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Impacts of Road Trains on the Geometric Design of Highways

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IMPACTS OF ROAD TRAINS ON THE GEOMETRIC

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ABSTRACT

Traffic congestion and greenhouse gas emissions from vehicles have alarmingly increased over the past decades as a result of people's daily driving. Building newer and larger roads to improve traffic flow and decrease emissions is no longer an option. Transportation needs to embrace higher levels of sustainability and efficiency in order to solve one of the greatest 21st century's problems. Not surprisingly, engineers and researchers develop nowadays many valuable and green ideas for transportation changes. One such idea creates automated or semi-automated road trains of vehicles on highways in order to achieve multiple benefits including considerable reduction in fuel consumption, relief of traffic congestion, and improvement of driver safety and comfort. Required new technology is mostly built into vehicles and further targets their operation, which results in a lack of necessity to continue to extend the existing roadway infrastructure. Still, the interactions between the human factors, or truly the lack thereof, and the new technologies may directly impact on the traditional guidelines for the geometric design of highways.

This thesis presents these potential changes in design guidelines achieved for road trains. The investigation of a continuum of transitory to end state scenarios concluded that overall road train modes of highway operation displayed a strong potential to significantly reduce the minimum lengths requirements on roadway curves, as well as to increase travel speeds on existing roadway curves designed to AASHTO standards given the newly proposed guidelines. Existing freeway designs are thus more than satisfactory for the deployment of these vehicular operational modes.

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NOMENCLATURE

a	=	Deceleration rate, m/s²
A	=	Algebraic difference in grades, $G_1 - G_2$, %
d	=	Upward divergence of light beam from vehicle's longitudinal axis, °
d_B	=	Braking distance, m
d_R	=	Perception reaction distance, m
e	=	Roadway superelevation, %
G_1, G_2	=	Grades of forward and backward tangents of vertical curve, %
h_1	=	Height of the driver's eyes above roadway surface, m
h_2	=	Height of the obstacle above roadway surface, m
h_3	=	Headlight height, m
HSO	=	Horizontal sight line offset, m
L	=	Length of vertical curve, m
L_{min}	=	Absolute minimum length of vertical curve, m
PRT	=	Perception reaction time, s
R	=	Radius of curve, m
R_{min}	=	Minimum radius of curve based on stability in the transversal direction to defeat centrifugal acceleration, m
S	=	Available sight distance, m
SSD	=	Minimum required stopping sight distance, m
V	=	Design speed, km/h
V_{max}	=	Maximum travel speed on a curve based on L_{min} requirement, km/h

CHAPTER 1

INTRODUCTION

The AASHTO Guide, also known as "*A Policy on Geometric Design of Highways and Streets*," defines the geometric design of roadways as the "positioning of the three-dimensional physical elements of the roadway, alignment, profile and cross sections, according to some standards and constraints as to provide a smooth-flowing, crash-free facility" (*AASHTO 2011*). Positioning of the three-dimensional physical elements is determined through calculations of the horizontal and vertical alignments of the highway centerline, based on a variety of operational considerations (*Wright 2004*). The previous definitions stress that highway design engineers must take into account certain design criteria and guidelines in dispatching their duties.

Nowadays however, a design that only meets the criteria and guidelines is not enough. Efficiency and sustainability are two terms with which today's engineers must gain extreme acquaintance and knowledge. Sustainability is the capability to endure making the least impact on the environment and on the future generations. Never before have highway engineers put so much effort in building in an environmentally friendly manner. And, the geometric design guidelines themselves need revising to accommodate the new vehicle designs and the new modes of operation proposed by green designs. A green design is none other than a design that incorporates sustainability as a factor along with other, more traditional, variables such as economic impacts or usage.

The impetus for sustainable designs comes from the somber realization that our ways of commuting for the journey to and from work are not sustainable and can no longer be maintained. The increasing amount of greenhouse gases (GHG) in the atmosphere that is emitted from vehicles has led highway engineers to think more green and more efficiently.

The primary GHG produced by the transportation sector are carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and hydro fluorocarbons (HFC). Transportation GHG emissions account for 29% of total GHG emissions in the United States of America, and over 5% of global GHG emissions. Carbon dioxide is a product of fossil fuel combustion that accounts for 95% of transportation GHG emissions in the United States. Transportation GHG emissions have been growing steadily in recent decades. From 1990 to 2006 alone, transportation GHG emissions increased 27 percent, accounting for almost one-half of the increase in total U.S. GHG emissions for the period. In 2006, emissions from on-road vehicles accounted for 79% of transportation GHG emissions (*USDOT 2010*).

Additionally, the number of vehicles found on the roads increases every day, further contributing to traffic congestion and thus, to the rise in fuel emissions and potentially to global warming. "In 2000, the 75 largest metropolitan areas experienced 3.6 billion vehicle-hours of delay, resulting in 5.7 billion U.S. gallons in wasted fuel and $67.5 billion in lost productivity, or about 0.7% of the nation's gross domestic product" (*Texas Transportation Institute 2007*). Further, the annual cost of congestion for each driver was approximately $1,000 in very large cities and $200 in small cities.

Still, traffic congestion has continued to increase in major cities and delays have become more frequent in smaller cities and in rural areas.

Furthermore, the global population increases at an accelerated rhythm like never before. 7 billion people live on planet earth at present. The world population doubled up in the last 40 years, and is expected to again double up by the year 2100 to 14 billion. Not only does this population need transportation infrastructures, but also, food, energy, resources and education. Many researchers wonder whether the earth can even support today's global population, in view of the late-2000's recession, already known by some as the Second Great Depression, and the doubling in population anticipated in the near future. "Seven billion people are 7 billion good reasons for sustainable infrastructure development," states Daryl Dulaney, president and CEO of Siemens Industry, a leading supplier of transportation and building technology (*El Nasser 2011*).

Still, due to lack of sustainability, the extension of the roadway infrastructure, through the construction of more and larger roadways, to mitigate traffic congestion and increase the capacities of vehicular transportation systems, is no longer seen as a viable option by transportation planners. New technologies, surpassing the forefathers' imaginations, need to be implemented in order for the transportation emission and congestion problematic to be mitigated. Plug-in hybrid electric vehicles, hydrogen cars, bio fuels, intelligent vehicles, increased use of public transit are some of the new technological ideas that researchers currently propose and investigate. Nevertheless, some of these new technologies require exorbitant funding; as such they may be prohibitive in times of economical hardship or recession when people survive with the least. Therefore, researchers continue to generate new ideas, focusing on affordable means of mobility and accessibility using still sustainable transportation infrastructures.

One approach to transportation sustainability is the development of automated or semi-automated highways that feature a certain number of lanes on which vehicles equipped with specialized sensors and wireless communication systems could travel under computer control at closely spaced intervals, in small convoys or "platoons" entitled road trains. Vehicles could temporarily be linked together in communication networks, which could allow for the continuous exchange of information about relative speed and acceleration, needs for braking to avoid obstacles, etc. Small networks of computers installed in vehicles, preferably, and/or along selected roadways, possibly, would closely coordinate vehicles and harmonize traffic flow, reducing speed fluctuations and traffic shock waves, while maximizing the highway capacity and passenger safeties (*Ashley 1998*). Since the traveling speed would be similar in every vehicle within the road train, system errors or malfunctions, if present, would only result in minor collision damage.

Experimental projects such as the Californian PATH, the European SARTRE Project, the European PROMOTE CHAUFFEUR or the German KONVOI continue to research the mostly vehicular and communication design aspects of road trains. This thesis specifically addresses the direct impacts of the new road train technology on the adequacy of existing highways and the revised criteria and guidelines for geometric design of highways that ensue from road train operation. The sections that follow address in turn, the literature review, which presents among other things the four pre-cited projects in further details, the methodology, which drafts varied road train deployment scenarios based on on-going experimental designs and “what-if” considerations, the findings, the conclusions and the highly anticipated future studies.

CHAPTER 2

REVIEW OF LITERATURE

The review of the literature presented focuses on (1) the various past and ongoing experimental designs and modes of operation of road trains, (2) the existing guidelines for highway geometric designs. Only those aspects of the existing guidelines likely to undergo changes due to the contemplated road train modes of operation are examined.

2.1. Ongoing Experimental Road Trains

A number of experimental projects have focused their main activities on the investigation into road train possibilities, along with studies on the design and environmental/pollution reduction impacts and other diverse safety aspects of this new technology. Current studies identified through a literature review include those from the Californian PATH, the European SARTRE and PROMOTE CHAUFFEUR I and II, and the German KONVOI. The discussion that follows addresses in turn these projects, which overall aim to lower the fuel consumption, the green house gas and the noise emissions and to mitigate the congestion issues on surface highways through longitudinal and lateral control of vehicle platoons.

The Institute of Transportation Studies (ITS) at the University of California, Berkeley, administers the California program entitled Partners for Advanced Transportation Technology (PATH) in collaboration with the California Department of Transportation—also known as Caltrans. PATH's mission is to develop innovative intelligent transportation systems strategies and technologies to improve the safety, flexibility, mobility, stewardship and delivery of transportation systems in California, the United States and the world. PATH developed a technology whereas magnets buried at given intervals in the roadbed provide an autonomous way for vehicles to monitor and adjust their locations and velocities within a platoon. PATH achieved a tight coordination of the vehicles' maneuvering by combining range information from forward-looking radar with information from a radio communication system that provides vehicle speed and acceleration updates 50 times per second; thus the response to changes in the motions of vehicles ahead occurs much more quickly than for human drivers (*PATH 1998*). A successful demonstration was celebrated in August 1997 near San Diego, CA, where the National Automated Highway System Consortium (NAHSC) along with the U.S. Department of Transportation (US DOT) led the driverless 8-vehicle platoon experiment, traveling at 105 km/h at a fixed separation of 6.5 m. PATH thus successfully demonstrated the automated highway system's (AHS) technical feasibility. However, it is generally intended to minimize the modifications to the highway. More recent projects have developed systems that do not require any such modifications, as for instance with the European SARTRE.

- The SARTRE (Safe Road Trains for the Environment) project is a three-year program funded by the European Commission under the Framework 7 program including Ricardo UK Ltd, Idiada and Robotiker Tecnalia of Spain, Institut fuer Kraftfahrwesen Aachen (IKA) of Germany, SP Technical Research Institute of Sweden, Volvo Car Corporation and Volvo Technology of Sweden. SARTRE aims to encourage an evolutional change in the use of personal transportation means through the development of safe and environmental road trains on unmodified public highways given full interaction with other vehicles (*Robison 2010*). Thus, the SARTRE project addresses three cornerstones of transportation issues including: greenhouse gas emissions, passenger safety, and traffic congestion (*Davila 2010*).

"SARTRE has explored the issues around operating platoons on motorways and the integration of the necessary technologies to achieve this, as well as the human factors that are relevant in the operation of the system" (*Bergenhem 2010*). Both lateral and longitudinal control systems have been designed, tested and proven to have higher performance than even highly skilled human drivers. Further requirements included global and local control systems, which were accomplished wirelessly, as in aviation (*Robison 2010*).

A successful demonstration was held in May 2012 near Barcelona, Spain, where a 5-vehicle road train was led and controlled by a truck with a trained driver placed in the front vehicle; thereby allowing the vehicles to accelerate, to a speed of 85 km/h at a separation within the range of 5 m to 15 m, and to brake together as a whole. Vehicles in a platoon, other than the lead vehicle, could enter a semi-autonomous control mode that allows their drivers to execute tasks normally prohibited for safety reasons; such as operate a phone, read the newspaper or revise a presentation for work; thus increasing driver comfort. SARTRE is currently undertaking a new environmental phase in order to determine the total percent reduction in fuel consumption achieved. Other anticipated benefits include; reduction in fatalities, increased following driver convenience by means of autonomous systems, and increase in effective traffic throughput.

- The PROMOTE CHAUFFEUR I and II European research projects, are from a consortium promoted by Daimler-Benz AG, Renault S.A. and Industrial Vehicle Corporation (IVECO) in Germany, France and Italy, and funded by the European Commission. PROMOTE CHAUFFEUR made an effort from 1997 to 2003 to demonstrate the capability to operate trucks autonomously on public highways by means of an electronic tow bar and an infrared pattern-recognition system. The gap between the trucks traveling at highway speeds is reduced through longitudinal and lateral control in order to lower the fuel consumption (up to 17% achieved), the green house gas and noise emissions as well as to mitigate congestion issues (*Braun 1999*).

- The German KONVOI project arose as a continuation to the PROMOTE-CHAUFFEUR I and II program. Promoted by the "Insitut fuer Kraftfahrzeuge" (Department of Motor Vehicles) and funded by the German "Bundesministerium fuer Bildung und Forschung" (Federal Ministry of Education and Research), the KONVOI project "analyzes the use of electronically regulated truck convoys on highways, as well as examines the drivers' work load and acceptance by means of driving tests in the simulator" (*Deutschle 2010*).

Table 1 presents the two most significant technologies that this thesis addresses in order to derive subsequent scenarios toward analysis of the impacts of road train technologies on the geometric design of highways. This thesis does not include a mechanical explanation of the controlling systems. Readers are thus referred to the specific literature for further study.

Table 1: Summary of Relevant Road Train Technologies.

	PATH	**SARTRE**
Date	1997	2012
Location	California, USA	Barcelona, Spain
System	Automated, driverless	Semi-automated, truck with trained driver in front
Controlling Device	Magnetometers in vehicle, magnets in roadway	Cameras, radars, lateral and longitudinal sensors in vehicle
Fuel Consumption Decrease	20%	Under study
No. Vehicles in Road Train	8	3 - 5
Vehicle gap	6.5 m	5.0 - 15.0 m
Maximum Speed	105.0 km/h	85.0 km/h

2.1.1. Potential Funding Sources

Certain implementation strategies, as discussed next, could generate possible funding sources for road train modes of operation if introduced. Those strategies include the following:

- Regular vehicles, operating outside of a platoon, and thus contributing to higher levels of emissions, could be charged a fee by usage or by mile of highway driven. This idea would encourage the population to adapt to the new technology and would bring the highest income to the Departments of Transportation (*Smart 2001*).

- Fuel could be more expensive for those who still want to drive individually their vehicles (or whose vehicles cannot operate in a platoon.) This would also encourage adoption of the new technology. The same could apply to insurance as for fuel cost or a vehicle tax could be applied to individually driven vehicles only.

- Preferential lanes' assignment to road trains that are tantamount to the lanes currently utilized by high-occupancy or electronic toll vehicles would promote as well the adoption of the new technology if they were in sufficient numbers to ensure free or steady-state flow for road train vehicles.

2.2. Anticipated Road Train Benefits

The benefits and advantages of these new systems of vehicle platoons are enormous and include the reduction in fuel consumption, the relief of traffic congestion, the improvement in safety, the greater comfort of drivers, the lack of necessity for road infrastructure expansion, the reduction in the construction cost of roadway. Each of the varied benefits is discussed in turn in the discussion that follows.

- Fuel Consumption Reduction – Vehicles in a road train are spaced closer to each other than otherwise and headways can be reduced down to 2 m, thus the air resistance to vehicle motion is minimized. Further, there is no need for the vehicles to unnecessarily accelerate, decelerate and/or stop due to human errors. Thus both, the consumption of fuel and the carbon dioxide emissions, are reduced. PATH investigated very closely the potential benefits to be achieved by a platoon when operating in both, highway and urban areas. Results showed a reduction in average drag for all road train members as a function of both inter-vehicle spacing and the number of vehicles in the platoon, pointing to an advantageous fuel consumption reduction in the magnitude of 20% (*Zabat 1995*). Table C-1 in Appendix C illustrates such a relationship for PATH. The PROMOTE CHAUFFEUR I and II achieved 17% reduction in fuel consumption through the platooning of trucks on highways. Generally, smaller gaps between vehicles yield greater benefits in terms of energy consumption. However, smaller gaps are more challenging for the platoon control system, so a balance needs to be established.

- Traffic congestion relief - Since cars in road trains can drive closer to each other, the capacity of the roadway system can be maximized to carry more efficiently twice or three times as many vehicles. Road train technologies will aid with the delays from congested traffic, maintaining a constant speed and vehicle-gap, where the capacity is dependent upon the required traffic vehicle-space and the time gap. The latter is minimized in platoons at any given speed, and thus the road capacity is enhanced and traffic congestions are avoided. PATH also estimated that an effective throughput of about 4200 vehicles per hour per lane could be achieved by operating vehicles in platoons versus a throughput range of 2,000 to 2,500 vehicles per lane per hour under normal operating conditions (*PATH 1998*). Further, the road train achieves much benefit when it abandons a traffic congestion state, as the acceleration is sufficient enough to promote a faster dissolving of the congestion (*Davila 2010*).

- Improvement in safety - Drivers of the following vehicles in platoons relinquish the driving task, thus human factors such as the very slow human perception-response times can be bypassed for these vehicles. Sensors may detect hazards, obstacles or dangers in the vehicles' pathways faster than human drivers would, thereby stopping the vehicles in much quicker time to prevent accidents. Safety is increased by the auto motion and close coordination between vehicles, and by the small relative speed difference between the cars in the platoon. Because the cars in the platoon travel together at the same speed, a small distance apart, even extreme accelerations and decelerations cannot cause a serious crash impact between the cars. With regards to stopping sight distance for instance, braking distance may dominate over reaction distance.

- Greater driver comfort - As the following vehicles in platoons will drive themselves to their desired locations, drivers are left to conduct other tasks, such as reading the newspaper, making phone calls, preparing for work and so forth. Also, due to a lack of congestion, lesser levels of driver frustrations and faster journeys prevail.

- No further road infrastructure expansions needed - Since often the system changes are built into the vehicles, as in the SARTRE project, no investment on new roadways is required.

- Potential reduction in the design cost of roadway alignments - The reductions in required stopping sight distance result in reduced rates or radii of curvature, and thus shorter curves can be achieved on roadways designed for road trains than would otherwise. Research has indicated that longer curves result in greater constructions costs because additional excavation or fill quantities would be needed to provide a greater curve length (*Fambro 1997*). For this matter, road train modes of operations are likely to greatly reduce construction costs as design criteria change, including the human factors.

Road train modes of operations are also likely to induce a reduction in cross section width. The highly performing and precise systems utilized for lateral guidance by driverless or autonomous vehicles in road trains may result in a decrease of 0.6 m to 0.9 m (2 ft to 3 ft) at most in lane width below the standard design width of 3.7 m (12 ft) (*Shladover 2008*). Width reduction per lane, when spread over the whole length of the design project, amount to lower needs to pave or repave. Therefore, further savings could be realized for highways dedicated to road train operations during construction and maintenance. This thesis does not further investigate the exact magnitude of cost reductions due to road train modes of operation for either highway alignment or cross sections.

Various disadvantages are shortly herein discussed, too. It is challenging to think of a world where humans are not allowed to drive their own vehicles anymore. Public acceptance upon driverless cars, the necessity for new laws for this type of driving, the interactions with the passengers' human factors, and the potential for higher private costs of vehicles capable of operating in both, driverless and non-driverless systems, drive the criticism of road trains and the necessity to conduct extensive road train experiments prior to highway implementation (*Hayes 2011*). However, road train technologies are well worth investigating. Next section reviews the existing guidelines for the geometric design of highways.

2.3. Existing Guidelines for Highway Geometric Designs

A main design principle of a highway alignment, whether horizontal or vertical, ascertains that the available sight distance must be greater than the required sight distance everywhere along this alignment. When the available sight distance fails to exceed that required, vehicle, driver and passenger safeties may be compromised. It is thus necessary to acquaint the reader with both, the derivations of required and available sight distances along an alignment.

Chapter 3 of the AASHTO Guide, 2011, provides the user with guidelines on the derivations of the requested sight distance and that available along all curve types. The sections that follow succinctly present the guidelines while placing the emphasis on those guideline aspects that are likely to change due to road train operation.

Since the required sight distance does not vary much with the nature of the design element, it will be addressed firstly and outside of the discussions of the guidelines for a specific design element. On the contrary, available sight distance varies with the design element and will be discussed within the applicable section addressing a specific design element.

2.3.1. Required Sight Distance

The AASHTO Guide, 2011, defines sight distance as the length of the curve ahead that is visible to the driver. Furthermore, the required stopping sight distance is the sum of two distances: the perception-reaction distance and the breaking distance as explained below.

- The perception-reaction distance, d_R, defined as the distance traversed by the vehicle during the driver's perception-reaction process, also known as perception intellection emotion volition (PIEV) process, through which the driver evaluates the situation faced and reacts accordingly to the stimulus received. This process spans the time window from the instant the driver sights an object necessitating a stop to that when the brakes are applied. Under most conditions, the driver needs not only to see the object but also to recognize it as a potential hazard. Such determination takes time, and the amount of time needed can vary greatly, being dependent upon many human factors such as driver's skills, visual, kinesthetic, vestibular and auditory senses, and also the roadway environment.

Literature presents an extensive review of reaction times, where it was estimated that a driver would need at least 1.64 s, thus representing the least complex roadway conditions for an unexpected event (*Fambro 1997*). Koppa concluded that more than 95% most of the drivers would necessitate less than 2.45 s as reaction time (*Koppa 1997*). Finally, the AASHTO Guide determined that under more complex roadway environment conditions, a 2.5-s reaction time accounts for most drivers' capabilities, exceeding the 90th percentile. Further discussion on PRT values will be addressed in later sections. For purposes of geometric design, the below equation derives the perception-reaction distance;

$$d_R = 0.278\, V\, PRT \tag{1}$$

Where:			
	d_R	=	Perception reaction distance, m
	V	=	Design speed, km/h
	PRT	=	Perception reaction time, 2.5 s

- The braking distance, d_B, is the distance needed to stop the vehicle from the instant brake application begins to a complete stop. It is affected by the original speed at which the vehicle was traveling, the vehicle's deceleration rate, the roadway grade, the type of braking system and the coefficient of friction between the tires and the pavement surface among other factors. A deceleration rate of 3.4 m/s^2 has been found to exceed the 90th percentile on wet pavement surfaces. Research showed through exhaustive experiments that most drivers can decelerate at a rate of 4.5 m/s^2 still on wet pavement (*Fambro 1997*). Latter value is considered in the methodology to further evaluate road train impacts on highway alignment. For purposes of geometric design, the below equation derives the vehicle braking distance;

$$d_B = 0.039 \frac{V^2}{a} \tag{2}$$

Where:	d_B	=	Braking distance, m
	V	=	Design speed, km/h
	a	=	Deceleration rate, 3.4 m/s^2

Thus, the stopping sight distance, *SSD*, may be defined as the total distance traveled by a vehicle from the time that the driver detects an obstacle in the way until it comes to a total stop. *SSD* depends mostly on driver's perception-reaction time, *PRT*, design speed and vehicle deceleration rate, and can be computed using the below Eq. 3. In essence, *SSD* is the sum of the two previously described distances.

$$SSD = 0.278\, V\, PRT + 0.039 \frac{V^2}{a} \tag{3}$$

Where:	SSD	=	Stopping sight distance, m
	V	=	Design speed, km/h
	PRT	=	Reaction time, 2.5 s
	a	=	Deceleration rate, 3.4 m/s^2

Table 2 presents both the calculated and the design stopping sight distance values on level roadways for a 2.5-s reaction time and 3.4-m/s^2 deceleration rate. Stopping sight distances exceeding values shown in Table 2 should be used as the basis for design whenever practical.

Table 2: Stopping Sight Distances on Level Roadways. From *A Policy on Geometric Design of Highways and Streets*, 2011, by AASHTO. Used by permission, see Appendix D.

Design Speed	Reaction Distance	Braking Distance	Stopping Sight Distance	
			Calculated	Design
[km/h]	[m]	[m]	[m]	[m]
20	13.9	4.6	18.5	20
30	20.9	10.3	31.2	35
40	27.8	18.4	46.2	50
50	34.8	28.7	63.4	65
60	41.7	41.3	83.0	85
70	48.7	56.2	104.9	105
80	55.6	73.4	129.0	130
90	62.6	92.9	155.5	160
100	69.5	114.7	184.2	185
110	76.5	138.8	215.2	220
120	83.4	165.2	248.6	250
130	90.4	193.9	284.2	285

For example, the calculated value of *SSD* associated with a speed of 100 km/h in Table 2, 184.2 m, can be obtained by entering Eq. 3 with a deceleration rate, *a*, of 3.4 m/s^2, a perception reaction time, *PRT*, of 2.5 s and a selected value of design speed, *V*, of 100 km/h. Alternately, Eqs. 1 and 2 could have been successively entered using the same data to yield values of the perception-reaction and breaking distances of 69.5 m and 114.7 m, respectively. Rounding up the calculated *SSD* to a multiple of 5 m leads to the design *SSD*, 185 m, also listed in Table 2.

Reading from Table 2, a driver operating a vehicle at a design speed of 100 km/h detects an obstacle on the road and necessitates performing a complete stop. The distance traveled from the point when the driver sights the obstacle to the point when the brakes are completely applied is 69.5 m, and the distance traveled from the brakes' application to a complete stop is 114.7 m, yielding a total calculated *SSD* of 184.2 m, rounded up to a multiple of 5 m as a design *SSD*, 185 m.

As stated previously, the sight distance available on a roadway, *S*, must be at all times greater than the required stopping sight distance, *SSD*. The available sight distance is highly dependent on the highway design element, and is typically even defined in related terms, such as the horizontal length of roadway ahead that is clearly visible to the driver around a horizontal curve, or beyond a vertical curve's crest or as illuminated on a vertical sag curve by the vehicle's headlight beams during night travel. Thus, the next subsections present the design guidelines for computing the available sight distances and the minimum recommended lengths separately for the various curve types encountered on the vertical highway and horizontal alignments. The curves are of interest per their potential to be impacted by road train technology and operation as will be explained later.

2.3.2. Vertical Alignment

In general terms, the vertical alignment can be described simply as a series of straight lines, the tangents, whether backward or forward, connected by vertical curves to provide a smooth ride without abrupt changes in grade. The optimal final alignment is the one that exhibits the best balance between grade and curvature.

Vertical curves should be simple in application and should enable the driver to clearly see ahead a length of highway equivalent to the required sight distance (*AASHTO 2011*). They should further enhance vehicle control, be pleasing in appearance and be adequate for drainage. Vertical curves can be classified into two different categories depending on the sign of the algebraic difference of the grades, crest curves or sag curves.

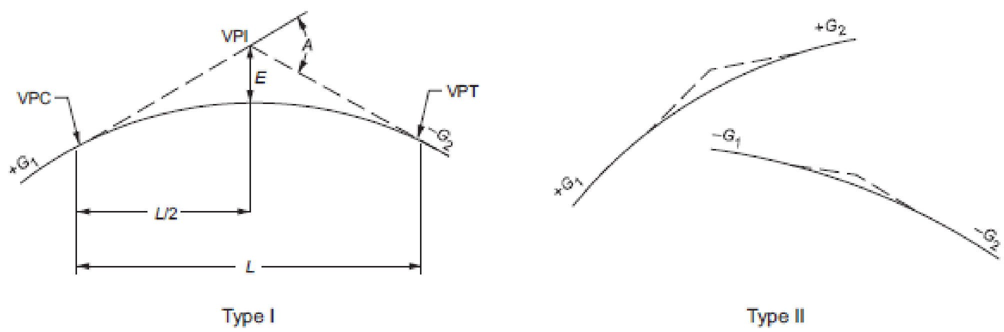


Figure 1: Types of Crest Vertical Curves. From *A Policy on Geometric Design of Highways and Streets*, 2011, by AASHTO. Used by permission, see Appendix D.

Fig. 1 illustrates above the varied types of crest vertical curves, of which the major design controls are the minimum required sight distance, the absolute minimum length of curve and the adequacy of drainage. Fig. 2 illustrates below the varied types of vertical sag curves, of which the major design controls are the minimum required sight distance, the driver's comfort, the adequacy of drainage, the absolute minimum length of curve and the pleasant aesthetics.

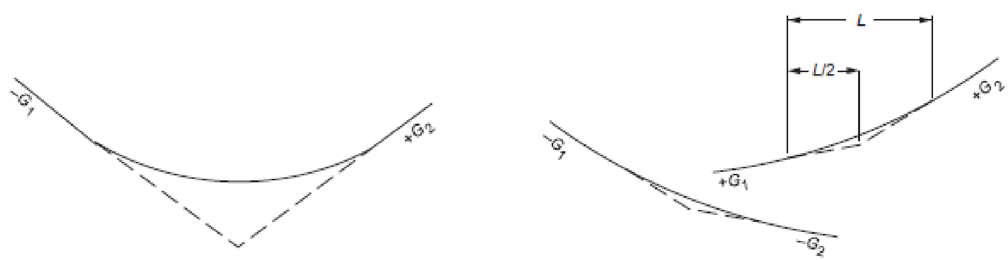


Figure 2: Types of Sag Vertical Curves. From *A Policy on Geometric Design of Highways and Streets*, 2011, by AASHTO. Used by permission, see Appendix D.

Generally, the change in grade over the curve's length is incremented at a constant rate, thus equal to the algebraic difference between tangent grades divided by the length of the curve. This parameter, *A*/*L*, expressed in percent per foot, is later discussed along with its reciprocal, *L/A*, also known as *K*, defined as the horizontal distance in meters needed to make a 1% change in gradient and thus representing a measure of curvature. No sight limitations exist on tangents. Only on vertical curves is sight distance limited. The design standards for crest and sag vertical curves involving available sight distance are discussed next.

2.3.2.1. Crest Vertical Curve Design Standards

The available sight distance on a crest vertical curve depends on a number of factors including the length of the curve, the algebraic difference between grades, the height of the driver's eyes above the road and the specified height above the highway surface of objects representing a hazard. Two cases can be considered for the computation of the length of the curve associated with an available sight distance per the Eq. 4 below.

When *S* is less then *L*,

$$L = \frac{AS^2}{100(\sqrt{2h_1} + \sqrt{2h_2})^2} \quad (4a)$$

When *S* is greater than *L*,

$$L = 2S - \frac{200(\sqrt{h_1} + \sqrt{h_2})^2}{A} \quad (4b)$$

Where:

Where:	L	=	Length of crest vertical curve, m
	S	=	Available sight distance, m
	A	=	Algebraic difference in grades, $G_1 - G_2$, %
	h_1	=	Height of driver's eyes above roadway surface, m
	h_2	=	Height of obstacle above roadway surface, m

For passenger-vehicle calculation purposes, the height of the driver's eyes is considered to be 1.08 m above the surface road. Alternatively, for trucks, the height of the driver's eyes is in the range from 1.80 m to 2.40 m, 2.33 m being the recommended design value (*AASHTO 2011*).

As for the obstacle, a height of 0.6 m above the roadway surface is considered to be appropriate for design purposes. The AASHTO Guide 2011 credits such a selection to research indicating that objects with heights less than 0.6 m rarely result in crashes. Further, using an object height of less than 0.6 m for stopping sight distance calculation purposes would not only result in longer curves without substantial decrease of the fatality rate, but also in a potential increase in the vertical curve design costs (*Fambro 1997*). Thus, an object with a height of 0.6-m is considered to be the lowest object to involve any kind of risk to drivers.

Later, discussions in the methodology will present variations in both the driver's eyes and the obstacle heights in accordance with the newly anticipated road train modes of operation and scenarios. Substituting 1.08 m and 0.6 m for driver's eyes and object heights, respectively, in Eq. 4 leads to simplified Eq. 5, below.

When S is less then L,

$$L = \frac{AS^2}{658} \tag{5a}$$

When S is greater than L,

$$L = 2S - \frac{658}{A} \tag{5b}$$

Where: L = Length of crest vertical curve, m
S = Available sight distance, m
A = Algebraic difference in grades, $G_1 - G_2$, %

The minimum recommended lengths of crest vertical curves for different values of A and for each design speed are shown in Fig. 3. One of the curved lines, as labeled, indicates where $S = L$ at various design speeds. To the left of this curve, where $S > L$, minimum stopping sight distances are computed on the basis of current practice, $L_{min} = 0.6V$, in m. These adjustments are shown as vertical lines at the lower left of the figure.

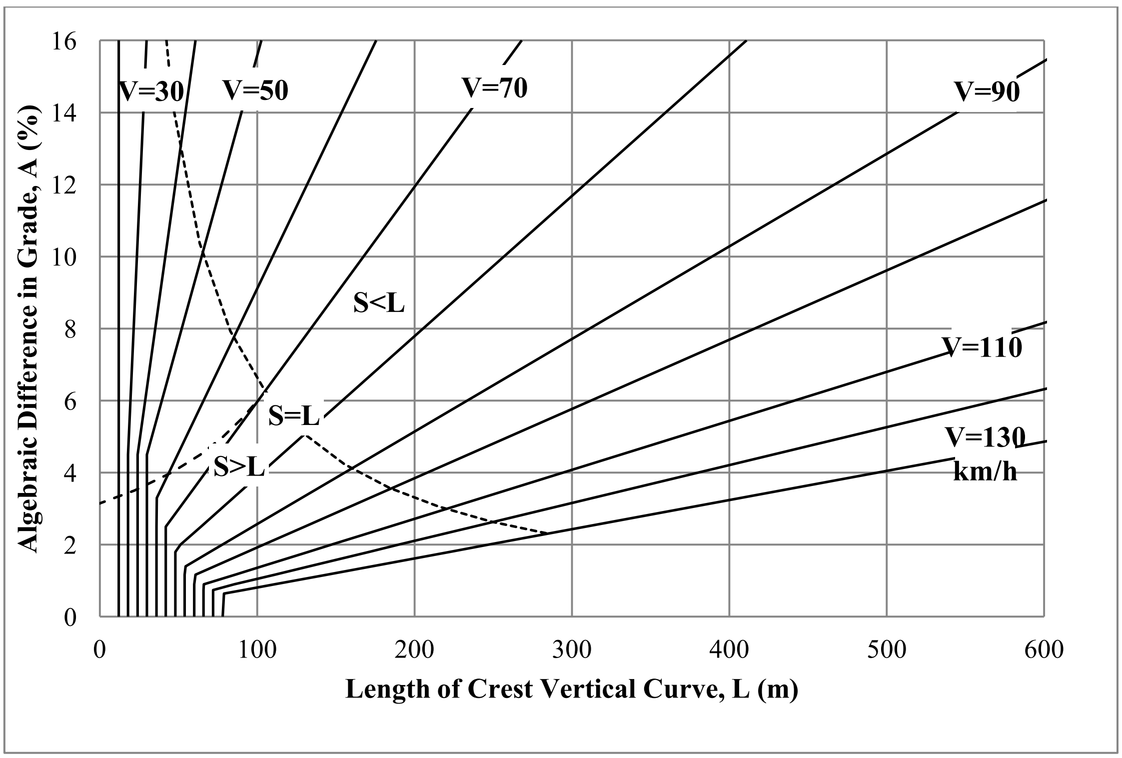


Figure 3: Design Controls for Crest Vertical Curves – Open Road Conditions. From *A Policy on Geometric Design of Highways and Streets*, 2011, by AASHTO. Used by permission, see Appendix D.

For example, entering Eq. 5 with an algebraic difference in grades, $A = 4\%$, a design speed, $V = 100$ km/h, and the corresponding stopping sight distance at this speed, $SSD = 185$ m, a minimum length of crest curve, or L equal to 208.1 m is calculated. This value may be rapidly checked by entering Fig. 3 with values of A = 4% and V = 100 km/h. A similar approach may be followed to solve for the minimum required crest curve lengths at other combinations of algebraic differences in grades and speeds. Note that a table corresponding to Eq. 4 and Fig 3 for determining minimum design lengths of crest curves can be found in Appendix A under Table A-1.

2.3.2.2. Sag Vertical Curve Design Standards

The available sight distance on a sag vertical curve becomes critical when the vehicle travels at nighttime contrarily to the daytime when no restriction on sight line exists. Thus, the headlight mounting height direction greatly affects the calculations of the available sight distance, S, on curve and of the minimum recommended length of curve. Two cases can be considered for the computation of the length of curve associated with an available sight distance as per the below Eq. 6.

When S is less then L,

$$L = \frac{AS^2}{200[h_3 + S(\tan(d))]} \tag{6a}$$

When S is greater than L,

$$L = 2S - \frac{200[h_3 + S(\tan(d))]}{A} \tag{6b}$$

Where:

	L	=	Length of sag vertical curve, m
	A	=	Algebraic difference in grades, $G_1 - G_2$, %
	S	=	Light beam distance, m
	h_3	=	Headlight height, 0.6 m
	d	=	Upward divergence of light beam from vehicle's longitudinal axis, 1°

For passenger-vehicle calculation purposes, a headlight height of 0.6 m (2 ft) is commonly utilized. Alternatively, for trucks, the height of the headlight ranges from 1.35 to 0.92 m, 0.97 m being the 95th percentile value. Since highways are not generally designed exclusively for trucks**,** there are no comparable recommended values in the AASHTO Guide for trucks. The methodology expands on this matter further.

As for the light beam's direction, a 1º upward divergence of the light beam from the longitudinal axis of the vehicle is considered to be appropriate for design purposes (*AASHTO 2011*). The upward spread of the light beam above the 1º divergence angle provides some additional visible length of roadway, but it is generally not considered for design purposes. Later discussions will present variations in the headlight height in accordance with the newly proposed road train methodologies and scenarios. Substituting 1º upward and 0.6 m for headlight beam direction and for headlight mounting height, respectively, in Eq. 6 leads to simplified Eq. 7, below.

When S is less then L,

$$L = \frac{AS^2}{120 + 3.5S} \tag{7a}$$

When S is greater than L,

$$L = 2S - \frac{120 + 3.5S}{A} \tag{7b}$$

Where:

L	=	Length of sag vertical curve, m
A	=	Algebraic difference in grades, $G_1 - G_2$, %
S	=	Light beam distance, m

In the same manner, the most important design features that control the design of sag vertical curves are the design speed, V, and the algebraic difference between grades, A, as shown in Fig. 4. One of the curved lines, as labeled, indicates in Fig. 4 where $S = L$ at various design speeds. To the left of this curve, where $S > L$, minimum stopping sight distances are computed on basis of current practice, $L_{min} = 0.6V$, in m. These adjustments are shown as vertical lines at the lower left of Fig. 4.

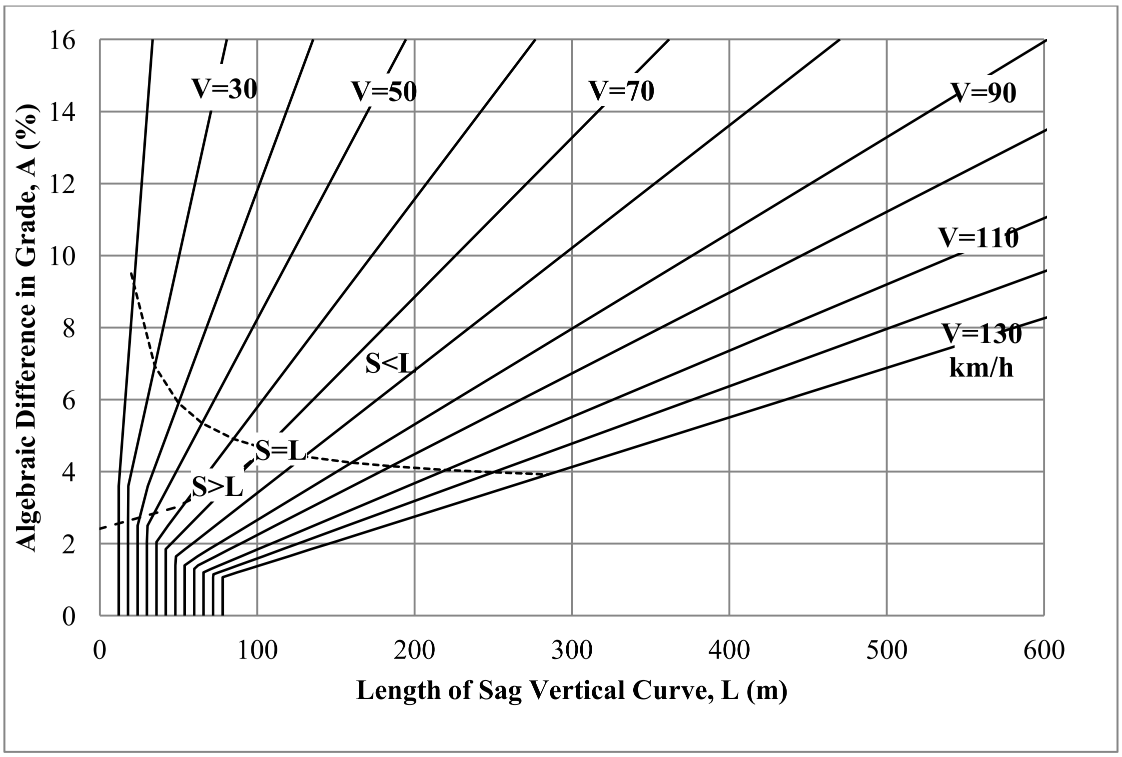


Figure 4: Design Controls for Sag Vertical Curves – Open Road Conditions. From *A Policy on Geometric Design of Highways and Streets*, 2011, by AASHTO. Used by permission, see Appendix D.

For example, entering Eq. 7 with an algebraic difference in grades, A = 4%, a design speed, V = 100 km/h, and the corresponding stopping sight distance, SSD = 185 m, a minimum length of sag vertical curve, or L equal to 178.4 m is calculated. This value may be rapidly checked by entering Fig. 4 with values of A = 4% and V = 100 km/h. This approach may be followed to solve for the minimum required sag curve lengths at other combinations of algebraic differences in grades and speeds. Note that a table corresponding to Eq. 6 and Fig 4 for determining minimum design lengths of sag curves can be found in Appendix A under Table A-2.

As stated previously, the main design controls of sag vertical curves include: available sight distance, passenger comfort, minimum absolute length, adequate drainage, and aesthetics. Drainage, comfort and aesthetics will not be further discussed as the new road train operation will not have a relevant impact on the limits placed by these controls. Also, they are not typically included in the AASHTO graphs, except maybe for drainage, and can be considered separately from these graphs as additional constraints.

It is evident that crest and sag vertical curve designs depend upon the heights of both the driver's eyes and the object, and upon the headlight beam position and direction. Specific values are given by AASHTO for these variables. It is also evident that different modes of road train operations may differently impact on the relevancy of the formulas, tables and figures for computing sight distance or more precisely on the selection of adequate representative criteria, such as driver's eyes height or headlight beam height, for facility design. The methodology further expands on these topics.

2.3.3. Horizontal Alignment

The design of roadway horizontal curves should be based on an appropriate relationship between design speed and curvature and their joint relationship with superelevation, also known as roadway banking, and on a side friction factor between tires and pavement. A horizontal curve provides a transition between two tangent sections of the roadway. In connecting straight sections with a horizontal curve, a smooth transition without abrupt changes in orientation is achieved, providing the traveling vehicle with great safety and great comfort (*AASHTO 2011*).

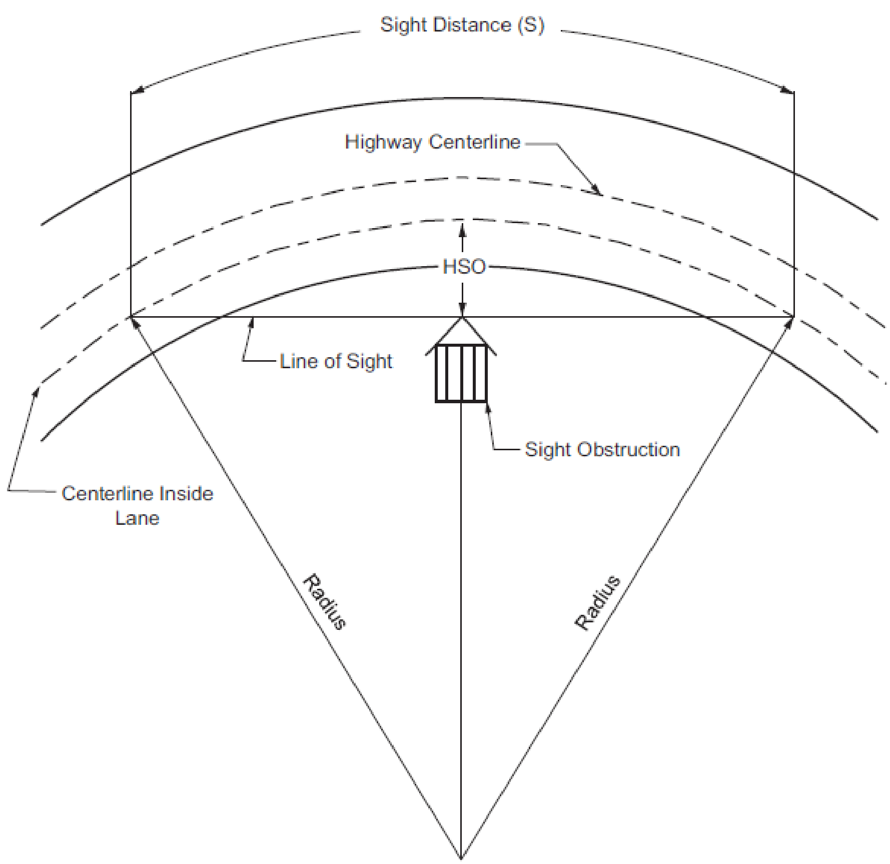


Figure 5: Components for the Determination of the Horizontal Sight Distance. From *A Policy on Geometric Design of Highways and Streets*, 2011, by AASHTO. Used by permission, see Appendix D.

On horizontal curves and mainly simple curves, as illustrated in Fig. 5, sight distance is limited by sight line obstructions including walls, cut slopes, buildings, among others. The available sight distance, *S*, is measured as the horizontal length of curve delimited by the sight line along the center of the inside lane, “as it is assumed to be the position of the driver’s eyes” (*Mannering 2004*). It is related to the horizontal sight line offset, *HSO*, as described in Fig.6, utilized for design and dependent upon the radius of curvature and the design speed according to Eq. 8 below.

$$HSO = R\left[1 - \cos\left(\frac{28.65S}{R}\right)\right] \tag{8}$$

Where:	HSO	=	Horizontal sight line offset, m
	S	=	Available sight distance, m
	R	=	Radius of curve, m

For example, entering Eq. 8 with a curve radius, *R* = 300 m, a design speed, *V* = 100 km/h, and the corresponding stopping sight distance, *SSD* = 185 m, a minimum required horizontal sight line offset, or *HSO*, equal to 14.2 m is necessary to achieve an available sight distance equal to that required. This value may be rapidly checked by entering Fig. 6 with the same values of *R* = 300 m and *V* = 100 km/h. Please note that a logarithmic base 10 scale is provided for radius in Fig. 6. As well, note that a table corresponding to Fig. 6 for determining horizontal sight line offsets can be found in Appendix A under Table A-3. An interpolation between the values of *HSO* given at the R values of 200 m and 500 m and at the speed *V* = 100 km/h should lead to approximately the same result, 14.2 m.

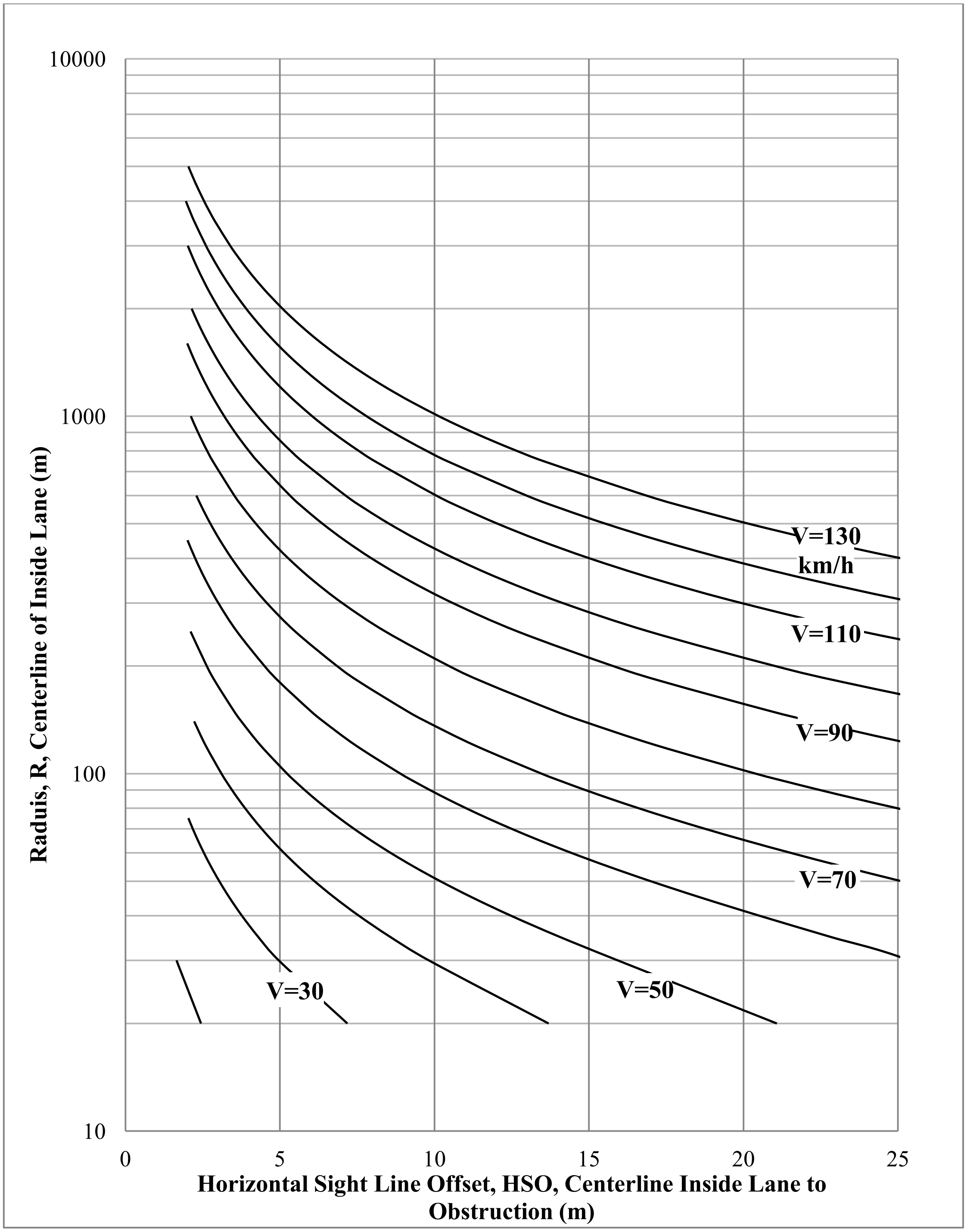


Figure 6: Design Controls for Stopping Sight Distance on Horizontal Curves. From *A Policy on Geometric Design of Highways and Streets*, 2011, by AASHTO. Used by permission, see Appendix D.

Additionally, the design of horizontal curves may require flatter slopes, banking, or other adjustments, which will, however, not be further discussed in this thesis. When offset distances cannot be provided for third party reasons, alternatives can be implemented including: increasing the radius, or reducing the design speed (*AASHTO 2011*).

CHAPTER 3

METHODOLOGY

This thesis' methodology focuses on the various anticipated designs and modes of operation of road trains. In addition to some of the earlier reviewed road train experimental designs, this chapter discusses "what-if" operational scenarios. The experimental scenarios for road trains enable the verification of the adequacy of existing highways. The sum total of existing and "what-if" scenarios for road train operation enable the derivation of impacts on the guidelines for the geometric design of highway features, vertical and horizontal alignments.

However, it is doubtful that existing highways will be re-designed for the exclusive use of road trains. It is thus intended to determine whether existing highways can accommodate road trains given only minor design adjustments. Still, over time, the highways of the future, whether rehabilitated or built anew, could be designed to satisfy guidelines derived specifically for road train modes of operation. Further, highways built to existing AASHTO, 2011, guidelines may accommodate travel speeds higher than those originally anticipated given the new road trains.

The anticipated reductions in perception-reaction times by road trains or driving systems and the potential higher driver's eyes location for road trains guided by trucks, among others, result in changes in the minimum required and available sight-distances on roadway curves. The newly derived sight distances result in new length requirements for the both, vertical and horizontal curves. Although, the general methodology for computing the available sight-distance on roadway curves still applies to road trains, the guidelines for curve design will themselves change given the anticipated change in design criteria; namely perception-reaction time, driver's eyes and light beam heights, and the deceleration rate. Thus, the methodology anticipates the necessary design guideline changes to accommodate the upcoming road train modes of operation at implementation.

Each experimental pilot, as earlier described in literature review, per its implementation approach dictates criteria for 5 distinct design variables that impact on the derivation of the vertical and horizontal highway alignments. These criteria encompass: the *PRT* value and the deceleration rate necessary to the computation of the required, or stopping, sight distance on all curves; the driver's eyes, the obstacle and the headlight mounting heights necessary to the computation of the available sight distance on vertical curves. No direct changes in *HSO* are anticipated by this thesis as they are not likely to result from the varied road train modes of operation. Decreases in *PRT* along with increases in deceleration rate favor the decrease in required, or stopping, sight distance on curves. On the other hand, increases in driver's eyes, obstacle or headlight mounting heights favor increases in available sight distance on vertical curves.

Modes of operation that promote either change, a decrease in required sight distance or an increase in available sight distance, favor the adequacy of existing highways. Past and ongoing experimental projects as described, California PATH, European SARTRE, European PROMOTE CHAUFFEUR I and II, and German

KONVOI all favor either one of the prior stated changes or the both. As such, they all promote per design the adequacy of existing highways.

In brief, all earlier cited experimental pilots of road trains decrease *PRT* either through the use of expert drivers or the complete elimination of this factor given autonomous vehicles. In addition, SARTRE, PROMOTE CHAUFFEUR I and II and KONVOI increase the driver's eyes and the headlight mounting heights given the use of a lead truck. PATH enhances driver's eyes height given the use of camera or radar systems placed in the back of the front rear view mirror. All have the potential to increase the deceleration rate of vehicles in road trains, again due to expert drivers or systems with autonomous vehicles. The lower the *PRT*s, the higher the deceleration rates, the driver's eyes, the obstacle and the headlight mounting heights, the smaller the required sight distances or the larger the available sight distances on curves than currently advocated by AASHTO, 2011. Thus, the adequacy of existing highway guidelines is demonstrated for the past and ongoing modes of road train operation. This adequacy is not accidental but rather intentional; to limit the extent of investment in highway infrastructures, and "what-if" scenarios contemplated would have to be as accommodating of existing highways.

Road train operation results in decreases in sight distance requirements or increases in available sight distances that in turn motivate recommendations for shorter minimum curves on alignments than currently advocated by AASHTO. These notions reinforce the adequacy of existing highways. Given the anticipated decreases in required and increases in available sight distance, quite likely highways built to existing design standards may accommodate faster vehicle travel.

The methodology further determines the exact extent of the decreases in the recommended (1) design vertical curve lengths, (2) design horizontal curve radii/lengths and (3) the increases in design, or allowable travel speeds realized by road train operation are herein addressed. Firstly, it selects the road train scenarios to study and determines the resulting changes in design criteria. It then derives the impacts on the geometric design of highways.

3.1. Road train Scenarios

This thesis assumes a number of highway operational scenarios in order to derive the impacts of road trains on the geometric design of highways. The do-nothing scenario provides the basis for comparison between existing and revised guidelines for geometric design given road train operation. Existing experimental projects constitute the entire basis for two of the scenarios, the SARTRE-like and the PATH-like scenarios. However, two other scenarios were derived based on the developmental pattern of experimental projects.

SARTRE claims to represent a transitory state toward full deployment of autonomous trains such as those proposed by PATH. With regards to geometric design, the move from individually and human-driven vehicles to SARTRE entails a higher performing driver and a taller design vehicle. The resulting changes in *PRT*, driver's eyes height, h_1, and headlight mounting height, h_3, promote less stringent required and more clement available sight distances. The move from SARTRE to PATH entails autonomous vehicles, or an elimination of the human factors, and a back of the rear view mirror location of "visual" systems. The resulting changes in *PRT* and

h_1 also advantageously impact on sight distances, required and available. Although PATH drops the headlight mounting height, h_3, below the levels of SARTRE, its negligible *PRT* and enhanced vision system height more than compensate for this drop with regards to minimum curve lengths as will be seen later.

The derivation of pilot systems thus seeks to achieve combined levels of *PRT*, deceleration, driver's eyes height, headlight mounting height to loosen the restrictions placed on curve designs by sight distance, required or available. *PRT* sways a continuum of values, between 2.5 s and 0 s, for conditions ranging from 90th percentile human drivers to alternate machine visions/decisions gauging complex situations. Deceleration, for this study purposes, takes on two levels, 3.4 m/s^2 and 4.5 m/s^2, reached by average drivers and expert professional drivers or machine, respectively. Driver's eyes height takes on four levels, 1.08 m, 1. 20 m, 2.33 m and 2.50 m, reached for passenger vehicle-led road trains, given human and machine visions, and for truck-led road trains, given the same, respectively. Headlight beam height takes on two levels, 0.6 m and 1.0 m, for passenger vehicle-led and truck-led platoons, respectively.

An optimum scenario fixes all of the above mentioned variables to their most clement values and thus would be PATH-like and strictly formed by autonomous vehicles (*PRT* at 0 s), somewhat SARTRE-like and truck-led, although with no human drivers (h_1 = 2.50 m given machine vision and h_3 = 1.0 m given truck-led platoon), with a generous deceleration rate that ensues from autonomous machines, $a \geq 4.5$ m/s^2. However, a global optimal system would stretch the limits of these criteria; such as for instance locate driver's eyes height at infinity, thus removing entirely the sight distance requirements on highway geometric design, whether in the daytime or the nighttime. Such a system could be interpreted in real life as providing satellite-assisted and/or GPS-enabled vision to leading vehicles in platoons.

Road trains vary firstly in the nature of their lead vehicle, whether passenger vehicle-led (*P*) or truck-led (*T*). Further, the design criteria, driver's eyes height, h_1, and headlight mounting height, h_3, undergo changes jointly with the lead vehicle type, the vision system type and the driving system. Vision or driving systems can be human (*H*) or machine (*M*) based. For instance, autonomously driven trains, such as PATH, tend to adapt their vision systems of machine type, *M*, to the back of the rear view mirror. This trend is expected to keep for autonomous vehicles, whether the lead vehicle is of type *P* or *T*. Since height of the rear view mirror itself changes with vehicle type, driving system type, *M* in this case, does not uniquely identify driver's eyes height. Still, it is conceivable that a SARTRE-like scenario, even though human driven, could be enhanced with machine vision to assist in the driving task, providing alerts to the driver that inform on hazardous conditions ahead. Driver's eye height would thus not be uniquely determined by driving system and vehicle type alone; Sartre and the earlier described Sartre-like scenario would have completely different values of h_1. Also, driving and vision systems, *H* or *M*, impact jointly on *PRT* and acceleration, *a*, regardless of lead vehicle type. Vision system must be considered a scenario design control regardless of lead vehicle and driving system types.

Thus, the choice of lead vehicle, vision and driving systems, uniquely determines all the road train design criteria. In summary, three design controls uniquely define a road train mode of operation, the lead vehicle (*P* or *T*), the driving system (*H* or *M*) and the vision system (*H* or *M*). The possible combinations of road trains to deploy are not many and involve a choice in given order of 2 types of lead vehicles, 2 types of driving systems and 2 types of vision systems. Thus, 8 combinations need be considered, *PHH*, *PHM*, *PMH*, *PMM*, *THH*, *THM*, *TMH*, *and TMM*, assuming that the first to third letter represent the lead vehicle, driving system and vision system types, respectively.

A review of these potential combinations and an interpretation of their probabilities for deployment and of the advantageous gains in design achieved by them led to the choice of the SARTRE-like scenario with obstacle-detection system hinted above, *THM*, and of the global optimal scenario to further investigate. The earlier constitutes one more transitory state of road train deployment placed between SARTRE and PATH and the latter, the design end goal.

PHH is SARTRE-like, as such it is human driven with a human vision system, but yet showcases a lead passenger car. A passenger vehicle as lead vehicle offers no real advantages over a truck per say (maybe in acceleration up slope). Safety is anticipated to be a major driving force for road train deployment. A lead-truck much enhances safety. *PHM* is similar to *PHH* with machine vision as enhancement. Safety remains a strong deterrent in comparison to SARTRE. *PMH* is PATH-like with a human vision system and as such presents no real advantage over PATH. Further, the use of a human simply as scout or vigil in this scenario makes it very improbable. The introduction of human factors and delayed *PRT*s would take much away from the accomplishments of autonomous driving. PATH exemplifies *PMM*, which will be treated with this experiment.

SARTRE exemplifies *THH*, which warrants no further consideration external to this experiment. *THM* is SARTRE-like with obstacle-detection/automated vision system. This scenario presents some advantage over SARTRE as it is likely to decrease *PRT* and result in more clement requirements on sight distance than SARTRE and is investigated herein as mentioned above. *TMH* presents similar disadvantages to *PMH*. *TMM* is a PATH-like scenario that is however truck-led. This scenario presents some advantage above and beyond a PATH given a truck-led platoon, higher vision system and headlight mounting heights. However, it presents none over the global optimal with an infinite driver's eyes location and the complete removal of sight distance limitations.

In summary, the study selects 2 "what-if" scenarios, *THM* and the global optimal scenarios, to add to the 2 different SARTRE-like and Path-like experimental scenarios, *PMM* and *THH*, to generate a total of 5 study scenarios that include the do-nothing. Three likely scenarios are discounted, *PHH*, *PHM* and *TMM*, to limit study scope while pursuing a wide breath of interesting scenarios to compare with those already experimental, *PMM* and *THH*. Further, two highly unlikely scenarios, *PMH* and *TMH*, were discounted. The sections that follow introduce and describe all scenarios analyzed.

3.1.1. Scenario 0 (*S.*0)*—Do-Nothing Scenario*

The scenario zero is deemed the null scenario and entails no road train implementation and thus no changes in the current design guidelines. It serves as base scenario for gauging the performance of road train enabling scenarios.

3.1.2. Scenario 1 (*S.*1)—*SARTRE-like Scenario*

The development of this SARTRE-like scenario, also called *S.*1, is based on the ongoing experimental European SARTRE project. It retains all of its features that could impact on geometric design including a truck-led platoon with a professionally trained driver. Thus, changes in *PRT*, deceleration rate, driver's eyes and headlight heights are at play. All the pre-cited changes would affect the resulting sight distances on curves, horizontal or vertical. Not only would required sight distances on all curves decrease due to reduced driver *PRT* and enhanced deceleration, but also available sight distance on vertical curves would increase as compared to *S.*0 due to greater driver's eyes and vehicle headlight mounting heights.

3.1.3. Scenario 2 (*S.*2)—*SARTRE-like Scenario with Obstacle Warning System*

To achieve further design benefits, the author envisioned a transitory "what-if" scenario, *S.*2, between SARTRE and PATH, which incorporates PATH-like obstacle-warning systems into the SARTRE-like truck-led road trains operated by trained drivers. Such systems would alert the drivers to the necessity to decelerate to avoid potential collisions with obstacles on the highway. Thus, complex situations, which require long human *PRT*s would convert into simple ones that require much shorter *PRT*s, where the interpretation of a consistent and simple message, an alarm or a sign on screen for instance, becomes a routine and expected simple task.

Obstacles would be detected by means of systems that replace the human driver's eyes; forward and side-looking radar sensors installed on the passenger vehicle's bumpers or video imaging apparatus on the back of the rear view mirror.

Logically, a rear view mirror height for an obstacle detection system yields greater "driver's eyes"/vision height and thus available sight distance on existing curves than does a SARTRE-like scenario or alternately, results in the recommendation of shorter minimum lengths of curves to achieve a given sight distance.

3.1.4. Scenario 3 **(*S*.3)**—*PATH-like Scenario*

The PATH's 8-vehicle platoon experiment, also known as PATH Demo '97, is considered as basis for the development of this scenario, *S*.3. Humans no longer control the vehicle; instead the vehicle control is autonomous by means of navigation systems, as well as similar radar and vision sensors as with the previous scenario, *S*.2. Indeed, human reaction times are really huge in comparison to those of the machines, where information updates occur at a rate of 50 times per second (*PATH 1998*). Thus, highly performing driverless/autonomous vehicles in road train systems may react in a very small to almost negligible amount of time. The required sight distances on curves are expected to decrease as compared to *S0*, thereby justifying shorter recommendations for minimum curve lengths.

3.1.5. Scenario 4 **(*S*.4)**—*PATH-like Scenario with Satellite Vision System*

To achieve optimal design benefits, the author envisioned a further ideal/end-state scenario, *S*.4, beyond PATH, which incorporates remote obstacle-warning systems into the PATH-like passenger car-led platoons with autonomous vehicles. Such devices would have unlimited view of the highway and would remove available sight distance as a design constraint. Available sight distance would in theory be unlimited, hence would exceed that required under any design option. The minimum absolute required length of curves would prevail based, for vertical curves, or the absolute minimum length, $L = 0.6V$, and for horizontal curves, based on the minimum radius. Determination of the feasibility of such a remote vision enhanced system is beyond the scope of this study.

3.1.6. Scenario Comparison

As earlier hinted, the 4 scenarios introduced provide a natural transition for the evolution of current highway modes of operation toward full deployment of autonomous road trains with remote vision systems on highways. All scenarios promote reductions in required or increases in available sight distances. Both the changes translate into recommendations for shorter minimum lengths of curves at any given design speed. Alternately, existing curves, designed to AASHTO, 2011, or *S0* standards, could be traveled at higher design speeds. Given the natural progression of the scenarios adopted toward the design end goal, more advanced scenarios are expected to generate more or less more savings than less advanced ones.

The literature indicates that longer curves results in greater construction costs because additional excavation or fill would typically be needed to provide a greater curve length (*Fambro 1997*). The Path-like scenario with remote vision system is expected to prove most construction cost-effective. The complete elimination of the human factors by this scenario engenders unlimited sight distance on highways regardless of curve lengths, vehicle type or headlight mounting heights and removes sight distance as geometric design constraint. The absolute minimum curve lengths satisfy the recommended lengths for this scenario.

The geometric design impacts of all the scenarios and of the changes that they dictate are further discussed in the following sections. Those impacts concern mostly the horizontal and vertical alignments as only minor changes are anticipated for cross-sections. The highly performing and precise systems utilized for lateral guidance by driverless or autonomous vehicles in road trains may result in a decrease of 0.6 m to 0.9 m (2 ft to 3 ft) at most in lane width below the standard design width of 3.6 to 3.7 m (12 ft). No implications for safety are found in the literature for lanes narrower than 3.7 m even for individually human-driven vehicles (*Hauer 2000*). Thus, the cross-section reduction impacts per say would actually be minor. Still, a width reduction per lane, when spread over the whole length of the design project, amounts to lower needs to pave or repave. Thus, further savings could be realized for highways dedicated to road train operations during construction and maintenance.

Any mixed operation on highways of human-driven and autonomous vehicles would render moot the positive impacts contemplated in sight distance and minimum curve lengths and thus in construction costs. Thus, this study envisions for all scenarios the use of specialized lanes that move road trains in exclusivity similarly to the totally divided lanes currently dedicated at times to high occupancy or electronic toll vehicles (HOV). Best yet, it contemplates separate whole highways for the different operation modes; thus justifying the separate revised guidelines herein derived for the geometric design of highways.

3.2. Design Criteria for All Scenarios

The considered changes in the criteria for the design of roadway curves, namely, crest and sag vertical as well as horizontal curves, for each studied scenario are presented below including perception-reaction times, deceleration rates, driver's eyes height, obstacle height and headlight beam height. Such changes enable derivation of reduction in curve lengths or curve radii.

3.2.1. Scenario 1 (*S*.1)—*SARTRE-like Scenario*

S.1 assumes the operation of road trains led by trucks and driven by trained professionals. It is anticipated that the *PRT*s of trained professional drivers, will be much reduced compared to those of regular drivers. Unfortunately, a review of the literature did not pinpoint a specific 90th percentile time to be used as representative of the overall population of trained/professional truck drivers. Hence, this scenario *S*.1 assumes the use of two values of *PRT*, 2.0 s and 1.5 s, in deriving the impacts of a SARTRE-like scenario on the guidelines for the geometric design of highways. Results for values of *PRT* within or slightly outside these limiting values can be inter- or extrapolated.

Note that the standard AASHTO guidelines have adopted the *PRT* value of 2.5 s since 1954, which exceeds the 90th percentile value for all drivers (*AASHTO 2011*). Further, other countries utilize values as small as 2.0 s for design purposes under normal operation, for individually and human-driven vehicles (*Fambro 1997*). The achieved *PRT* value for alerted drivers equals 1.64 s under the same normal conditions.

The deceleration rate of the road train is considered to be greater than that adopted by AASHTO for human-driven individual vehicles, 3.4 m/s^2. For scenario-developing purposes, 4.5 m/s^2 is thus considered as the anticipated changed deceleration rate feature, since the trained lead drivers of road trains are expected to perform better than the average drivers anticipated by AASHTO. Literature shows that most drivers are able to decelerate at rates greater than 4.5 m/s^2 (*AASHTO 2011*) without sacrificing comfort.

Also *S*.1 results in an increase in the headlight mounting height of the design vehicle, the lead truck. For the purpose of this scenario, h_1 in Eq. 4, is taken as 2.33 m (7.6 ft) to account for truck rather than regular vehicle, 1.08 m (3.5 ft), operation by the driver. Note the enhancement in height obtained by designating trucks as lead vehicles of road trains as is characteristic of this SARTRE-like scenario. For all scenarios, the height of the obstacle remains unchanged from AASHTO's basic value at 0.6 m to prevent damages to all road train vehicles and not just to the lead vehicle.

For sag curve design, *S*.1 also results in an increase in the height of the vehicle headlight beam, h_3, in this case a truck. Research studies indicate that headlight heights for trucks vary from 0.92 m to 1.35 m, with 0.97 m and 1.08 m being the 95th and the 90th percentiles height, respectively (*Fambro 1997*). For design and safety purposes, 1.0 m (3.28 ft) is selected for *S*.1 as the basis for sag curve design under road train operation. A significant enhancement above the AASHTO's level of 0.6 m in headlight mounting height is obtained by designating trucks as lead vehicles of road trains, in percentage mostly rather than in actual value, in *S*.1. Then, h_3 in Eq. 6 is modified to reflect the 1.0-m height earlier discussed.

As can be seen in Eq. 8, the unique design control for horizontal curves is the minimum required sight distance. No criterion other than *PRT*, as earlier determined, is necessary for computing the minimum lengths of horizontal curves herein.

3.2.2. Scenario 2 **(*S*.2)**—*SARTRE-like Scenario with Obstacle Warning System*

Design criteria for deceleration rate, obstacle height and headlight mounting height in this *S*.2 scenario are very similar to those for *S*.1 given a similar truck-led platoon driven by a professionally trained driver. As per *S*.1, the SARTRE-like scenario, the deceleration rate remains at 4.5 m/s^2 given trained drivers, the headlight mounting height at 1.0 m and the obstacle height at 0.6 m above the highway surface. Also, the achieved *PRT* for a trained driver under this scenario may differ from that for alerted drivers, 1.64 s, under complex situation for the null scenario. Thus, the *PRT* for *S*.2 is further decreased to values of 0.5 s and 1.0 s. Results for values within this range could be interpolated.

The obstacle warning system affords a much greater visual height of the highway ahead than do normal driver's eyes. The stereovision imaging sensor is considered located in the back of the rear view mirror, between the truck's height, 2.72 m, and the truck driver's eyes height, 2.33 m, with both values taken at their 95th percentile (*Fambro 1997*), and thus approximately at 2.50 m above the highway surface. For crest curve design considerations, h_1, in Eq. 4, is firstly modified to 2.50 m.

As for sag curve design, h_3 equal to 1.0 m enters Eq. 6 to determine the minimum lengths of sag vertical curves associated with varied design speeds. As well, for horizontal curves, required sight distance uniquely controls the design of horizontal curves. No criterion other than *PRT*, as earlier determined, is necessary for computing the minimum lengths of horizontal curves for this scenario.

3.2.3. Scenario 3 (*S*.3)—*PATH-like Scenario*

Aspects of this fully-automated *S.3* scenario entail the use of radar or stereoscopic vision sensors for obstacle detection mechanisms assumed placed in the back of the rear view of a passenger vehicle, unlike *S*.2, at height 1.20 m. The main design feature is the elimination of the human factors given fully autonomous vehicles. For a negligible *PRT*, approximately equal to 0 s, the derivation of stopping sight distance in Eq. 3 only involves the braking distance; meaning that only the distance necessary for the vehicle to brake must be considered in this derivation. As for *S*.2, the deceleration rate is considered to be 4.5 m/s^2. Conceivably, deceleration probably could be boosted above this level to the limit comfortable to human passengers.

A radar or camera vision sensor device that acts as a hazard-detection mechanism to replace the driver's eyes has been investigated since the early 1990s (*PATH 1998*). This *S*.3 scenario with passenger cars considers the stereovision imaging sensor to be located between the vehicle height, 1.32 m, and the driver's eyes height, 1.08 m, with both values taken at their 95th percentile (*Fambro 1997*), and thus approximately at 1.20 m above the roadway surface. For crest curve design purposes, h_1 equal to 1.20 m enters Eq. 4 to determine the minimum lengths of crest vertical curves associated with varied design speeds.

The headlight beam height, h_3, remains unchanged from that advocated by AASHTO at 0.6 m above the roadway surface for sag curve design. Then, h_3 equal to 0.6 m enters Eq. 6 to determine minimum lengths of sag vertical curves associated with varied design speeds for *S3*. Also, and similarly to *S*.1 and *S*.2, no criterion other than *PRT*, as earlier determined, is necessary for computing the minimum lengths of horizontal curves for this scenario.

3.2.4. Scenario 4 **(*S*.4)*—PATH-like Scenario with Satellite Vision System***

Most criteria for this scenario are not distinguishable from those of *S*.3. The assumption of a satellite vision system, however, fixes the value of the "driver's eyes" height at infinity.

Table 3 summarizes the derived design criteria for all scenarios to analyze. Sub-scenarios *S*.1.1 and *S*.1.2 of *S*.1 as well as *S*.2.1 and *S*.2.2 of *S*.2 are also introduced as associated with different specified values of *PRT*s. Table 3 enables the direct comparison of these scenario criteria revealing their similarities and dissimilarities. The methodology further utilizes the design criteria derived in combination with the traditional methodology from AASHTO, 2011, to derive the guidelines for geometric design of highways under road train operation.

Table 3: Variables in Design Features of Highway Alignment per Scenario.

Scenarios	Perception-Reaction Time	Deceleration Rate	Driver's eyes/ Obstacle Warning System Height	Obstacle Height	Light Beam Height
	PRT **(s)**	***a*** **(m/s²)**	h_1 **(m)**	h_2 **(m)**	h_3 **(m)**
***S*.0**	2.5	3.4	1.08	0.6	0.6
***S*.1.1**	2.0	4.5	2.33	0.6	1.0
***S*.1.2**	1.5	4.5	2.33	0.6	1.0
***S*.2.1**	1.0	4.5	2.50	0.6	1.0
***S*.2.2**	0.5	4.5	2.50	0.6	1.0
***S*.3**	0	4.5	1.20	0.6	0.6
***S*.4**	0	4.5	∞	0.6	0.6

3.3. Sight Distance Recalculation for all Scenarios

The newly derived design criteria, *PRT* and *a*, for each scenario, as summarized in Table 3, lead to the associated *SSD* values. In turn, the *SSD* values, presented below, enable determination of revised recommendations for minimum lengths of vertical curve and minimum sight line offsets for horizontal curves.

3.3.1. Scenario 1 (*S*.1)*—SARTRE-like Scenario*

Entering Eq. 3 with the values of *PRT* and *a* associated with *S*.1 in Table 3, *PRT* = 2.0 s and 1.5 s, a = 4.5 m/s^2, enables re-computation of the minimum required stopping sight distance related to this scenario. Table 4 presents these minimum values at varied design speeds. Note that calculated *SSD* values are rounded up to multiples of 5 m, into design values, as is customary with AASHTO.

Table 4: Minimum Required Stopping Sight Distances for Scenario 1 Compared to AASHTO Values for Customary Design on Level Roadways.

Design Speed	***SSD* for *S*.0**		***SSD* for *S*.1.1**		***SSD* for *S*.1.2**	
	Calculated	**Design**	**Calculated**	**Design**	**Calculated**	**Design**
[km/h]	**[m]**	**[m]**	**[m]**	**[m]**	**[m]**	**[m]**
20	18.5	20	14.6	15	11.8	15
30	31.2	35	24.5	25	20.3	25
40	46.2	50	36.1	40	30.5	35
50	63.4	65	49.5	50	42.5	45
60	83.0	85	64.6	65	56.2	60
70	104.9	105	81.4	85	71.7	75
80	129.0	130	99.9	100	88.8	90
90	155.5	160	120.2	125	107.7	110
100	184.2	185	142.3	145	128.4	130
110	215.2	220	166.0	170	150.7	155
120	248.6	250	191.5	195	174.8	175
130	284.2	285	218.7	220	200.7	205

Reading from Table 4 and given *S*.1.1, a vehicle driver traveling at speed *V* = 100 km/h who detects an obstacle on the road, requires a total *SSD* of 142.3 m, rounded to 145.0 m, to come to a complete stop. Similarly, given *S*.1.2, a vehicle driver traveling at speed *V* = 100 km/h who detects an obstacle on the road requires a total *SSD* of 128.4 m, rounded to 130.0 m for the same.

*3.3.2. Scenario 2 (**S**.2)—SARTRE-like Scenario with Obstacle Warning System*

Entering Eq. 3 with the values of *PRT* and *a* associated with *S*.2 in Table 3, *PRT* = 1.0 s and 0.5 s, a = 4.5 m/s^2, enables re-computation of the minimum required stopping sight distance related to this scenario. Table 5 presents these minimum values at varied design speeds. Note that calculated *SSD* values are rounded up to multiples of 5 m, into design values, as is customary with AASHTO.

Table 5: Minimum Required Stopping Sight Distances for Scenario 2 Compared to AASHTO Values for Customary Design on Level Roadways.

Design Speed	***SSD* for *S*.0**		***SSD* for *S*.2.1**		***SSD* for *S*.2.2**	
	Calculated	**Design**	**Calculated**	**Design**	**Calculated**	**Design**
[km/h]	**[m]**	**[m]**	**[m]**	**[m]**	**[m]**	**[m]**
20	18.5	20	9.0	10	6.2	10
30	31.2	35	16.1	20	12.0	15
40	46.2	50	25.0	25	19.4	20
50	63.4	65	35.6	40	28.6	30
60	83.0	85	47.9	50	39.5	40
70	104.9	105	61.9	65	52.2	55
80	129.0	130	77.7	80	66.6	70
90	155.5	160	95.2	100	82.7	85
100	184.2	185	114.5	115	100.6	105
110	215.2	220	135.4	140	120.2	125
120	248.6	250	158.2	160	141.5	145
130	284.2	285	182.6	185	164.5	165

Reading from Table 5 and given *S*.2.1, a vehicle driver traveling at speed V = 100 km/h who detects an obstacle on the road, requires a total *SSD* of 114.5 m, rounded to 115.0 m, to come to a complete stop. Similarly, given *S*.2.2, a vehicle driver traveling at speed V = 100 km/h who detects an obstacle on the road requires a total *SSD* of 100.6 m, rounded to 105.0 m for the same.

3.3.3. Scenario 3 (S.3)—PATH-like Scenario

Entering Eq. 3 with the values of *PRT* and a associated with *S*.3 in Table 3, *PRT* = 0 s, a = 4.5 m/s^2, enables re-computation of the minimum required stopping sight distance related to this scenario. Table 6 presents these minimum values at varied design speeds. Note that calculated *SSD* values are rounded up to multiples of 5 m, into design values, as is customary with AASHTO.

Table 6: Minimum Required Stopping Sight Distances for Scenario 3 Compared to AASHTO Values for Customary Design on Level Roadways.

Design Speed	*SSD* for *S*.0		Reaction Distance	Braking Distance	*SSD* for *S*.3	
	Calculated	Calculated			Calculated	Design
[km/h]	[m]	[m]	[m]	[m]	[m]	[m]
20	18.5	20	0	3.5	3.5	5
30	31.2	35	0	7.8	7.8	10
40	46.2	50	0	13.9	13.9	15
50	63.4	65	0	21.7	21.7	25
60	83.0	85	0	31.2	31.2	35
70	104.9	105	0	42.5	42.5	45
80	129.0	130	0	55.5	55.5	60
90	155.5	160	0	70.2	70.2	75
100	184.2	185	0	86.7	86.7	90
110	215.2	220	0	104.9	104.9	105
120	248.6	250	0	124.8	124.8	125
130	284.2	285	0	146.5	146.5	150

Reading from Table 6 and given *S*.3, a vehicle driver traveling at speed $V = 100$ km/h who detects an obstacle on the road, requires a total *SSD* of 86.7 m, rounded to 90.0 m, to come to a complete stop.

3.3.4. Scenario 4 (S.4)—PATH-like Scenario with Satellite Vision System

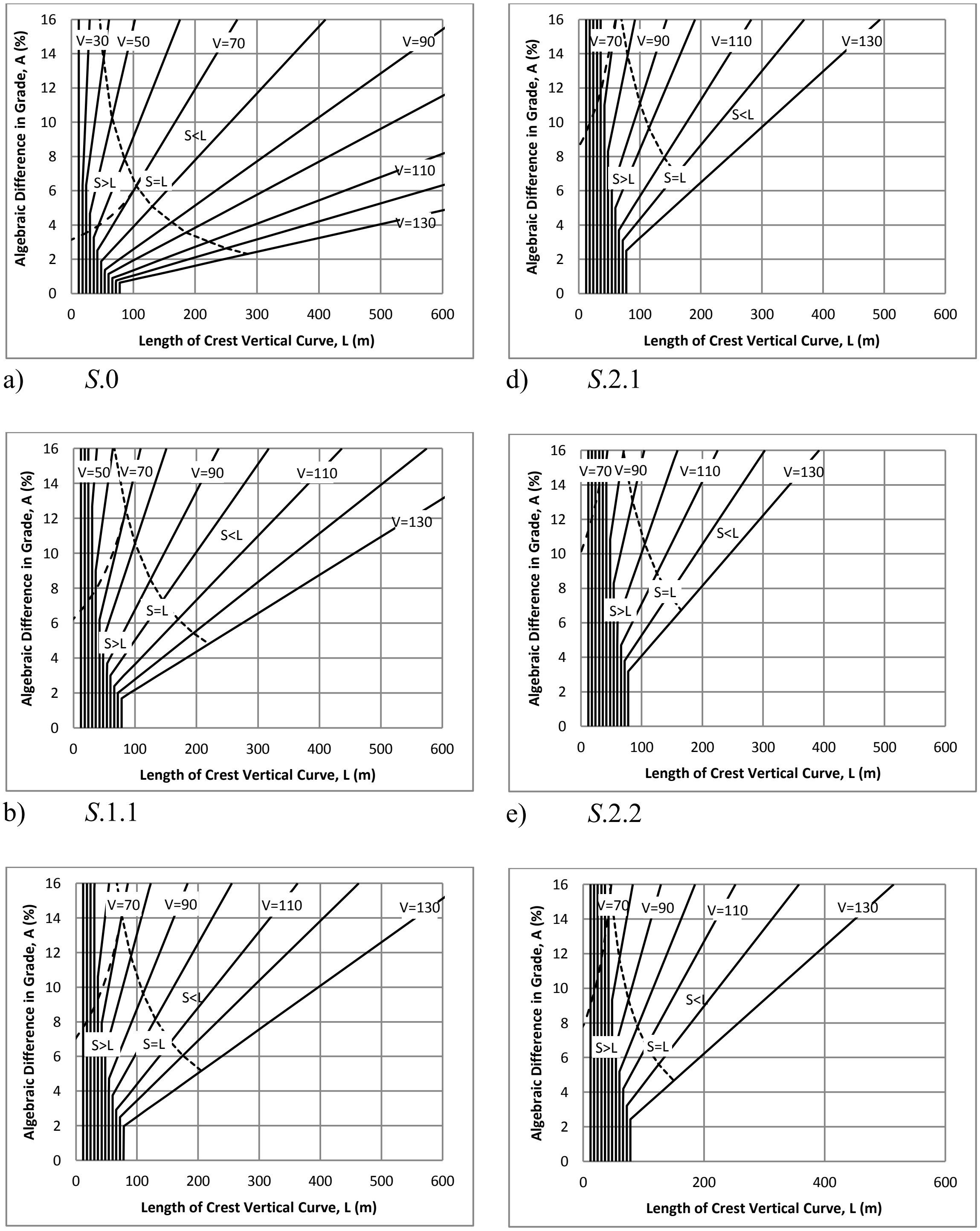
Since this *S*.4 scenario's *SSD* values do not differ from those of *S*.3, they remain as presented above in Table 6.

In summary, the preceding paragraphs have re-computed *SSD* for the varied studied scenarios. The newly computed design values for *SSD* enable the derivation of recommended minimum lengths of vertical curves (Eqs. 4, and 6) and minimum clearance distances to horizontal curves (Eq. 8).

3.4. Recalculations of Curve Length Design Guidelines

The methodology further equates the available sight distances on curves to those minimum required, thereby enabling determination of the minimum recommended lengths of vertical curves or radii of horizontal curves and of the reductions in these variables associated with the operation of road trains. Determination of the minimum lengths' and radii entails the substitution of the pre-computed stopping sight distances, *SSD*, as tabulated above in Tables 4 to 6, for *S* into the equations for minimum length of curves, Eqs. 4, and 6, and the equation for horizontal curve radii, Eq. 8. Care must be taken to substitute the design criteria associated with the varied road train scenarios, in Table 3, for the default AASHTO criteria in Eqs. 4, and 6. Figs. 7, 8 and 9 present newly computed relations for (1) crest vertical curve, (2) sag vertical curve, and (3) horizontal curve designs. Tables corresponding to below shown figures are placed in Appendix A for a more reader-friendly review under Tables A-4 to A-18.

Fig. 7 presents the newly recommended minimum lengths of crest curves under all road train scenarios. For example, given scenario *S*.1.1, entering Eq. 5 with an algebraic difference in grades, A = 4%, a design speed, V = 100 km/h, and the corresponding stopping sight distance at this speed, *SSD* = 145 m, a minimum length of crest curve, or L equal to 80.1 m is calculated. This value may be rapidly checked by entering Fig. 7b) with values of A = 4% and V = 100 km/h for scenario *S*.1.1. Note the difference in the minimum length of crest curve as determined in Fig. 7a) for scenario *S*.0, the current AASHTO's guidelines, at a value of 208.8 m. A similar approach may be followed to solve for the minimum required crest curve lengths for all other scenarios.

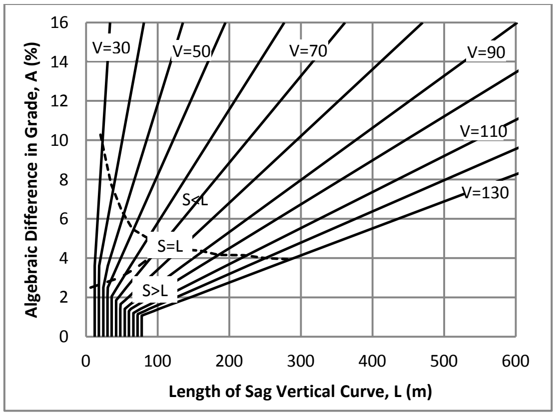


a) *S*.0
d) *S*.2.1
b) *S*.1.1
e) *S*.2.2
c) *S*.1.2
f) *S*.3

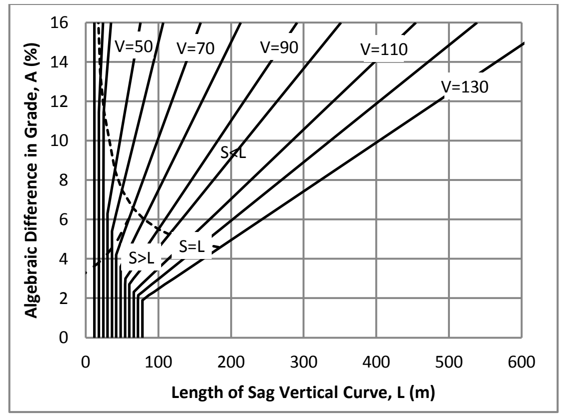
Figure 7: Design Controls for Crest Vertical Curves in Meters for all Scenarios.

Fig. 8 presents the newly recommended minimum lengths of sag curves under all road train scenarios including *S*.0, *S*.1.1, *S*.1.2, *S*.2.1, *S*.2.2, and *S*.3. For example, given scenario *S*.1.1, entering Eq. 7 with an algebraic difference in grades, A = 4%, a design speed, V = 100 km/h, and the corresponding stopping sight distance at this speed, *SSD* = 145 m, a minimum length of sag curve, or L equal to 118.9 m is calculated. This value may be rapidly checked by entering Fig. 8b) with values of A = 4% and V = 100 km/h for *S*.1.1. Note the difference in minimum length of sag curve when determined by Fig. 8a) corresponding to scenario *S*.0, or the current AASHTO's guidelines, at a value of 178.4 m. A similar approach may be followed to solve for the minimum required sag curve lengths for all other scenarios.

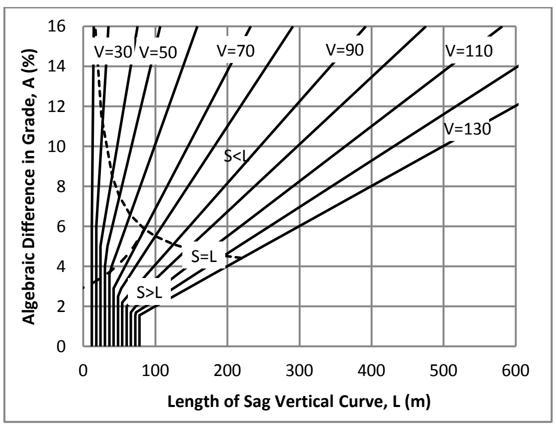
Fig. 9 depicts the newly calculated relationships between horizontal sight line offset and the radii of curves under all road train scenarios including *S*.0, *S*.1.1, *S*.1.2, *S*.2.1, *S*.2.2, and *S*.3. For example, given scenario *S*.1.1, entering Eq. 8 with a horizontal sight line offset of 10 m and the stopping sight distance at V = 100 km/h, which equals to *SSD* = 145 m, a minimum radius of horizontal curve, or R equal to 245.5 m is calculated. This value may be rapidly checked by entering Fig. 9b) with the value of *HSO* = 10 m for *S*.1.1. However, AASHTO provides a minimum radius equal to 328 m given V = 100 km/h and superelevation e = 12%, which must be respected. Note the difference in minimum radius of horizontal curve when determined by Fig. 9a) corresponding to scenario *S*.0, or the current AASHTO's guidelines, at a value of 403.3 m. A similar approach may be followed to solve for the minimum required sag curve lengths for all other scenarios.



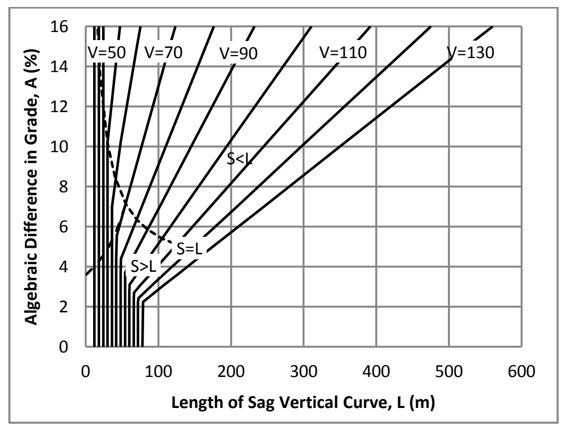
a) *S*.0



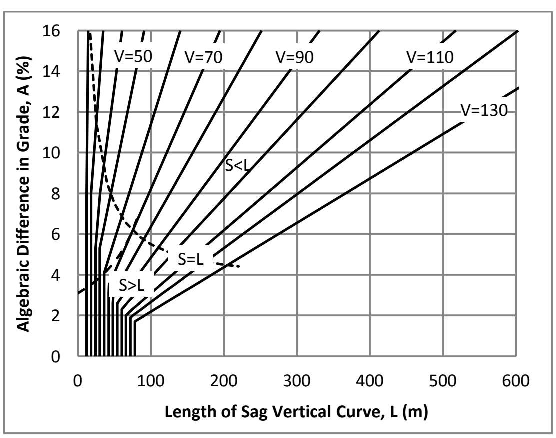
d) *S*.2.1



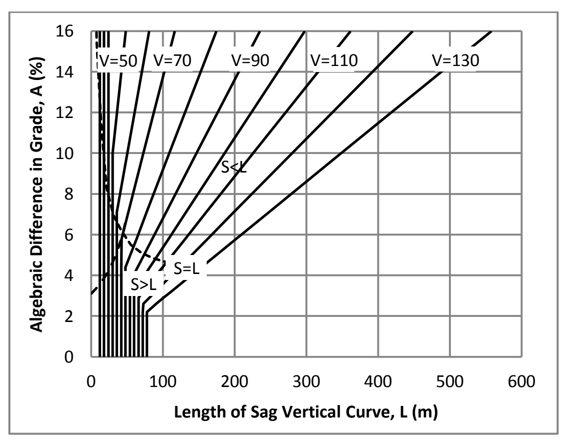
b) *S*.1.1



e) *S*.2.2

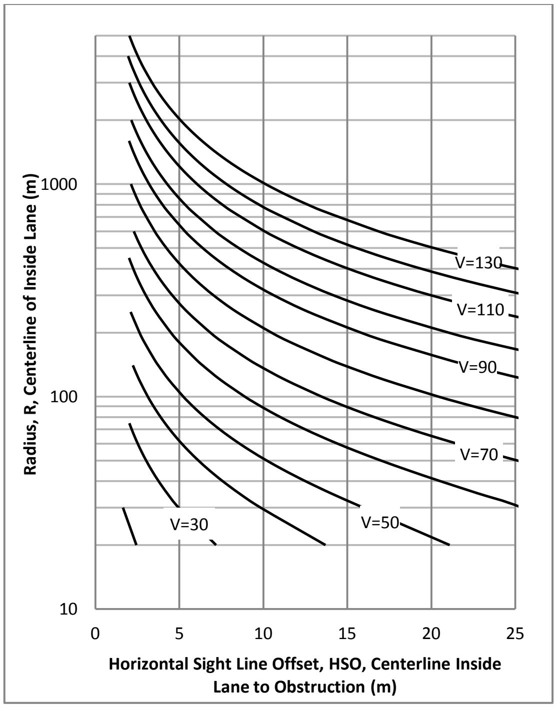


c) *S*.1.2

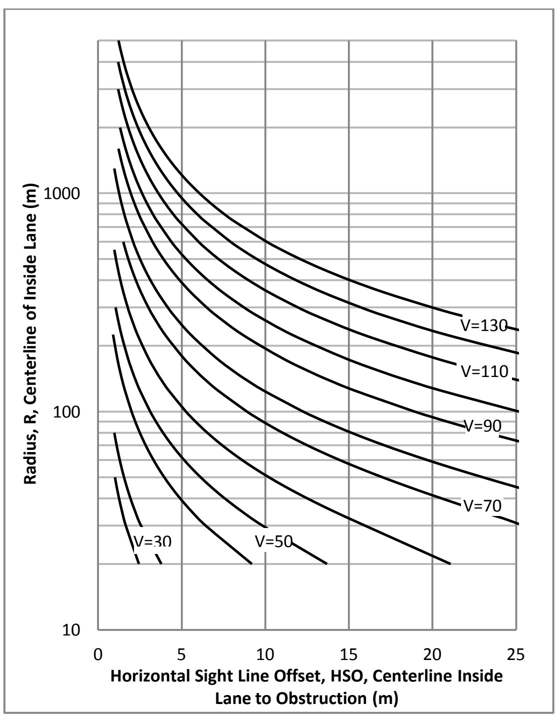


f) *S*.3

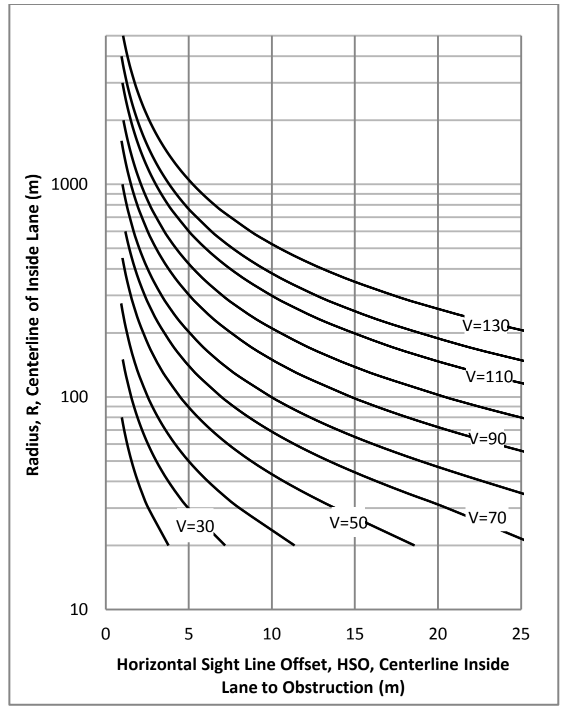
Figure 8: Design Controls for Sag Vertical Curves in Meters for all Scenarios.



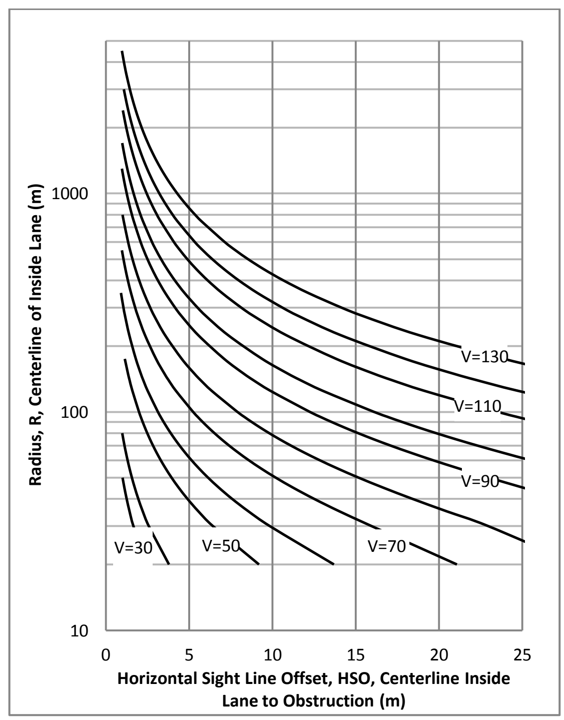
a) *S*.0



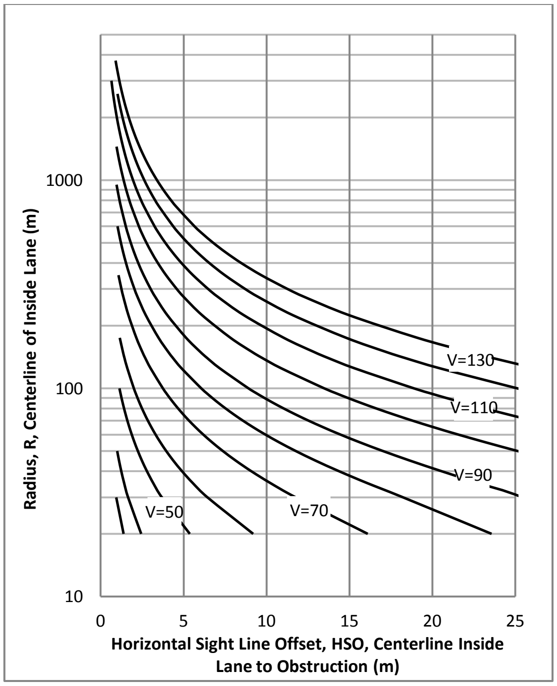
b) *S*.1.1



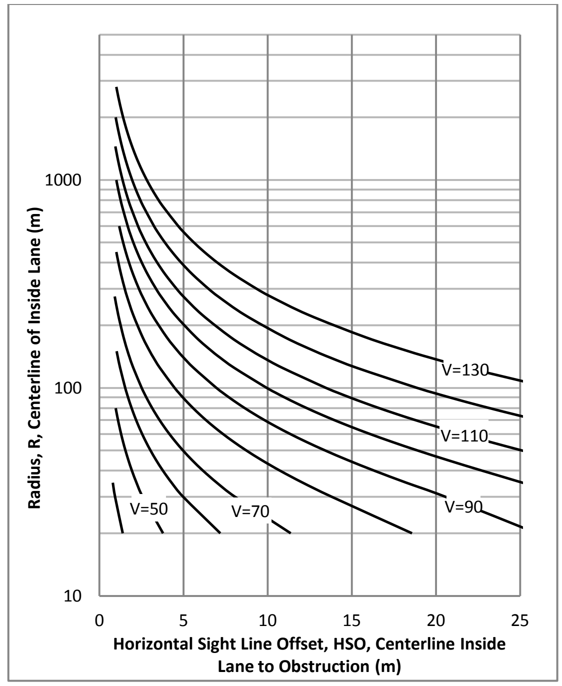
c) *S*.1.2



d) *S*.2.1



e) *S*.2.2



f) *S*.3

Figure 9: Design Controls for Horizontal Curves in Meters for all Scenarios.

3.5. Design Speed Calculations

A further interesting consideration is the determination of the increases in design speed allowed for road trains on existing roadways, as built to AASHTO, 2011, guidelines. Given the anticipated decreases in their required sight distances, the longer lengths of curves provided by AASHTO, 2011, could accommodate increased design speeds for road trains.

Available sight distances, S, are calculated from Eqs. 4 and 6, corresponding to crest and sag curves, respectively, given the AASHTO minimum lengths of curves, L, recommended at different values of speed and the control criteria, h_1, h_2, h_3 and a for each individual road train scenario. Then, the newly obtained S values enter Eq. 3 to determine the maximum speeds at which the driver may be traveling for each road train mode of operation, given road train design criteria for *PRT* and *a*.

Obtained speed values may represent an enhancement over design speed that may relieve traffic congestion on highways. Increases in travel speeds or free flow speeds for certain roadways may be linked to increases in capacity that can further help mitigate traffic congestion beyond and above that permitted by road train operation. Overall, increases could be achieved for most values of curve design lengths for crest and sag curves. On some rare occasions, at low values of the as-built design speed, the maximum speeds on curves, $V_{max} = L/0.6$, might be exceeded. Thus, the maximum travel speeds based on absolute curve lengths supersede those calculated based on sight distances. Maximum travel speeds will, in this case, prevail, as documented in Appendix B. In general, overdesigned curves, whose lengths exceed the minimum AASHTO, 2011 recommended lengths, could accommodate the newly recalculated road train travel speeds. Refer to Appendix B for calculated results of maximum travel speeds on crest, Tables B-1, B-4 and B-7 as well as on sag vertical curves, Tables B-2, B-5 and B-8, designed to current AASHTO, 2011 guidelines.

Assuming scenario *S*.2.1, for example, the AASHTO minimum required crest curve length, *L*, of 208 m, Table *A*-1, corresponding to an initial *V* = 100 km/h and *A* = 4%, enters Eq. 4 to solve for sight distance, *S*, which equals 240 m. Note that criteria h_1 and h_2 are 2.5 m and 0.6 m, respectively, as described in Table 3 for scenario *S*.2.1. Then, obtained sight distance, *S* = 240 m enters Eq. 3 given *PRT* = 1.0 s and $a = 4.5$ m/s^2 as further described in Table 3 for scenario *S*.2.1 in order to find *V* = 151 km/h. Note the enhancement in design speed as opposed to AASHTO's value of 100 km/h.

Assuming scenario *S*.2.1 still, the AASHTO minimum required sag curve length, *L*, of 178 m, Table *A*-2, corresponding to an initial $V = 100$ km/h and $A = 4\%$, enters Eq. 6 to solve for sight distance, *S*, which equals 201 m. Note that criterion h_3 is 1.0 m as described in Table 3 for scenario *S*.2.1. Then, obtained sight distance, $S = 201$ m, enters Eq. 3 given $PRT = 1.0$ s and $a = 4.5$ m/s^2 as further described in Table 3 for scenario *S*.2.1 in order to find $V = 137$ km/h. Note the enhancement in design speed as opposed to AASHTO's value of 100 km/h. Similar approaches as above may be followed to solve for the design speeds at other values of the algebraic differences in grades for crest as well as sag vertical curves.

The procedure is slightly tweaked for horizontal curves. Assuming road trains that operate on curves designed to current AASHTO, 2011 guidelines, namely *S*.0, the variables *R*, *S*, and *HSO* are fixed. Still, given the design criteria for road trains, they can travel at faster speeds while achieving the same sight distance. Sight distance for the both are equated and solved for road train travel speed given AASHTO travel speed and human factors for the both, AASHTO and road train. The value of *R* is then determined for either scenarios using Eq. 8, and the minimum radius associated with the new travel speeds for road trains determined as well. As long as the provided radii exceed the minimum radii able to resist the centripetal acceleration at the recomputed speeds for road train operation, those speeds may be achieved. Otherwise, although the potential for increased speed exists, those speeds may not materialize due to stability concerns. In this case, maximum absolute speeds would prevail. Here too, overdesigned curves as-built may accommodate the recomputed speed depending on their radii values.

Assuming scenario *S*.2.1, given fixed horizontal sight line offset of *HSO* = 10 m, the AASHTO minimum required sight distance, *S*, of 184 m, corresponding to an initial *V* = 100 km/h, enters Eq. 3 m given *PRT* = 1.0 s and *a* = 4.5 m/s^2 as described in Table 3 for scenario *S*.2.1 in order to find *V'* = 131 km/h. Note the enhancement in design speed as opposed to AASHTO's value of 100 km/h. Similar approaches as above may be followed to solve for the design speeds at other values of horizontal sight line offsets.

Overall, the recomputed minimum radii for road train operation exceeded by far those strictly requested for sight distance by AASHTO, 2011. Over-designed curves could thus accommodate the new travel speeds for road train, but not those built to minimum AASHTO sight distance around curve guidelines. Speeds were recalculated for a specific value of *HSO* to limit the scope of work. The general approach outlined enables derivations at other values of *HSO*. Refer to Appendix B for recalculated travel speeds on horizontal curves under Tables B-3, B-6 and B-9.

The next study section expands on this thesis' findings with regards to minimum curve lengths and radii recalculations as well as to design speed back-calculations and thus on the impacts of road train modes of operation on the geometric design of highways for all scenarios. These impacts are entertained in turn by the various chapter sections.

CHAPTER 4

FINDINGS

This section shows specifically the impacts of different road train modes of operation on the geometric design of highways for the diverse previously discussed scenarios and using the recalculation methods outlined in the methodology. Such impacts specifically include: the revised guidelines for minimum curve lengths, the reduction in minimum recommended curve lengths and the increases in operational speed limits contemplated.

4.1. Impacts on Roadway Design Standards

As explained in the methodology, the expected changes in design criteria associated with the operation of road trains will have an impact on the required and available sight distances on highway curves. They thus motivate the re-computation of the minimum lengths of vertical curves and the minimum radii of horizontal curves to recommend per revised guidelines on the geometric design of highways. These re-computed values were presented in the methodology, Figs. 7, 8, and 9, for the different scenarios analyzed and different curve types. Given enhanced human factors, roads designed to AASHTO’s 2011 guidelines can accommodate faster travel by road trains. Those faster speeds potentially achieved were recomputed as well and tabulated in Appendix B.

To better apprehend the comparative performance of the varied scenarios for all curve types, the findings stress results for a common set of design speed and algebraic difference in grades, 100 km/h and 4%, respectively. Figs. 10, 11 and 12 present performance graphs across all scenarios at these values. A fixed horizontal sight line offset of 10 m is assumed for horizontal curves.

Fig. 10 specifically addresses the recommended minimum lengths of crest curves under all road train scenarios at the specified values of speed and percent difference in algebraic grades. For example, for scenario *S*.1.1, entering Eq. 5 with an algebraic difference in grades, A = 4%, a design speed, V = 100 km/h, and the corresponding stopping sight distance at this speed, SSD = 145 m, a minimum length of crest curve, or L equal to 80 m is calculated. This value may be rapidly checked by entering Fig. 10 with value of A = 4% for *S*.1.1. Similarly, Fig. 10 may be entered to solve for the minimum required lengths of crest curve for other scenarios or other algebraic differences in grades given a travel speed of 100 km/h.

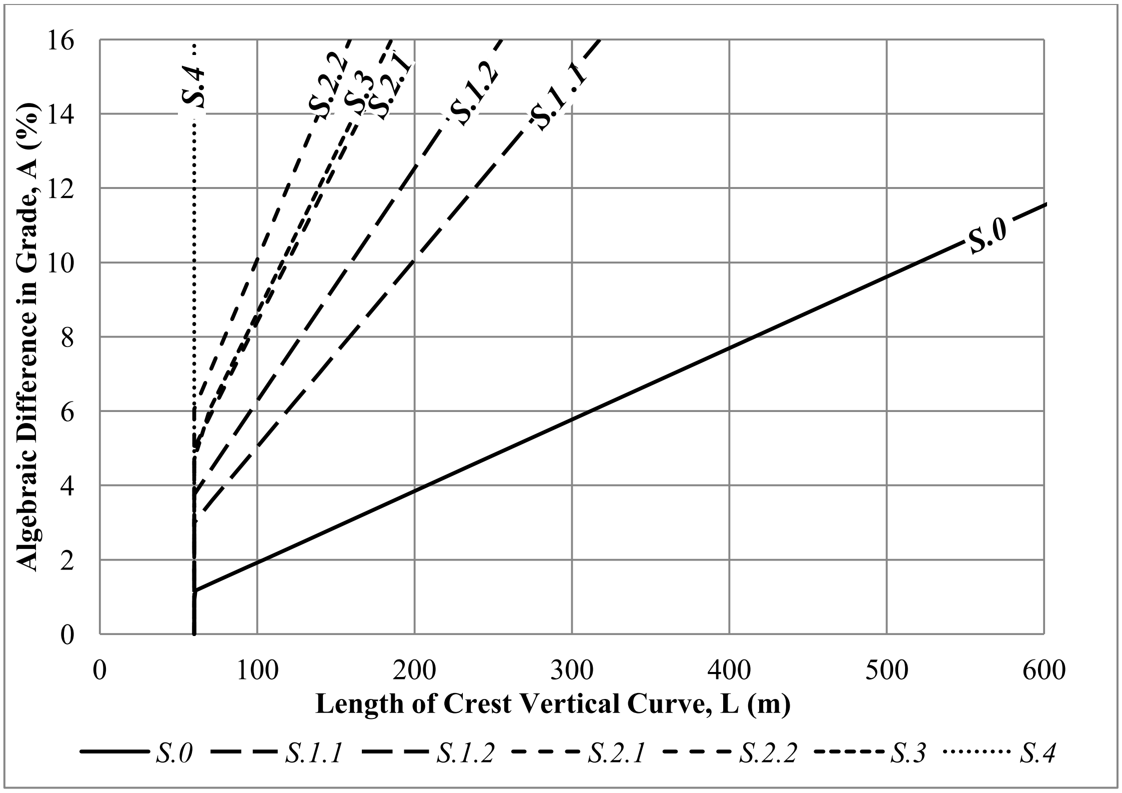


Figure 10: Minimum Recommended Lengths of Crest Curves for all Scenarios.

The crest vertical curve length recommendations for scenarios *S*.1.1, *S*.1.2, *S*.2.1, *S*.2.2, *S*.3 and *S*.4 equal 80. m, 64 m, 60 m, 60 m, 60 m and 60 m, respectively. Note the drastic reduction in crest curve length achieved relative to the customary AASHTO value of 208 m under *S*.0. The total anticipated reductions in curve lengths achieved by all scenarios in comparison with *S*.0 are summarized in Table 7. It is shown that reductions in minimum recommended curve length within the range of 130 m to 150 m or 60% to 70% are expected for this very likely combination of travel speed, 100 km/h, and percent difference in algebraic grades, 4%, on highways.

Fig. 11 presents specifically the newly recommended minimum lengths for sag curves under all road train scenarios at the specified values of speed and percent difference in algebraic grades. For example, for scenario *S*.1.1, entering Eq. 7 with an algebraic difference in grades, A = 4%, a design speed, V = 100 km/h, and the corresponding stopping sight distance at this speed, SSD = 145 m, a minimum length of sag curve, or L equal to 119 m is calculated. This value may be rapidly checked by entering Fig. 11 with value of A = 4% for S.1.1. Similarly, Fig. 11 may be entered to solve for the minimum required lengths of sag curve for other scenarios or other algebraic differences in grades given a travel speed of 100 km/h.

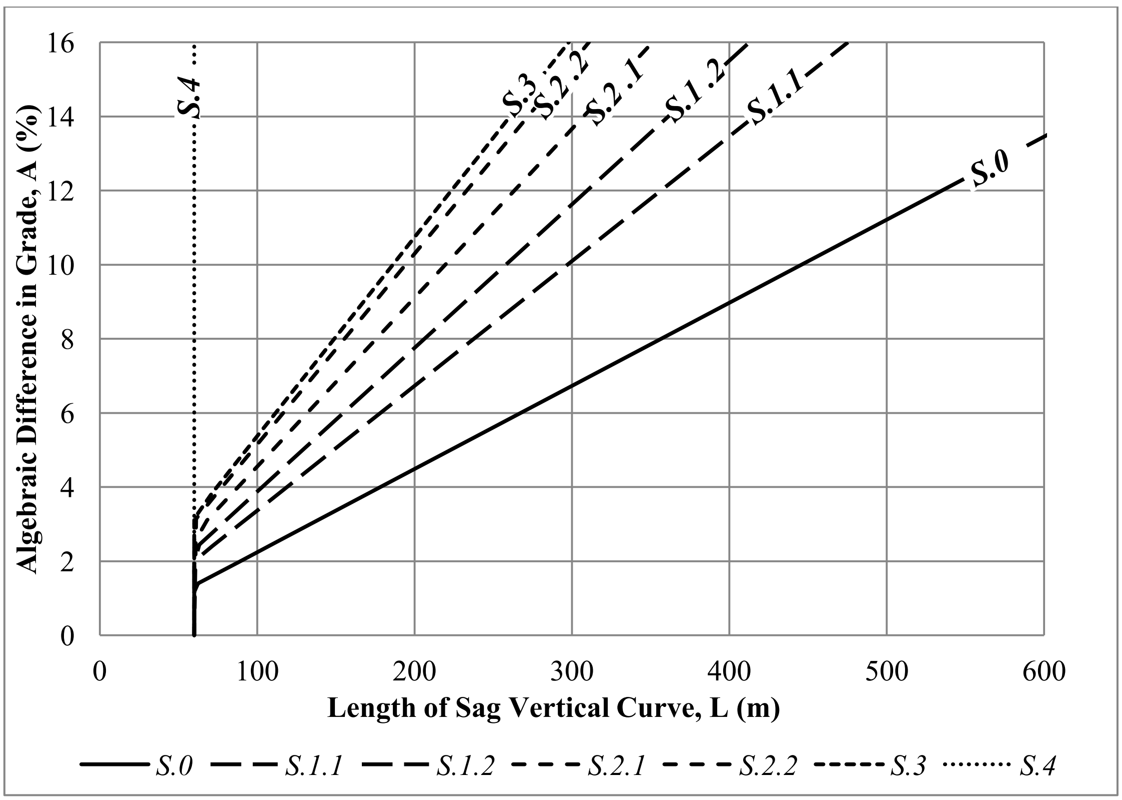


Figure 11: Minimum Recommended Lengths of Sag Curves for all Scenarios.

The sag vertical curve length recommendations for scenarios S.1.1, S.1.2, S.2.1, S.2.2, S.3 and S.4 equal 119 m, 106 m, 88 m, 78 m, 74.5 m and 60 m, respectively. Note the reductions in sag curve length achieved relative to the customary AASHTO value of 180 m under S.0. Here, overall reductions are not as drastic as for crest curves. Still, significant reductions in length ensue for the PATH-like and PATH-like with obstacle detection scenarios. The total anticipated reductions in curve lengths achieved by all scenarios in comparison with *S*.0 are summarized in Table 7. Reductions within the range of 60 m to 120 m and 40% to 67% are anticipated for sag curves for this very likely combination of driving speed, 100 km/h, and percent algebraic difference in grades on highways.

Fig. 12 depicts the newly calculated relationships between horizontal sight line offset and the radii of curves under all road train scenarios at the specified values of speed and percent difference in algebraic grades. For example, for scenario *S*.1.1, entering Eq. 8 with a horizontal sight line offset of 10 m and stopping sight distance at V = 100 km/h equal to SSD = 145 m, a minimum radius of horizontal curve, or R equal to 246 m is calculated. This value may be rapidly checked by entering Fig. 11 with value of HSO = 10 m for *S*.1.1. However, AASHTO provides a minimum radius equal to 328 m given V = 100 km/h and superelevation e = 12%, which supersedes that computed, 246 m, in this case. Similarly, Fig. 12 may be entered to solve for the minimum radii of horizontal curve for other scenarios and at other values of sight line offsets.

Given a horizontal sight line offset of 10 m, the recommended minimum radius of horizontal curve to be provided under scenarios *S*.1.1, *S*.1.2, *S*.2.1, *S*.2.2, *S*.3 and *S.4* all equal the absolute minimum curve radius, 328 m per AASHTO, 2011 as illustrated in Fig 12. For comparison purposes, the AASHTO customary value of 403 m, reflecting *S*.0, is also shown in Fig. 12. The total anticipated reductions in curve radius achieved by all scenarios in comparison to *S*.0 are summarized in Table 7. It can be seen that the reduction in radius associated with horizontal curves equal 79 m or 19%. The linear reduction would have to be multiplied by a factor of $\prod\Delta/180$ in absolute values to compute the reduction in minimum recommended curve lengths. For an average angle of 40 degrees, this factor equals approximately 0.7. Thus, not much in reduction of the minimum recommended lengths of curves is expected for horizontal curve design due to the high value of the minimum radius on curve. More can be gained if mechanisms could be found to stabilize the lateral movement on vehicles on curve (through enhanced side friction on wet pavement for instance) within road train designs and decrease the minimum radius of curve.

Table 7 summarizes below the total anticipated reductions in curve lengths and curve radii in percent as well as the reductions in *SSD* on curves for all the studied scenarios given 4% in algebraic grade difference, a traveling speed of 100 km/h and a deceleration rate of 4.5 m/s^2. All the road train scenarios contemplated quickly lead to the absolute minimum requirement for curve lengths, 60 m, 60 m, 328 m, for crest curves, sag curves and horizontal curves, respectively. This outstanding performance truly prevents comparisons between the various scenarios. For sag curves however, the absolute minimum length is only reached by the PATH-like satellite vision system. This system as anticipated performs overall as well or better than all other systems. Also, as expected, PATH outperforms SARTRE and the sub-scenarios of the both perform better at lower *PRT* values than at higher ones (where a comparison is enabled). However, the SARTRE-like scenario with obstacle detection comes close to performing as well as PATH-like scenarios. The high value of the absolute minimum requirement for horizontal curve radius truly prevents any outstanding gains in minimum recommended lengths of horizontal radii or in total curve lengths. To enable further gains, the limiting absolute values of minimum radii would have to drop significantly.

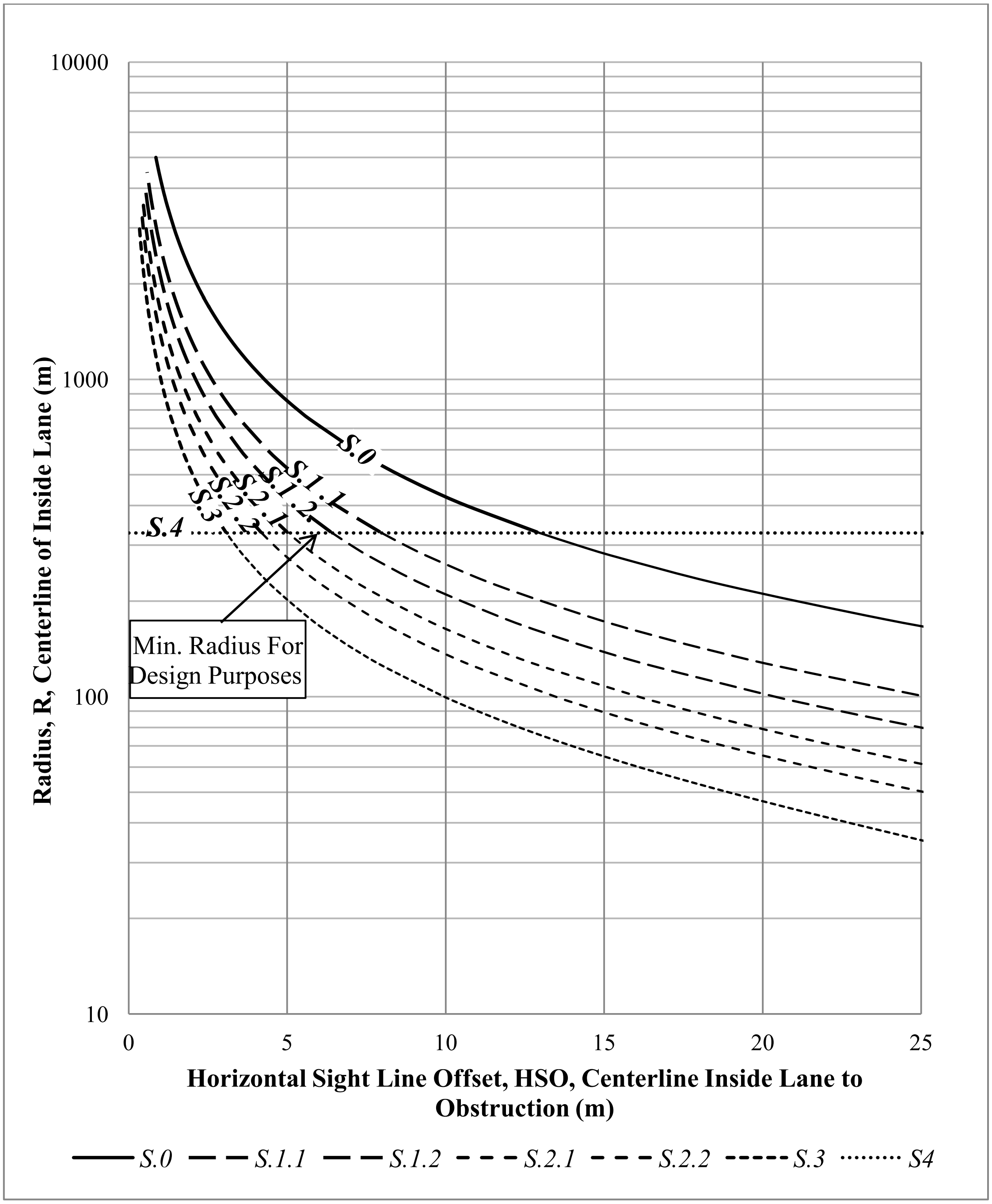


Figure 12: Minimum Recommended Radii for Horizontal Curves for all Scenarios.

Table 7: **Total Computed Reductions in Curve Lengths or Radii for *V* = 100 km/h per Scenario.**

	Scenario	Curve/Radius Length (m)	Radius/Length Reduction (m)	Radius/Length Reduction (%)
Crest Vertical Curve	***S*.0**	208	0	0
	***S*.1.1**	80	128	62
	***S*.1.2**	64	144	69
	***S*.2.1**	60	148	71
	***S*.2.2**	60	148	71
	***S*.3**	60	148	71
	***S*.4**	60	148	71
Sag Vertical Curve	***S*.0**	178	0	0
	***S*.1.1**	119	61	34
	***S*.1.2**	106	74	41
	***S*.2.1**	88	92	51
	***S*.2.2**	78	102	57
	***S*.3**	75	106	59
	***S*.4**	60	120	67
Horizontal Curve	***S*.0**	403	0	0
	***S*.1.1**	328	75	19
	***S*.1.2**	328	75	19
	***S*.2.1**	328	75	19
	***S*.2.2**	328	75	19
	***S*.3**	328	75	19
	***S*.4**	328	75	19

4.2. Impacts on Design Speeds

In order to limit this thesis' findings, horizontal sight line offset had to be fixed at 10 m while deriving road train impacts on design/travel speed. Other parameters remain at their same values, 100 km/h and 4% for speed and algebraic difference in grades, respectively. Findings on the allowable increase in design speed at other speed values can be found in Tables B-1 through B-9 under Appendix B.

Tables B-1, B-4 and B-7 in the Appendix B provide the newly derived design or maximum travel speeds on crest vertical curves as built to AASHTO, 2011 guidelines. For instance, assuming scenario *S*.3, in Table B-7, it is desired to calculate the speed at which vehicles could travel on a specific crest curve designed to the original AASHTO guidelines. Firstly, the sight distance on curve afforded to *S*.3 road trains is established. Hence, L = 208 m, corresponding to V = 100 km/h for AASHTO-like scenario *S*.0 and the design criteria for *S*.3 from Table 3 enter again Eq. 4 to solve for the available sight distance on curve, S = 191 m. Please note the slight increase in sight distance when compared to AASHTO's 184 m at 100 km/h.

Then, the speed for which required sight distance equals available sight distance is determined. Hence, obtained sight distance, S = 191 m enters Eq. 3 given *S*.3 design criteria, *PRT* = 0 s and a = 4.5 m/s^2, in order to find V' = 148 km/h. Note the enhancement in design speed as opposed to AASHTO's value of 100 km/h. It is verified that this speed does not exceed the maximum speed on crest curve per the prescribed absolute length of crest curve, $V_{max} = L/0.6$. Table B-7 in Appendix B displays both the maximum travel speed on crest curve per sight distance limitation and that per absolute minimum length of curve for *S*.3. In this case, the calculated speed per sight distance is retained, V' = 148 km/h.

Tables B-2, B-5 and B-8 in the Appendix B provide the newly derived design or maximum travel speeds on sag curves as built to AASHTO, 2011 guidelines. For instance, assuming scenario *S*.3, in Table B-7, it is desired to calculate the speed at which vehicles could travel on a specific crest curve designed to the original AASHTO guidelines. Firstly, the sight distance on sag curve afforded to *S*.3 road trains is established. Hence, L = 178 m, corresponding to V = 100 km/h for AASHTO-like scenario S.0 and the design criteria for S.3 from Table 3 enter again Eq. 4 to solve for the available sight distance on curve, S = 185 m.

Then, the speed for which required sight distance equals available sight distance is determined. Hence, obtained sight distance, S = 185 m enters Eq. 3 given S.3 design criteria, PRT = 0 s and a = 4.5 m/s^2, in order to find V' = 146 km/h. Note the enhancement in design speed as opposed to AASHTO's value of 100 km/h. It is verified that this speed does not exceed the maximum speed on sag curve per the prescribed absolute length of crest curve, $V_{\max} = L/0.6$. Table B-8 in Appendix B displays both the maximum travel speed on sag curve per sight distance limitation and that per absolute minimum length of curve for S.3. In this case, the calculated speed per sight distance is retained, V' = 146 km/h.

Tables B-3, B-6 and B-9 in the Appendix B provide the newly derived design or maximum travel speeds on horizontal curves as built to AASHTO, 2011 guidelines. For instance, assuming scenario S.3, it is desired to calculate the speed at which vehicles could travel on a specific horizontal curve designed to the original AASHTO guidelines. For this curve, R, HSO and S are fixed to a set value whether for regular car travel in S.0 or for road trains in S.3. To obtain the new travel speed on curve, the values of sight distance are set equal for both the scenarios, using the design criteria for these scenarios. One simplifying assumption sets HSO = 10 m, not to compute travel speed at all possible values of HSO.

The tabulated sight distance on curve for S.0, S = 184 m, at V = 100 km/h enters Eq. 8 to solve for the minimum recommended curve radius, R = 423 m, at this sight distance. Then, the speed at which the available sight distance on curve, S = 184 m, equals that required for an S.3 mode of operation is determined. Hence, S = 184 m and the design criteria for S.3 in Table 3, PRT = 0 s and a = 4.5 m/s², enter Eq. 3 to solve for a new speed equal to 146 km/h. Note the enhancement in design speed as opposed to AASHTO's value of 100 km/h. However, it is relevant to note that such a value of speed cannot be achieved if the minimum radius, R_{min}, at the newly computed speed exceeds that recommended by AASHTO, R, due to stability concerns. Hence, maximum absolute speed prevails over computed design, V_{max} = 111 km/h. Table B-9 displays the computed values of R, R_{min}, V' and V_{max} at all values of design speed by scenario S.3 road trains.

Similar approaches as above may be followed to recalculate the design speeds for crest, sag or horizontal curves assuming road train modes of operation and any combination of as-built design speed, algebraic difference in grades, horizontal sight line offsets. Table 8 shows increases in design speed, in km/h, on crest, sag and horizontal curves for all scenarios given the approach discussed in the methodology. In addition, the infinite driver's eyes height of S.4 removed sight distance as a design constraint and in essence results in maximum speeds on curves as described in Table 3.

Table 8: Total Computed Increase in Design Speed, in km/h, Given *S*.0 Curve Lengths or Radii for *V* = 100 km/h per Scenario.

	Scenario	Design Speed (km/h)	Design Speed Increase (km/h)	Design Speed Increase (%)
Crest Vertical Curve	***S*.0**	100	0	0
	***S*.1.1**	136	36	36
	***S*.1.2**	142	42	42
	***S*.2.1**	151	51	51
	***S*.2.2**	159	59	59
	***S*.3**	148	48	48
	***S*.4**	520	420	420
Sag Vertical Curve	***S*.0**	100	0	0
	***S*.1.1**	123	23	23
	***S*.1.2**	130	30	30
	***S*.2.1**	137	37	37
	***S*.2.2**	144	44	44
	***S*.3**	146	46	46
	***S*.4**	297	197	197
Horizontal Curve	***S*.0**	100	0	0
	***S*.1.1**	111	11	11
	***S*.1.2**	111	11	11
	***S*.2.1**	111	11	11
	***S*.2.2**	111	11	11
	***S*.3**	111	11	11
	***S*.4**	111	11	11

Overall, speed increases of up to 59% were obtained for crest vertical curves for scenario *S*.2.2. As commented above, as *S*.2.2 proved to be more length reduction-achieving than *S*.3 due to the great enhancement in driver's eyes height, greater increase in design speed was as well obtained. As for sag vertical curves, scenario *S*.3 achieved the greatest increase in design speed. However, the increase was not as substantial as for crest curves, still very potential, up to 46%. Horizontal curves, as expected, derived the least design speed increase of 11% for scenario *S*.3. Then, scenario *S*.4 resulted in absolute maximum travel speeds for crest and sag vertical curves but minimal for horizontal curves given stability concerns. Refer to Appendix B for a more specific review regarding design speed calculations.

Next study session, conclusions and recommendations, closes this thesis' work and presents concisely the achieved goals and importance of these newly computed guidelines for the geometric design of highways given road train operation on highways.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Global gas emission, reduction in highway construction costs and increase in driving safety have motivated the realization of this graduate master's thesis to explore the impacts of newly proposed and "what-if" road train modes of highway operation on the geometric design of highways. This thesis shows that existing highway can accommodate these new modes as well as result in significant reductions in the minimum lengths of crest curves and moderate overall reductions in sag curve lengths and horizontal curve radii/lengths.

An exhaustive literature review scrutinized the experimental modes of road train operations and the current guidelines on the geometric design of highways for vertical and horizontal curves. Experimental modes formed the basis of the provided discussion in addition to "what-if" scenarios. In total, 4 different road train experimental and "what-if" projects were investigated, for truck, passenger car, or mixed operations.

The methodology presented the changes in design criteria for the geometric design of highways, such as the reduced perception-reaction time, the enhanced deceleration rate, as well as the increased driver's eyes and light beam heights, associated with studied scenarios, including the do-nothing scenario based on AASHTO guidelines. As expected, the smaller the perception-reaction time, all other factors being unchanged within the same general scenario, the shorter the minimum recommended vertical curve length or horizontal curve radius. In spite of its lower vision system and headlight mounting height, PATH exceeds the performance of SARTRE in curve length reduction induced. However, a SARTRE-like scenario equipped with obstacle detection assisted vision system, seems to generate reductions in crest curve lengths tantamount to those of the fully automated PATH given a reduced level of complexity in obstacle recognition.

No single scenario has more potential to reduce curve length than a remote sensor vision assisted PATH-like scenario, whether passenger vehicle- or truck-led, as sight distance restrictions get lifted, and the absolute minimum recommendations prevail for vertical and horizontal curves. The incredible geometric design performance of this system makes its feasibility worth investigating.

Sensibility analyses may be conducted in the future in order to determine the impact that every parameter in the highway alignment guidelines may have. In the process of deriving scenarios, the author stumbled over a number of valid scenarios and adopted two as study subjects, the SARTRE-like scenario with Obstacle Warning System and the PATH-like scenario with Satellite Vision System. In the process, the author discounted three potentially valid scenarios, to limit the scope of the study while considering a wide breath of scenarios. They include: *PHH*, a passenger vehicle-led, human-driven (expert professional driver expected) with human vision scenario, *PHM*, a passenger lead, human-driven and machine vision (obstacle detection) assisted scenario and *TMM*, a truck-led, machine/autonomously driven and machine vision assisted scenario as well. The anticipation of these systems enables their scrutiny within the scope of other studies that may not relate to geometric design and is seen as a contribution to the state-of-the-art in road train deployment.

Hence, the pre-cited described changes entered the corresponding equations in order to derive newly computed relations between algebraic difference in grades and design speed on crest and sag vertical curves as well as newly derived relations between curve radii and design speeds on horizontal curves. New relations in turn resulted in substantial reductions of curve lengths, as well as reduction of curve radii—directly associated with curve lengths—in all studied scenarios, when keeping a limited number of parameters fixed including; (1) design speed on curves equal to 100 km/h, (2) algebraic difference in grades equal to 4% on vertical curves, and (3) horizontal sight line offset equal to 10 m. Maximum reductions in the range of 71%, 67% were computed for crest and sag vertical curve lengths, as well as 19% for horizontal curve radii.

This thesis anticipated too an increase in traveling speeds on roadway curves by reducing available and required minimum sight distances by back-calculating design speeds given the computed minimum length or radius of curve. More or less significant increases in design speed were obtained for all scenarios and types of curves. Speed increases of up to 59% were obtained for crest vertical curves, up to 46% for sag vertical curves and only 11% for horizontal curves, due to stability concerns. Then, removal of the sight distance constraint for *S*.4 derived further speed increases such as 420% for crest and 197% for sag vertical curves. Refer to Appendix B for a more specific review regarding design speed calculations.

It is hoped that the undertaken study may serve to guide the selection of road trains in any overall study where various cost or design advantageous or disadvantageous aspects of their deployment must be weighed. The current study constitutes a valuable guide in weighing the advantages of one system over the other with regards to geometric highway design. A method and an insight into assessing the advantages of varied transitory and of an end state or road train systems were provided. In general, this thesis has presented the total impacts of road trains on the geometric design of highways concerning mostly roadway alignment and sight distance concerns.

As any mixed operation on highways of human-driven and autonomous vehicles would render moot the positive contemplated impacts on the design of highways, this thesis recommends the separation of road train operation lanes from the passenger car traffic. By converting existing high occupancy vehicles (HOV) lanes into road train lanes, or incorporating such road train lanes into future highway projects, the benefits may be maximized. It is important to note that this thesis does not suggest the redesign of existing roads.

Although, the reduction in the cost of highways was considered beyond the scope of this thesis' work, literature indicated that shorter curves in general reduce the construction cost via reducing the required earthen work. Future studies will also extend to the assessment of the ensued reductions in construction cost, the potential increases in traffic capacities as well as the exact determination of the reductions in fuel consumption tied to road train operation.

APPENDIX A

Appendix A includes the tables that present the modified minimum lengths of curve for both crest and sag vertical curves as well as minimum curve radii for horizontal curves for all scenarios. Note that this appendix too comprises scenario *S*.0 with the corresponding AASHTO customary values for non-road train operation. Approaches to calculate such values were presented in the literature review in Eqs. 4, 6, and 8 for the design of crest, sag and horizontal curves, respectively.

Please note that blanks in tables corresponding to horizontal curve newly computed relations represent fluctuations in the cosine function that, in general, are not considered for design.

Table A-1: Computed Crest Curve Lengths in Meters for Scenario *S*.0 Given Various Operating Speeds and Grade Differences.

V	**A (%)**											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.6	22.3	26.1	29.8
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	30.4	38.0	45.6	53.2	60.8
50	30.0	30.0	30.0	30.0	30.0	30.0	38.5	51.4	64.2	77.1	89.9	102.7
60	36.0	36.0	36.0	36.0	36.0	43.9	65.9	87.8	109.8	131.8	153.7	175.7
70	42.0	42.0	42.0	42.0	42.0	67.0	100.5	134.0	167.6	201.1	234.6	268.1
80	48.0	48.0	48.0	48.0	51.4	102.7	154.1	205.5	256.8	308.2	359.6	410.9
90	54.0	54.0	54.0	54.0	77.8	155.6	233.4	311.2	389.1	466.9	544.7	622.5
100	60.0	60.0	60.0	60.0	104.0	208.1	312.1	416.1	520.1	624.2	728.2	832.2
110	66.0	66.0	66.0	73.6	147.1	294.2	441.3	588.4	735.6	882.7	1029.8	1176.9
120	72.0	72.0	72.0	95.0	190.0	379.9	569.9	759.9	949.8	1139.8	1329.8	1519.8
130	78.0	78.0	92.6	123.4	246.9	493.8	740.7	987.5	1234.4	1481.3	1728.2	1975.1

Table A-2: Computed Sag Curve Lengths in Meters for Scenario *S*.0 Given Various Operating Speeds and Grade Differences.

V	**A (%)**											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.6	16.8	21.1	25.3	29.5	33.7
30	18.0	18.0	18.0	18.0	18.0	20.2	30.3	40.4	50.5	60.6	70.7	80.8
40	24.0	24.0	24.0	24.0	24.0	33.9	50.8	67.8	84.7	101.7	118.6	135.6
50	30.0	30.0	30.0	30.0	30.0	48.6	72.9	97.3	121.6	145.9	170.2	194.5
60	36.0	36.0	36.0	36.0	36.0	69.2	103.8	138.4	173.1	207.7	242.3	276.9
70	42.0	42.0	42.0	42.0	45.2	90.5	135.7	180.9	226.2	271.4	316.6	361.8
80	48.0	48.0	48.0	48.0	58.8	117.6	176.3	235.1	293.9	352.7	411.5	470.3
90	54.0	54.0	54.0	54.0	75.3	150.6	225.9	301.2	376.5	451.8	527.1	602.4
100	60.0	60.0	60.0	60.0	89.2	178.4	267.6	356.7	445.9	535.1	624.3	713.5
110	66.0	66.0	66.0	66.0	108.8	217.5	326.3	435.1	543.8	652.6	761.3	870.1
120	72.0	72.0	72.0	72.0	125.6	251.3	376.9	502.5	628.1	753.8	879.4	1005.0
130	78.0	78.0	78.0	78.0	145.4	290.7	436.1	581.5	726.8	872.2	1017.6	1163.0

Table A-3: Computed Horizontal Sight Line Offset in Meters for Scenario $S.0$ Given Varying Operating Speeds and Curve Radii.

V	**R (m)**												
(km/h)	**1**	**10**	**20**	**30**	**40**	**50**	**100**	**150**	**200**	**500**	**1000**	**1500**	**5000**
20		4.6	2.4	1.7	1.2	1.0							
30			7.2	5.0	3.8	3.0	1.5	1.0					
40			13.7	9.8	7.6	6.1	3.1	2.1	1.6				
50			21.1	16.0	12.5	10.2	5.2	3.5	2.6	1.0			
60			30.5	25.4	20.5	17.0	8.9	6.0	4.5	1.6			
70			37.4	35.4	29.8	25.1	13.5	9.1	6.9	2.5	1.4		
80			39.9	46.8	42.2	36.6	20.4	13.9	10.5	3.8	2.1	1.4	
90					56.7	51.5	30.3	20.8	15.8	5.8	3.2	2.1	
100					67.0	63.8	39.8	27.6	21.0	7.8	4.3	2.9	
110						79.4	54.6	38.6	29.5	11.0	6.0	4.0	
120							68.5	49.1	37.8	14.1	7.8	5.2	
130							85.5	62.8	48.7	18.4	10.1	6.8	2.0

Table A-4: Computed Crest Curve Lengths in Meters for Scenario *S*.1.1 Given *PRT* = 2.0 s and h_1 = 2.33 m.

V	**A (%)**											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.4
50	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	33.3	38.1
60	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	40.2	48.3	56.3	64.4
70	42.0	42.0	42.0	42.0	42.0	42.0	42.0	55.0	68.8	82.6	96.3	110.1
80	48.0	48.0	48.0	48.0	48.0	48.0	57.1	76.2	95.2	114.3	133.3	152.4
90	54.0	54.0	54.0	54.0	54.0	59.5	89.3	119.0	148.8	178.6	208.3	238.1
100	60.0	60.0	60.0	60.0	60.0	80.1	120.1	160.2	200.2	240.3	280.3	320.4
110	66.0	66.0	66.0	66.0	66.0	110.1	165.1	220.2	275.2	330.3	385.3	440.4
120	72.0	72.0	72.0	72.0	72.4	144.9	217.3	289.7	362.1	434.6	507.0	579.4
130	78.0	78.0	78.0	78.0	92.2	184.4	276.6	368.8	461.0	553.1	645.3	737.5

Table A-5: Computed Crest Curve Lengths in Meters for Scenario *S*.1.2 Given *PRT* = 1.5 s and h_1 = 2.33 m.

V	A (%)											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
50	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.6
60	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	40.8	47.6	54.4
70	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.5	53.1	63.7	74.4	85.0
80	48.0	48.0	48.0	48.0	48.0	48.0	48.0	61.2	76.5	91.8	107.1	122.4
90	54.0	54.0	54.0	54.0	54.0	54.0	68.6	91.4	114.3	137.1	160.0	182.8
100	60.0	60.0	60.0	60.0	60.0	63.8	95.8	127.7	159.6	191.5	223.4	255.3
110	66.0	66.0	66.0	66.0	66.0	90.8	136.1	181.5	226.9	272.3	317.6	363.0
120	72.0	72.0	72.0	72.0	72.0	115.7	173.5	231.4	289.2	347.0	404.9	462.7
130	78.0	78.0	78.0	78.0	79.4	158.7	238.1	317.5	396.9	476.2	555.6	635.0

Table A-6: Computed Sag Curve Lengths in Meters for Scenario *S*.1.1 Given *PRT* = 2.0 s and h_3 = 1.0 m.

V	A (%)											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.5	14.3
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	21.7	26.1	30.4	34.8
40	24.0	24.0	24.0	24.0	24.0	24.0	28.2	37.6	47.1	56.5	65.9	75.3
50	30.0	30.0	30.0	30.0	30.0	30.0	40.0	53.3	66.7	80.0	93.3	106.7
60	36.0	36.0	36.0	36.0	36.0	39.5	59.3	79.1	98.8	118.6	138.4	158.1
70	42.0	42.0	42.0	42.0	42.0	58.1	87.1	116.2	145.2	174.3	203.3	232.4
80	48.0	48.0	48.0	48.0	48.0	72.7	109.1	145.5	181.8	218.2	254.5	290.9
90	54.0	54.0	54.0	54.0	54.0	98.0	147.1	196.1	245.1	294.1	343.1	392.2
100	60.0	60.0	60.0	60.0	60.0	118.9	178.3	237.7	297.2	356.6	416.0	475.5
110	66.0	66.0	66.0	66.0	72.7	145.4	218.1	290.8	363.5	436.2	508.9	581.6
120	72.0	72.0	72.0	72.0	86.2	172.4	258.5	344.7	430.9	517.1	603.2	689.4
130	78.0	78.0	78.0	78.0	99.8	199.6	299.4	399.2	499.0	598.8	698.6	798.4

Table A-7: Computed Sag Curve Lengths in Meters for Scenario *S*.1.2 Given *PRT* = 1.5 s and h_3 = 1.0 m.

V	**A (%)**											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.5	14.3
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	21.7	26.1	30.4	34.8
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	30.4	38.0	45.6	53.2	60.8
50	30.0	30.0	30.0	30.0	30.0	30.0	34.0	45.3	56.6	68.0	79.3	90.6
60	36.0	36.0	36.0	36.0	36.0	36.0	52.7	70.2	87.8	105.4	122.9	140.5
70	42.0	42.0	42.0	42.0	42.0	48.6	73.0	97.3	121.6	145.9	170.3	194.6
80	48.0	48.0	48.0	48.0	48.0	62.9	94.4	125.8	157.3	188.7	220.2	251.7
90	54.0	54.0	54.0	54.0	54.0	82.7	124.1	165.5	206.8	248.2	289.6	330.9
100	60.0	60.0	60.0	60.0	60.0	103.2	154.8	206.4	258.0	309.6	361.2	412.8
110	66.0	66.0	66.0	66.0	66.0	129.4	194.1	258.9	323.6	388.3	453.0	517.7
120	72.0	72.0	72.0	72.0	75.4	150.8	226.2	301.5	376.9	452.3	527.7	603.1
130	78.0	78.0	78.0	78.0	91.6	183.2	274.8	366.4	458.0	549.6	641.3	732.9

Table A-8: Computed Horizontal Sight Line Offsets in Meters for Scenario *S*.1.1 Given *PRT* = 2.0 s.

V	**R (m)**												
(km/h)	**1**	**10**	**20**	**30**	**40**	**50**	**100**	**150**	**200**	**500**	**1000**	**1500**	**5000**
20			2.4	1.7									
30			3.8	2.6	1.9	1.6							
40			9.2	6.4	4.9	3.9	2.0						
50			13.7	9.8	7.6	6.1	3.1	2.1	1.4				
60			21.1	16.0	12.5	10.2	5.2	3.5	2.3				
70			30.5	25.4	20.5	17.0	8.9	6.0	4.0	1.6			
80			36.0	32.9	27.4	23.0	12.2	8.3	5.5	2.3	1.2		
90				44.7	39.7	34.2	18.9	12.8	8.6	3.5	2.0	1.3	
100				52.5	49.6	44.0	25.2	17.2	11.6	4.8	2.6	1.8	
110					61.1	56.4	34.0	23.4	15.9	6.6	3.6	2.4	
120					70.5	68.5	43.9	30.6	20.8	8.6	4.8	3.2	
130						79.4	54.6	38.6	26.4	11.0	6.0	4.0	1.2

Table A-9: Computed Horizontal Sight Line Offsets in Meters for Scenario *S*.1.2 Given *PRT* = 1.5 s.

V	**R (m)**												
(km/h)	**1**	**10**	**20**	**30**	**40**	**50**	**100**	**150**	**200**	**500**	**1000**	**1500**	**5000**
20			1.4										
30			3.8	2.6	1.9	1.6							
40			7.2	5.0	3.8	3.0	1.5						
50			11.4	8.1	6.2	5.0	2.5	1.7	1.1				
60			18.6	13.8	10.7	8.7	4.5	3.0	2.0				
70			26.0	20.5	16.3	13.4	7.0	4.7	3.1	1.3			
80			32.6	27.9	22.8	18.9	10.0	6.7	4.5	1.8	1.0		
90			38.5	37.8	32.2	27.3	14.7	10.0	6.7	2.7	1.5	1.0	
100				46.8	42.2	36.6	20.4	13.9	9.3	3.8	2.1	1.4	
110					54.3	49.0	28.6	19.6	13.2	5.5	3.0	2.0	
120					63.1	58.9	35.9	24.8	16.8	6.9	3.8	2.6	
130						73.1	48.1	33.7	22.9	9.5	5.2	3.5	1.1

Table A-10: Computed Crest Curve Lengths in Meters for Scenario *S*.2.1 Given $PRT = 1.0$ s and $h_1 = 2.5$ m.

V	A (%)											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
50	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
60	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
70	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	45.7	53.3	60.9
80	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	57.7	69.2	80.7	92.3
90	54.0	54.0	54.0	54.0	54.0	54.0	54.1	72.1	90.1	108.1	126.1	144.2
100	60.0	60.0	60.0	60.0	60.0	60.0	71.5	95.3	119.2	143.0	166.8	190.6
110	66.0	66.0	66.0	66.0	66.0	70.6	106.0	141.3	176.6	211.9	247.2	282.5
120	72.0	72.0	72.0	72.0	72.0	92.3	138.4	184.5	230.7	276.8	322.9	369.0
130	78.0	78.0	78.0	78.0	78.0	123.3	185.0	246.7	308.4	370.0	431.7	493.4

Table A-11: Computed Crest Curve Lengths in Meters for Scenario *S*.2.2 Given *PRT* = 0.5 s and h_1 = 2.5 m.

V	**A (%)**											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
50	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
60	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
70	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	43.6
80	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	53.0	61.8	70.6
90	54.0	54.0	54.0	54.0	54.0	54.0	54.0	54.0	65.1	78.1	91.1	104.2
100	60.0	60.0	60.0	60.0	60.0	60.0	60.0	79.5	99.3	119.2	139.1	158.9
110	66.0	66.0	66.0	66.0	66.0	66.0	84.5	112.6	140.8	168.9	197.1	225.2
120	72.0	72.0	72.0	72.0	72.0	75.8	113.7	151.5	189.4	227.3	265.2	303.1
130	78.0	78.0	78.0	78.0	78.0	98.1	147.2	196.2	245.3	294.4	343.4	392.5

Table A-12: Computed Sag Curve Lengths in Meters for Scenario *S*.2.1 with *PRT* = 1.0 s and h_1 = 2.5 m.

V	A (%)											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	20.7	23.7
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	26.1	30.4	34.8
50	30.0	30.0	30.0	30.0	30.0	30.0	30.0	37.6	47.1	56.5	65.9	75.3
60	36.0	36.0	36.0	36.0	36.0	36.0	40.0	53.3	66.7	80.0	93.3	106.7
70	42.0	42.0	42.0	42.0	42.0	42.0	59.3	79.1	98.8	118.6	138.4	158.1
80	48.0	48.0	48.0	48.0	48.0	53.3	80.0	106.7	133.3	160.0	186.7	213.3
90	54.0	54.0	54.0	54.0	54.0	72.7	109.1	145.5	181.8	218.2	254.5	290.9
100	60.0	60.0	60.0	60.0	60.0	87.8	131.7	175.6	219.5	263.4	307.3	351.2
110	66.0	66.0	66.0	66.0	66.0	113.6	170.4	227.2	284.1	340.9	397.7	454.5
120	72.0	72.0	72.0	72.0	72.0	134.7	202.1	269.5	336.8	404.2	471.6	538.9
130	78.0	78.0	78.0	78.0	80.8	161.5	242.3	323.1	403.8	484.6	565.4	646.1

Table A-13: Computed Sag Curve Lengths in Meters for Scenario *S*.2.2 with *PRT* = 0.5 s and h_1 = 2.5 m.

V	A (%)											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
50	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	35.4	41.3	47.2
60	36.0	36.0	36.0	36.0	36.0	36.0	36.0	37.6	47.1	56.5	65.9	75.3
70	42.0	42.0	42.0	42.0	42.0	42.0	46.2	61.7	77.1	92.5	107.9	123.3
80	48.0	48.0	48.0	48.0	48.0	48.0	66.1	88.1	110.1	132.1	154.2	176.2
90	54.0	54.0	54.0	54.0	54.0	58.1	87.1	116.2	145.2	174.3	203.3	232.4
100	60.0	60.0	60.0	60.0	60.0	77.7	116.6	155.4	194.3	233.1	272.0	310.8
110	66.0	66.0	66.0	66.0	66.0	98.0	147.1	196.1	245.1	294.1	343.1	392.2
120	72.0	72.0	72.0	72.0	72.0	118.9	178.3	237.7	297.2	356.6	416.0	475.5
130	78.0	78.0	78.0	78.0	78.0	140.1	210.1	280.1	350.2	420.2	490.2	560.3

Table A-14: Computed Horizontal Sight Line Offsets in Meters for Scenario *S*.2.1 Given *PRT* = 1.0 s.

V	**R (m)**												
(km/h)	**1**	**10**	**20**	**30**	**40**	**50**	**100**	**150**	**200**	**500**	**1000**	**1500**	**5000**
20													
30			2.4	1.7	1.2	1.0							
40			3.8	2.6	1.9	1.6							
50			9.2	6.4	4.9	3.9	2.0	1.3					
60			13.7	9.8	7.6	6.1	3.1	2.1	1.4				
70			21.1	16.0	12.5	10.2	5.2	3.5	2.3	1.0			
80			28.3	22.9	18.4	15.2	7.9	5.3	3.5	1.5			
90			36.0	32.9	27.4	23.0	12.2	8.3	5.5	2.3	1.2		
100				40.2	34.7	29.6	16.1	10.9	7.3	3.0	1.7	1.1	
110					47.1	41.5	23.5	16.0	10.8	4.4	2.4	1.6	
120					56.7	51.5	30.3	20.8	14.1	5.8	3.2	2.1	
130						63.8	39.8	27.6	18.8	7.8	4.3	2.9	

Table A-15: Computed Horizontal Sight Line Offsets in Meters for Scenario *S*.2.2 Given *PRT* = 0.5 s.

V	R (m)												
(km/h)	**1**	**10**	**20**	**30**	**40**	**50**	**100**	**150**	**200**	**500**	**1000**	**1500**	**5000**
20													
30			1.4	0.9									
40			2.4	1.7	1.2	1.0							
50			5.4	3.7	2.8	2.2	1.1						
60			9.2	6.4	4.9	3.9	2.0	1.3					
70			16.1	11.7	9.1	7.4	3.8	2.5	1.7				
80			23.6	18.2	14.4	11.8	6.1	4.1	2.7	1.1			
90			30.5	25.4	20.5	17.0	8.9	6.0	4.0	1.6			
100				35.4	29.8	25.1	13.5	9.1	6.1	2.5	1.4		
110					39.7	34.2	18.9	12.8	8.6	3.5	2.0	1.3	
120					49.6	44.0	25.2	17.2	11.6	4.8	2.6	1.8	
130						54.0	32.1	22.1	15.0	6.2	3.4	2.3	

Table A-16: Computed Crest Curve Lengths in Meters for Scenario *S*.3 Given *PRT* = 0 s and h_1 = 1.20 m.

V	A (%)											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
50	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
60	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
70	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	42.0	46.3
80	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	51.5	61.8	72.1	82.4
90	54.0	54.0	54.0	54.0	54.0	54.0	54.0	64.3	80.4	96.5	112.6	128.7
100	60.0	60.0	60.0	60.0	60.0	60.0	69.5	92.6	115.8	139.0	162.1	185.3
110	66.0	66.0	66.0	66.0	66.0	66.0	94.6	126.1	157.6	189.2	220.7	252.2
120	72.0	72.0	72.0	72.0	72.0	89.4	134.0	178.7	223.4	268.1	312.8	357.4
130	78.0	78.0	78.0	78.0	78.0	128.7	193.0	257.4	321.7	386.0	450.4	514.7

Table A-17: Computed Sag Curve Lengths in Meters for Scenario *S*.3 Given *PRT* = 0 s and h_3 = 0.6 m.

V	**A (%)**											
(km/h)	**0**	**0.5**	**0.75**	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
30	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
40	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
50	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.1	36.1	42.2	48.2
60	36.0	36.0	36.0	36.0	36.0	36.0	36.0	40.4	50.5	60.6	70.7	80.8
70	42.0	42.0	42.0	42.0	42.0	42.0	43.8	58.4	73.0	87.6	102.2	116.8
80	48.0	48.0	48.0	48.0	48.0	48.0	65.5	87.3	109.1	130.9	152.7	174.5
90	54.0	54.0	54.0	54.0	54.0	58.8	88.2	117.6	147.1	176.5	205.9	235.3
100	60.0	60.0	60.0	60.0	60.0	74.5	111.7	149.0	186.2	223.4	260.7	297.9
110	66.0	66.0	66.0	66.0	66.0	90.5	135.7	180.9	226.2	271.4	316.6	361.8
120	72.0	72.0	72.0	72.0	72.0	112.1	168.2	224.2	280.3	336.3	392.4	448.4
130	78.0	78.0	78.0	78.0	78.0	139.5	209.3	279.1	348.8	418.6	488.4	558.1

Table A-18: Computed Horizontal Sight Line Offsets in Meters for Scenario *S*.3 given *PRT* = 0 s.

V	R (m)												
(km/h)	**1**	**10**	**20**	**30**	**40**	**50**	**100**	**150**	**200**	**500**	**1000**	**1500**	**5000**
20													
30													
40			1.4	0.9									
50			3.8	2.6	1.9	1.6							
60			7.2	5.0	3.8	3.0	1.5	1.0					
70			11.4	8.1	6.2	5.0	2.5	1.7	1.1				
80			18.6	13.8	10.7	8.7	4.5	3.0	2.0				
90			26.0	20.5	16.3	13.4	7.0	4.7	3.1	1.3			
100				27.9	22.8	18.9	10.0	6.7	4.5	1.8	1.0		
110					29.8	25.1	13.5	9.1	6.1	2.5	1.4		
120					39.7	34.2	18.9	12.8	8.6	3.5	2.0	1.3	
130						46.5	26.8	18.4	12.4	5.1	2.8	1.9	

APPENDIX B

Appendix B consists of Tables B-1 to B-9 that present the results obtained from the speed back-calculations for the studied types of curves under all scenarios. As presented in the methodology, available sight distances, S, are back-calculated from Eqs. 4, and 6, corresponding to crest, and sag vertical curves, respectively, given the AASHTO minimum lengths of curves, L, recommended at different values of speed and the control criteria for each individual road train scenario. Then, the newly obtained S values enter Eq. 3 to determine the maximum speeds at which the driver may be traveling for each road train mode of operation.

A slightly different approach was followed to find the increase in design speed at which vehicles can travel on horizontal curves. A fixed criterion of HSO = 10 m and studied values of S corresponding to reviewed values of the design speed, V, enter Eq. 8, to solve for horizontal curve radii, R. Then, maximum design speed was back-calculated from Eq. 3 based on control criteria for each individual road train scenario.

Approaches followed to compute such enhancement in design speed were described in the methodology for crest (Tables B-1, B-4, and B-7), and sag (Tables B-2, B-5, and B-8) vertical curves for an algebraic difference in grade equal to 4 %. Please note that such values are depicted in the column named V'. The speed values in the V_{max} column correspond to minimum curve length requirements, per relationship $L = 0.6V$, or in this case, $V_{max} = L/0.6$. Then, the bold values in V_{max} column depict where previously computed L values were less than L_{min}, thus V' was left as it is without any kind of enhancement to be contemplated. Then, when computed L values were greater than L_{min}, speed increases were achieved, which are shown in the bold values in column *V'*.

Table B-1 depicts the design speed back-calculation for a crest curve for scenarios *S*.1.1 and *S*.1.2. AASHTO minimum required lengths of crest curve, L, are presented in *L* column for *A* = 4%. Then, *L* values enter Eq. 4 to back-calculate stopping sight distances, *S*. Note that criteria corresponding to each scenario were introduced in Table 3. Obtained *S* values enter Eq. 3 given scenario specific criteria to finally solve for an enhanced design speed, *V'*. Please note that *S* values were not rounded up to multiples of 5 m.

More specifically, in Table B-1 for scenario S.1.1, the AASHTO minimum required crest curve length, *L*, of 208 m, Table A-1, corresponding to an initial *V* = 100 km/h and *A* = 4%, enters Eq. 4 to solve for sight distance, *S*, which equals 235 m. Then, obtained sight distance, *S* = 235 m enters Eq. 3 given *PRT* = 2.0 s and *a* = 4.5 m/s^2 as further described in Table 3 for scenario *S*.1.1 in order to find *V'* = 136 km/h. Note the enhancement in design speed as opposed to AASHTO's value of 100 km/h. The same approach was followed to compute the design speed increase on sag vertical curves, for example in Table B-2, using the corresponding equation, that is, Eq. 6. Then, an enhanced design speed was obtained from Eq. 3, as described previously.

As for horizontal curves (Tables B-3, B-6, and B-9), a fixed horizontal sight line offset, *HSO*, equal to 10 m was selected to find the increase in design speeds. Please note that such values are depicted in the column named *V'*. Minimum recommended radii, *R*, were found at all values of speeds given *HSO* = 10 m. Please note that blanks in this column *R* depict non-meeting points of the two conditions *HSO* equal to 10 m and those specific values of the design speed, V, equal to 20 and 30 km/h. Then, absolute R_{min} values, as dictated by AASHTO guidelines, were found given the newly derived design speeds. As long as the newly derived minimum radii, R_{min}, exceed those advocated by AASHTO, R, computed speeds may be achieved; meaning that the centripetal acceleration will be resisted. However, when R_{min} is greater than computed R, such computed V' values will not be achieved and V_{max} will prevail (depicted in bold under column V_{max}). Italicized values under column R_{min} represent those values where an extrapolation was found to be challenging given that AASHTO does not provide design guidelines for design speed values greater than 130 km/h.

Table B-3 depicts the design speed back-calculation for a horizontal curve for scenarios *S*.1.1 and *S*.1.2. AASHTO minimum required sight distances, S, are presented in S column for design criteria PRT = 2.5 s and a = 3.4 m/s². Note that criteria corresponding to each scenario were introduced in Table 3. Then, S values enter Eq. 3 to finally solve for an enhanced design speed, V'. Further columns include R, corresponding to horizontal sight line offsets equal to HSO = 10 m at all values of design speed, as well as R_{min}, exceeding at all times those radii, R, corresponding to HSO = 10 m. Please note that S values were not rounded up to multiples of 5 m.

More specifically, in Table B-3 for scenario S.1.1, given fixed criterion HSO = 10 m, the AASHTO minimum required sight distance, S, of 184 m, corresponding to an initial V = 100 km/h, enters Eq. 3 m given PRT = 2.0 s and a = 4.5 m/s^2 as described in Table 3 for scenario *S*.1.1 in order to find V' = 117 km/h, that exceeds V_{max}, thus V_{max} = 111 km/h prevails. Note the enhancement in design speed as opposed to AASHTO's value of 100 km/h.

Table B-1: Back-Calculations of the Design Speed in km/h for Crest Curve for Scenarios *S*.1.1 and *S*.1.2 Given *A* = 4%.

a) *S*.1.1

V	**L**	**S**	**V'**	**V_{max}**
(km/h)	**(m)**	**(m)**	**(km/h)**	**(km/h)**
20	12	56	55	**20**
30	18	69	63	**30**
40	24	80	69	**40**
50	30	89	74	**50**
60	44	108	**84**	73
70	67	133	**96**	112
80	103	165	**110**	171
90	156	203	**124**	259
100	208	235	**136**	347
110	294	279	**150**	490
120	380	317	**162**	633
130	494	362	**175**	823

b) *S*.1.2

V	**L**	**S**	**V'**	**V_{max}**
(km/h)	**(m)**	**(m)**	**(km/h)**	**(km/h)**
20	12	56	60	**20**
30	18	69	68	**30**
40	24	80	75	**40**
50	30	89	80	**50**
60	44	108	**90**	73
70	67	133	**102**	112
80	103	165	**116**	171
90	156	203	**131**	259
100	208	235	**142**	347
110	294	279	**157**	490
120	380	317	**169**	633
130	494	362	**182**	823

Table B-2: Back-Calculations of the Design Speed in km/h for Sag Curve for Scenarios *S*.1.1 and *S*.1.2 Given *A* = 4%.

a) *S*.1.1

V	**L**	**S**	**V'**	**V_{max}**
(km/h)	**(m)**	**(m)**	**(km/h)**	**(km/h)**
20	12	30	35	**20**
30	20	42	**44**	34
40	34	59	**56**	56
50	49	75	**66**	81
60	69	96	**78**	115
70	90	118	**89**	151
80	118	144	**101**	196
90	151	175	**114**	251
100	178	201	**123**	297
110	218	236	**136**	363
120	251	267	**146**	419
130	291	302	**157**	485

b) *S*.1.2

V	**L**	**S**	**V'**	**V_{max}**
(km/h)	**(m)**	**(m)**	**(km/h)**	**(km/h)**
20	12	30	40	**20**
30	20	42	**49**	34
40	34	59	**62**	56
50	49	75	**72**	81
60	69	96	**84**	115
70	90	118	**95**	151
80	118	144	**107**	196
90	151	175	**120**	251
100	178	201	**130**	297
110	218	236	**143**	363
120	251	267	**153**	419
130	291	302	**164**	485

Table B-3: Back-Calculations of the Design Speed in km/h for Horizontal Curve for Scenarios *S*.1.1 and *S*.1.2 Given *HSO* =10 m.

a) *S*.1.1

V	**S**	**R**	**V'**	$\mathbf{R_{min}}$	$\mathbf{V_{max}}$
(km/h)	**(m)**	**(m)**	**(km/h)**	**(m)**	**(m)**
20	18		24	10	
30	31		36	27	
40	46	25	48	56	35
50	63	49	59	95	45
60	83	84	71	147	57
70	105	136	82	208	69
80	129	206	94	283	**82**
90	155	300	106	375	**96**
100	184	423	117	502	**111**
110	215	578	129	649	**123**
120	249	771	140	*817*	**136**
130	284	1008	152	*1019*	**148**

b) *S*.1.2

V	**S**	**R**	**V'**	$\mathbf{R_{min}}$	$\mathbf{V_{max}}$
(km/h)	**(m)**	**(m)**	**(km/h)**	**(m)**	**(m)**
20	18		28	15	
30	31		41	37	
40	46	25	53	72	35
50	63	49	65	118	45
60	83	84	77	176	57
70	105	136	89	245	69
80	129	206	100	330	**82**
90	155	300	112	437	**96**
100	184	423	124	584	**111**
110	215	578	135	*741*	**123**
120	249	771	147	*930*	**136**
130	284	1008	159	*1156*	**147**

Table B-4: Back-Calculations of the Design Speed in km/h for Crest Curve for Scenarios *S*.2.1 and *S*.2.2 Given *A* = 4%.

a) *S*.2.1

V	**L**	**S**	**V'**	$\mathbf{V_{max}}$
(km/h)	**(m)**	**(m)**	**(km/h)**	**(km/h)**
20	12	58	67	**20**
30	18	71	76	**30**
40	24	82	82	**40**
50	30	91	88	**50**
60	44	110	**98**	73
70	67	136	**110**	112
80	103	169	**124**	171
90	156	208	**140**	259
100	208	240	**151**	347
110	294	286	**166**	490
120	380	325	**178**	633
130	494	370	**191**	823

b) *S*.2.2

V	**L**	**S**	**V'**	$\mathbf{V_{max}}$
(km/h)	**(m)**	**(m)**	**(km/h)**	**(km/h)**
20	12	58	74	**20**
30	18	71	83	**30**
40	24	82	89	**40**
50	30	91	95	**50**
60	44	110	**105**	73
70	67	136	**118**	112
80	103	169	**132**	171
90	156	208	**147**	259
100	208	240	**159**	347
110	294	286	**174**	490
120	380	325	**186**	633
130	494	370	**199**	823

Table B-5: Back-Calculations of the Design Speed in km/h for Sag Curve for Scenarios *S*.2.1 and *S*.2.2 Given *A* = 4%.

a) *S*.2.1

V (km/h)	L (m)	S (m)	V' (km/h)	V_{max} (km/h)
20	12	30	45	**20**
30	20	42	**55**	34
40	34	59	**68**	56
50	49	75	**78**	81
60	69	96	**91**	115
70	90	118	**102**	151
80	118	144	**114**	196
90	151	175	**127**	251
100	178	201	**137**	297
110	218	236	**150**	363
120	251	267	**160**	419
130	291	302	**171**	485

b) *S*.2.2

V (km/h)	L (m)	S (m)	V' (km/h)	V_{max} (km/h)
20	12	30	52	**20**
30	20	42	**62**	34
40	34	59	**75**	56
50	49	75	**85**	81
60	69	96	**98**	115
70	90	118	**109**	151
80	118	144	**121**	196
90	151	175	**134**	251
100	178	201	**144**	297
110	218	236	**157**	363
120	251	267	**168**	419
130	291	302	**179**	485

Table B-6: Back-Calculations of the Design Speed in km/h for Horizontal Curve for Scenarios *S*.2.1 and *S*.2.2 Given *HSO* = 10 m.

a) *S*.2.1

V	**S**	**R**	**V'**	$\mathbf{R_{min}}$	$\mathbf{V_{max}}$
(km/h)	**(m)**	**(m)**	**(km/h)**	**(m)**	**(m)**
20	18		33	22	
30	31		46	51	
40	46	25	59	93	34
50	63	49	71	148	45
60	83	84	83	212	57
70	105	136	95	291	69
80	129	206	107	387	**82**
90	155	300	119	524	**97**
100	184	423	131	*674*	**111**
110	215	578	142	*851*	**123**
120	249	771	154	*1063*	**136**
130	284	1008	166	*1317*	**148**

b) *S*.2.2

V	**S**	**R**	**V'**	$\mathbf{R_{min}}$	$\mathbf{V_{max}}$
(km/h)	**(m)**	**(m)**	**(km/h)**	**(m)**	**(m)**
20	18		39	33	
30	31		52	71	
40	46	25	65	121	34
50	63	49	78	182	45
60	83	84	90	256	57
70	105	136	102	346	69
80	129	206	114	464	**83**
90	155	300	126	615	**97**
100	184	423	138	*781*	**111**
110	215	578	150	*980*	**123**
120	249	771	162	*1219*	**136**
130	284	1008	173	*1508*	**148**

Table B-7: Back-Calculations of the Design Speed in km/h for Crest Curve for Scenario *S*.3 Given *A* = 4%.

V	L	S	V'	V_{max}
(km/h)	(m)	(m)	(km/h)	(km/h)
20	12	46	73	**20**
30	18	56	80	**30**
40	24	65	86	**40**
50	30	72	91	**50**
60	44	88	**101**	73
70	67	108	**112**	112
80	103	134	**124**	171
90	156	165	**138**	259
100	208	191	**148**	347
110	294	227	**162**	490
120	380	258	**172**	633
130	494	294	**184**	823

Table B-8: Back-Calculations of the Design Speed in km/h for Sag Curve for Scenario *S*.3 Given *A* = 4%.

V	L	S	V'	V_{max}
(km/h)	(m)	(m)	(km/h)	(km/h)
20	12	25	54	**20**
30	20	35	**64**	34
40	34	50	**76**	56
50	49	65	**87**	81
60	69	85	**99**	115
70	90	105	**110**	151
80	118	130	**122**	196
90	151	160	**136**	251
100	178	185	**146**	297
110	218	220	**159**	363
120	251	250	**170**	419
130	291	285	**181**	485

Table B-9: Back-Calculations of the Design Speed in km/h for Horizontal Curve for Scenario *S*.3 Given *HSO* = 10 m.

V	**S**	**R**	**V'**	**R_{min}**	**V_{max}**
(km/h)	**(m)**	**(m)**	**(km/h)**	**(m)**	**(m)**
20	18		46	52	
30	31		60	98	
40	46	25	73	157	34
50	63	49	86	226	45
60	83	84	98	311	57
70	105	136	110	414	69
80	129	206	122	564	**83**
90	155	300	134	*673*	**97**
100	184	423	146	*909*	**111**
110	215	578	158	*1134*	**123**
120	249	771	169	*1406*	**136**
130	284	1008	181	*1734*	**147**

APPENDIX C

Appendix C includes Fig. C-1, developed by Zabat et al in 1995, which shows general decreases in fuel consumption for platooning vehicles in highway operation. Up to 25 percent reduction can be achieved when more than 3 vehicles form the platoon as well as when the gap distance between vehicles is reduced to 0.25 spacing in vehicle lengths.

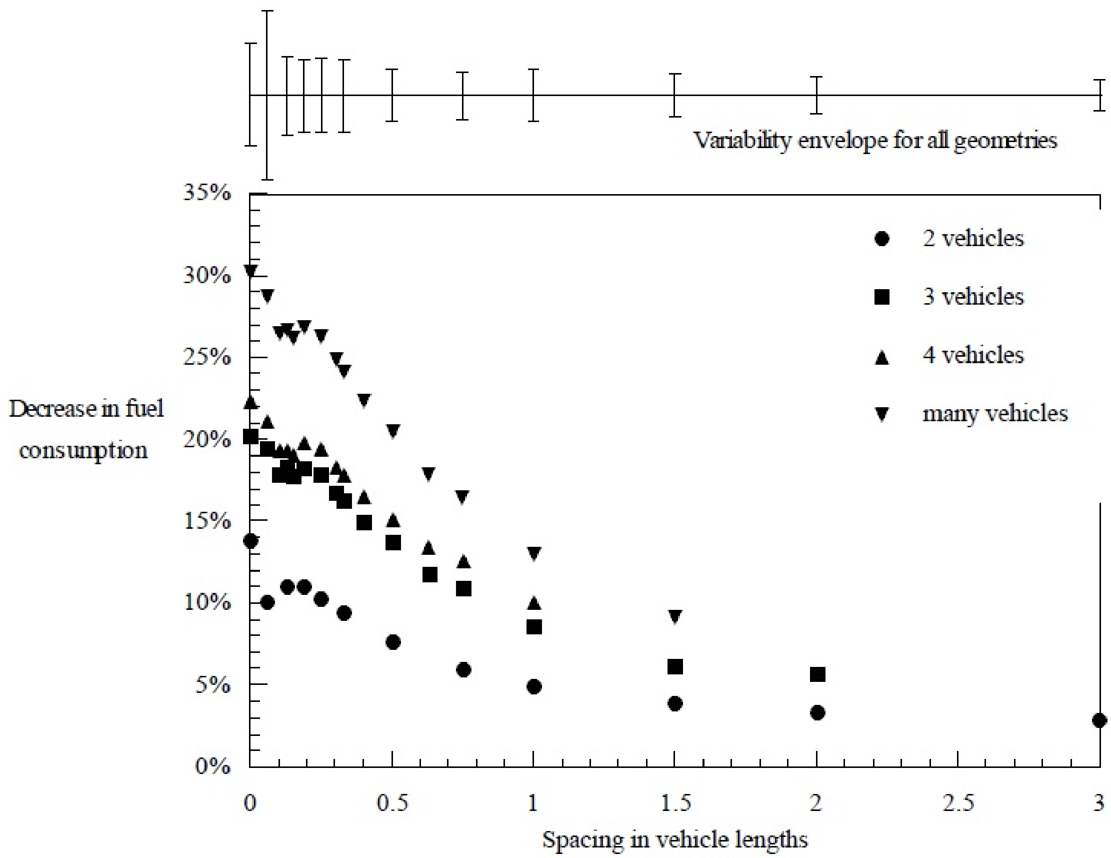


Figure C-1: All-Geometries-Average Decrease in Fuel Consumption for Platooning Vehicles in Highway Operation. From *The Aerodynamic Performance of Platoons, A Final Report*, 1995, by Zabat. Used by permission, see Appendix D.

APPENDIX D

Appendix D includes the two authorization letters from organizations American Association of State Highway and Transportation Officials (AASHTO) and California Partners for Advanced Transportation Technology (PATH) that were necessitated for the reproduction of media noted in this thesis as Figs. 1, 2, 3, 4, 5, 6 and C-1 as well as Table 2. Such media was part of the publications; *A Policy on Geometric Design of Highways*, 2011, by AASHTO and *The Aerodynamic Performance of Platoons: Final Report*, 1995 by Zabat, published by PATH.

AMERICAN ASSOCIATION OF
STATE HIGHWAY AND
TRANSPORTATION OFFICIALS
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October 10, 2012

Francisco Martinez
The University of Rhode Island
1 Lippitt Road
Kingston, RI 02881

Dear Mr. Martinez:

This refers to your request to include Figures 3-22, 3-23, 3-41, 3-43, and 3-44 as well as Table 3-1 from the AASHTO publication *A Policy on Geometric Design of Highways and Streets* in your thesis entitled *Impacts of Road Trains on Geometric Design of Highways.*

You have AASHTO's permission to use the above-mentioned excerpts. Please note that this authorization is for your thesis only. In addition, please include the following language or something similar with each excerpt:

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If you have any questions about this authorization, please do not hesitate to contact me at bobc@aashto.org or 202-624-8918.

Sincerely,

Robert Cullen
Information Resource Manager

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October 8, 2012

Dear Mr. Martinez-Perez,

This refers to your request to include Figure 23 from the PATH publication *The Aerodynamic Performance of Platoons: Final Report* in your thesis entitled Impacts of Road Trains on the Geometric Design of Highways. You have authorization to use the above-mentioned figure.

Please note that this authorization is limited to your thesis work. In addition, please include the following language or something similar with the figure: From *The Aerodynamic Performance of Platoons: Final Report*, 1995, by PATH. Used by permission.

Could you please send or email me a copy of the thesis when it is finished. If you have any further questions regarding this authorization, please do not hesitate to contact me at chriscos@berkeley.edu, 510-642-3593.

Christine Cosgrove, Communications Office, Institute of Transportation Studies, 113 McLaughlin Hall, UC Berkeley
510-642-3593 http://its.berkeley.edu/

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