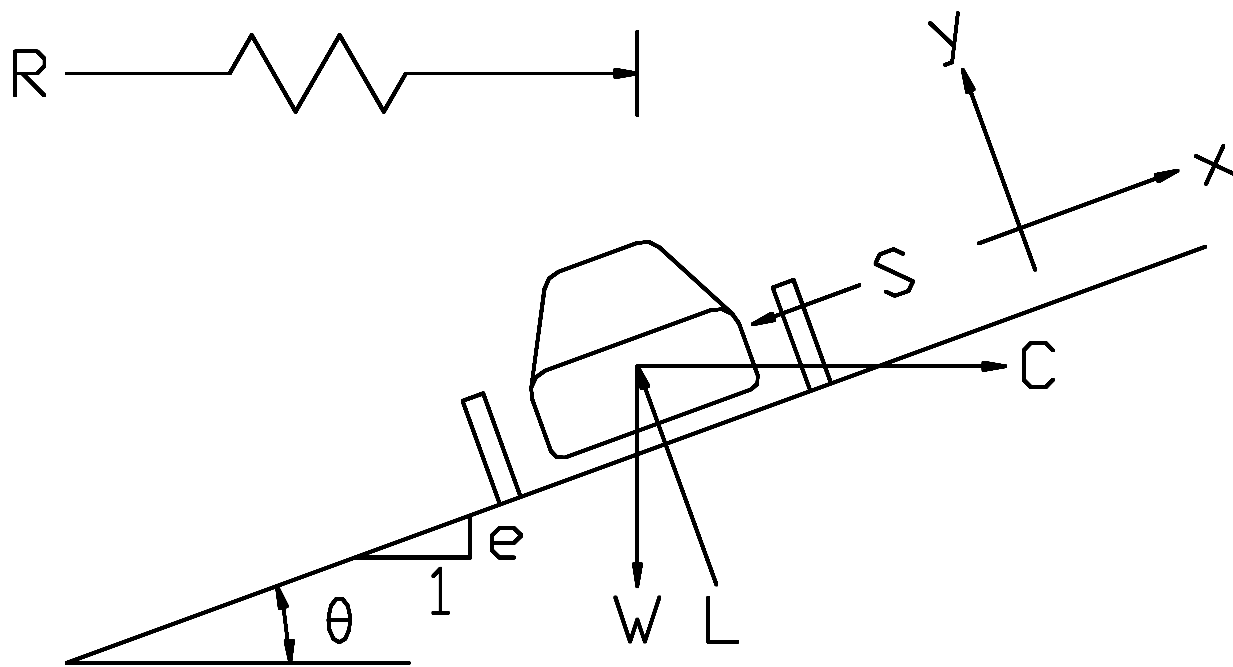
Solving for R , the radius of curvature for the curve is found to be

$$R = \frac{v^2}{g(e + k)} = \frac{V^2}{15(e + k)} \quad (3.6)$$

In Figure 3-6, the radius of curvature R is plotted against the design speed V for values of $(e + k)$. If one considers the curve on a conventional freeway with a design speed V of 80 mph, superelevation e of 0.05, and coefficient of side friction f_s of 0.20, then the radius of curvature R is

$$R = \frac{V^2}{15(e + f_s)} = \frac{80^2}{15(0.05 + 0.20)} = 1707 \text{ ft} \quad (3.7)$$

If it was attempted to design the magway such that a 300 mph curve could be placed with the same radius R , then $e + k = 3.5$. Since $k = S/W$, let $k = 1.0$. This creates the need for a superelevation of 2.5, or a 68° bank. Also note that the centrifugal acceleration on the vehicle, which is the centrifugal force on the driver, in G's is

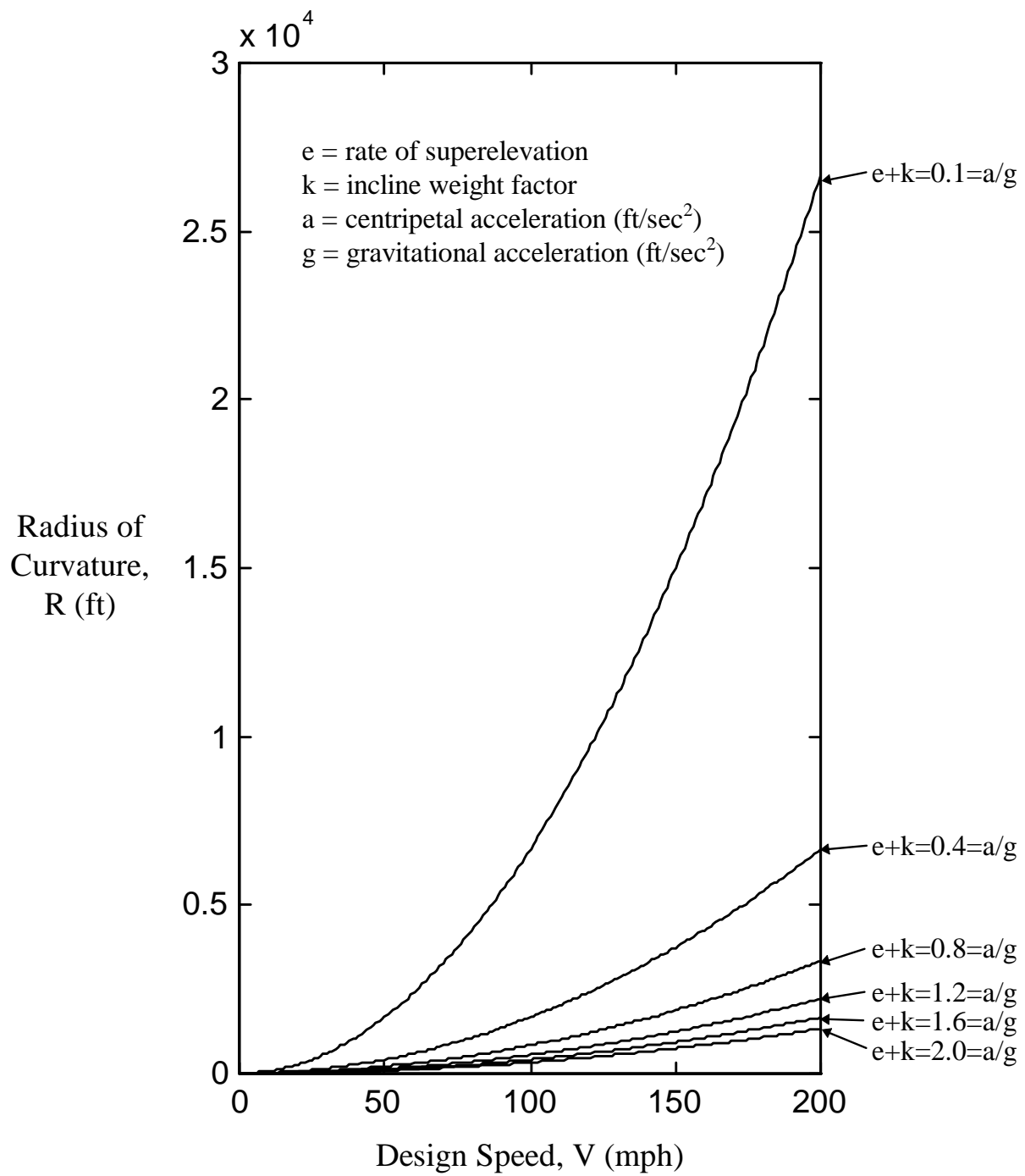


W = Weight of Vehicle (lbs)
 L = Levitation Force (lbs)
 S = Guidance Force (lbs)
 e = Rate of Superelevation
 R = Radius of Curvature (ft)

g = Acceleration of Gravity (ft/sec^2)
 θ = Angle of Incline (deg)
 v = Design Speed (ft/sec)
 V = Design Speed (mi/hr)
 C = Centrifugal Force (lbs)

Conditions For a Vehicle on AHS Maglev

Figure 3-5



Horizontal Curve Relationships on AHS Magway

Figure 3-6

$$G = \frac{a}{g} = \frac{v^2/R}{g} = e + k \quad (3.8)$$

In the above curve $e + k = 3.5$, thus creating a 3.5 G force on the driver. Conditions like this are found only in amusement parks, so they evidently don't belong in our transportation network. If one looks at the same curve but with a 200 mph design speed, $e + k = 1.56$, which is much more reasonable a force for the traveling public. If $k = 1$, $e = 0.56$ which leads to a bank of just under 30° , which is also acceptable. So by setting the AHS operational speed to 200 mph in curves, for the most part, the AHS Magway system could be placed in the right-of-way of the Interstate Highway System.

3.3 AHS Operations

Due to the necessity to limit speeds through curves several different operational characteristics exist on the same magway. Namely there is the 200 mph maximum speed on curved sections while on the tangent sections the obtainable speed is dictated by the magway vehicle and not the guideway. Under the same operating conditions (i.e. headway and platooning policy) the velocity is the controlling factor in potential capacity. Drew et. al. [15] have envisioned that the AHS guideway would consist of three types of sections: (1) unrestricted capacity sections (UCS), (2) restricted capacity sections (RCS), and (3) speed transition sections (STS). The UCS exist along the tangent sections where unlimited speeds create the potential for unlimited capacity. The RCS consist of sections such as curves which restrict the vehicle speed, and thus capacity, through compromising geometrics. The STS exist to allow for a transition between the higher speed travel of the UCS and the limited speed travel of the RCS.

Since all interchanges must be located in a UCS (see Figures 3-3 and 3-4), the capacity through a STS and the accompanying RCS must remain the same as on the UCS leading in the STS. Therefore the practical capacity of the guideway Q is determined by the lowest capacity section, the RCS. Note that the capacity of the RCS is controlled by the section's design speed $V(RCS)$.

Let L be the average length of a vehicle and ϵ be the safe following distance required by the AHS technology. Then

$$Q = V(RCS) \times \frac{5280}{S} \quad (3.9)$$

where $S = L + \epsilon$. Since the volume Q must be the same in the UCS but while operating at a high speed, $V(UCS)$, the vehicle headway on the UCS, $S(UCS)$, must increase. Therefore we need

$$S(UCS) = S \times \frac{V(UCS)}{V(RCS)} \quad (3.10)$$

It is the purpose of the STS to safely and smoothly change the vehicle headway from $S(UCS)$ to $S(RCS)$ and then back while transitioning the vehicle speed and maintaining a safe following distance between vehicles through the whole operation.

Referring to Equation (3.9), it can be seen that the other controlling factor besides $V(RCS)$ is the headway S . So to determine the capacity of an AHS Magway the headway must be found. From Figure 3-7, the safe headway for the i^{th} vehicle, s_i , is

$$s_i = d_i + L - d_{i-1} \quad (3.11)$$

where d_i and d_{i-1} are the required stopping distances for vehicles i and $i-1$, respectively. This can be broken into

$$d_i = d_1 + d_2 + d_3 \quad (3.12)$$

where d_1 is the reaction distance, d_2 is the distance traveled during the increase in deceleration, and d_3 is the distance traveled during constant deceleration. Therefore

$$d_1 = v_0 t_r \quad (3.13)$$

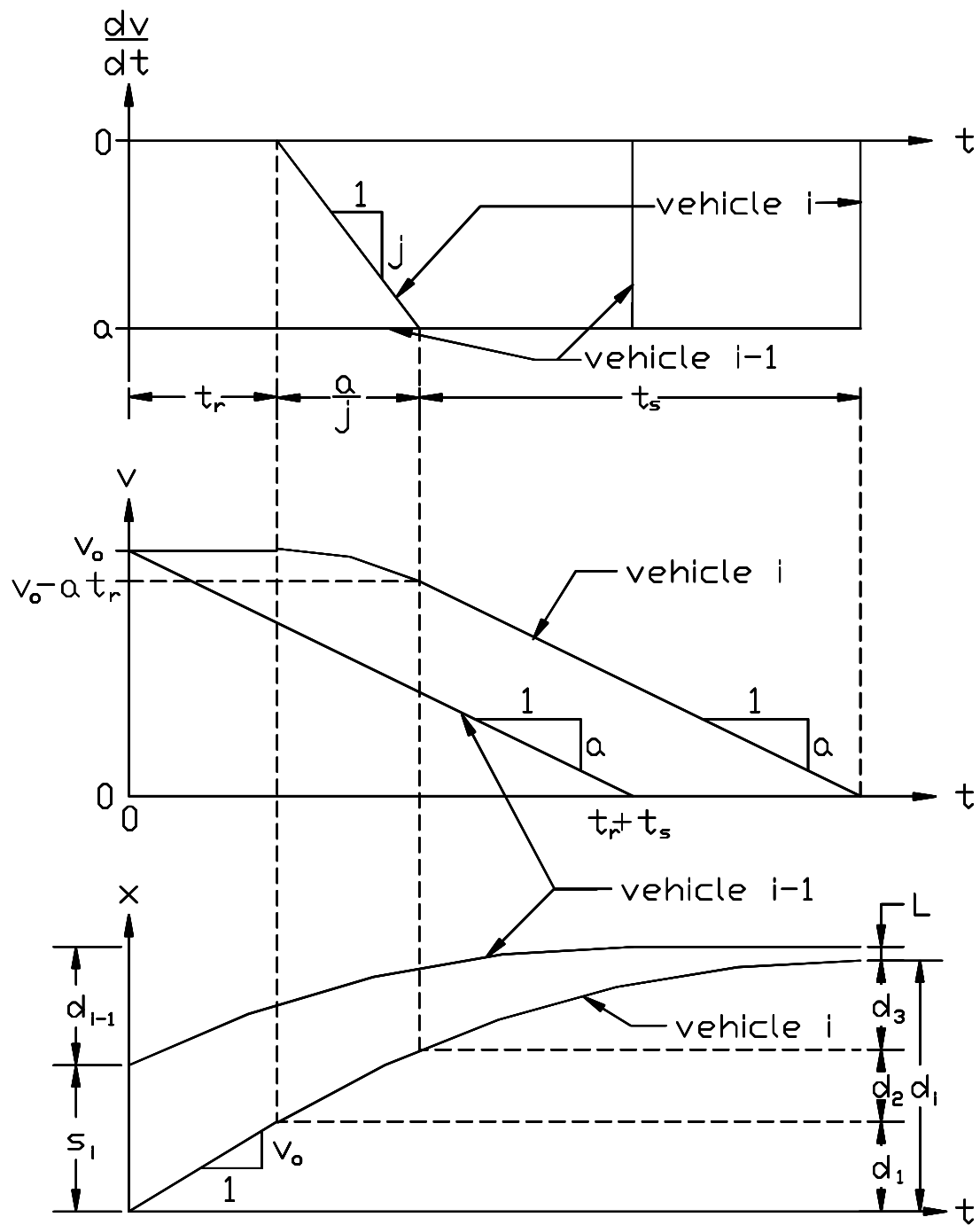
and

$$d_3 = \int_0^{t_s} v \, dt \quad (3.14)$$

From the velocity-time graph the velocity of vehicle i from $t_r + a/j$ to $t_r + a/j + t_s$ can be found to be

$$v = (v_0 - at_r) - at \quad (3.15)$$

Since velocity is the derivative of distance,



Vehicle Kinematics of Safe-Following Distance

Figure 3-7

$$d_3 = \int_0^{t_s} ((v_0 - at_r) - at) dt \quad (3.16)$$

Integrating finds that

$$d_3 = (v_0 - at_r)t_s - \frac{1}{2}at_s^2 \quad (3.17)$$

where v_0 is the initial velocity, t_r is the sensor reaction time, and t_s is the time to come to a stop once the constant deceleration a is reached. The distance d_2 can be found by

$$d_2 = \int_0^{a/j} v dt \quad (3.18)$$

where v is the velocity of vehicle i from t_r to $t_r + a/j$. This velocity can be found by

$$v = \int_0^t a dt \quad (3.19)$$

where a , the acceleration of vehicle i from t_r to $t_r + a/j$, can be found from the acceleration-time graph to be

$$a = -jt \quad (3.20)$$

Substituting Equation (3.20) into Equation (3.19) and integrating gives

$$v = -\frac{1}{2}jt^2 + c \quad (3.21)$$

The constant c can be found to be the initial velocity v_0 when t is set equal to zero, thereby letting

$$v = v_0 - \frac{1}{2}jt^2 \quad (3.22)$$

Substituting Equation (3.22) into Equation (3.18)

$$d_2 = \int_0^{a/j} \left(v_0 - \frac{1}{2}jt^2 \right) dt \quad (3.23)$$

Integrating Equation (3.21) and simplifying provides

$$d_2 = v_0 \left(\frac{a}{j} \right) - \frac{a}{6} \left(\frac{a}{j} \right)^2 \quad (3.24)$$

Substituting Equations (3.13), (3.17), and (3.24) into Equation (3.12),

$$d_i = v_0 t_r + v_0 \left(\frac{a}{j} \right) - \frac{a}{6} \left(\frac{a}{j} \right)^2 + (v_0 - at_r)t_s - \frac{1}{2}at_s^2 \quad (3.25)$$

Reorganizing the terms,

$$d_i = v_0 \left(\frac{a}{j} \right) - \frac{a}{6} \left(\frac{a}{j} \right)^2 + v_0(t_r + t_s) - at_r t_s - \frac{1}{2} at_s^2 \quad (3.26)$$

By completing the square on the last two terms in Equation (3.26) d_i becomes

$$d_i = v_0 \left(\frac{a}{j} \right) - \frac{a}{6} \left(\frac{a}{j} \right)^2 + v_0(t_r + t_s) - \frac{1}{2} a(t_r + t_s)^2 + \frac{1}{2} at_r^2 \quad (3.27)$$

To find the equation of d_{i-1} , first, from the velocity-time graph, find that the velocity of vehicle $i-1$ is

$$v_{i-1} = v_0 - at \quad (3.28)$$

Knowing that integrating the velocity equation provides the distance equation,

$$d_{i-1} = \int_0^{t_r+t_s} (v_0 - at) dt \quad (3.29)$$

Through integration the distance d_{i-1} is found to be

$$d_{i-1} = v_0(t_r + t_s) - \frac{1}{2} a(t_r + t_s)^2 \quad (3.30)$$

Finally, substituting Equations (3.27) and (3.30) into Equation (3.11) and simplifying,

$$s_i = v_0 \left(\frac{a}{j} \right) - \frac{1}{6} a \left(\frac{a}{j} \right)^2 + \frac{1}{2} at_r^2 + L \quad (3.31)$$

As technology improves, the sensor reaction time t_r will become smaller and smaller, ultimately approaching zero. If t_r is taken to be zero, the safe following distance becomes

$$s_i - L = v_0 \left(\frac{a}{j} \right) - \frac{1}{6} a \left(\frac{a}{j} \right)^2 \quad (3.32)$$

It is the safe following distance, $s_i - L$, which ultimately is going to determine the maximum capacity of the system. Thus the sensor reaction time t_r , the maximum deceleration a , the initial velocity entering the maneuver v_0 , and the jerk j become the controlling factors. Of these both deceleration and jerk are limited by the driver's comfort. The speed entering the maneuver is also limited to that which is comfortable to anyone in the vehicle. The sensor reaction time is

limited by the availability and quality of the technology being used to control the headways and sensing what the vehicle in front is doing.

As can be seen, the operational methods on the AHS Magway need to vary depending on which section the vehicles are on. While the restricted capacity sections will limit speed and capacity due to the geometrics, vehicles can be run through the section tightly spaced so as to utilize every bit of its available capacity. The speed transition sections will fulfill the important role of altering the traffic headway and speed between two sections, a RCS and an UCS. It is here that the abilities of the longitudinal control systems will be utilized the most and thus the performance through the STS will depend heavily on the quality and type of technology used. It is the operations on the unrestricted capacity sections which become of the most interest. While capacity on these sections are ultimately limited by the capacity of the RCS, other considerations, like the merging and weaving of entering and exiting vehicles, must be considered. These sections also raise the issue of platooning policy, as with the need to provide gaps for entering vehicles the management of vehicles through these sections becomes a crucial issue.