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Highway Geometric Design Changes in Response to a Fully Autonomous Vehicle Fleet

By

Kamar Ali Amine

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Student Name: KAMAR AMINE I.D. #: 201301096

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The undersigned certify that they have examined the final electronic copy of this thesis and approved it in Partial Fulfillment of the requirements for the degree of:

MASTERS in the major of CIVIL ENGINEERING

Thesis Advisor's Name JOHN KHOURY	Sig[redacted]	E: 13 / 08 / 2018 (Day / Month / Year)
Committee Member's Name Mahmoud [illegible]	Sig[redacted]	E: 13 / 08 / 2018 (Day / Month / Year)
Committee Member's Name Caesar Abi Shdid	Sig[redacted]	E: 13 / 8 / 2018 (Day / Month / Year)

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To my parents, Ali and Abir, whose endless hard work made it all possible.

To my aspiring brother, Amir
To my passionate sister, Raghad

With love and respect.

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ABSTRACT

This research investigates the potential changes in the geometric design of highway elements in response to a fully autonomous vehicle fleet. When driverless vehicles completely replace conventional vehicles, the human driver will no longer be a concern. Currently, and for safety reasons, the human driver plays an inherent role in designing highway elements, which depend on the driver's perception-reaction time (PRT), driver's eye height and other driver parameters. This study focuses on the geometric design elements that will directly be affected by the replacement of the human driver with fully autonomous vehicles. Stopping Sight Distance (SSD), Decision Sight Distance (DSD), and length of sag and crest vertical curves are geometric design elements directly affected by the inevitable change. Revised formulations for such design elements are presented herein. The effects of the proposed revised formulations are quantified using a real-life scenario. An existing real-life roadway designed using current AASHTO standards has been redesigned with the revised formulations. Compared with the existing design, the new design shows significant economic and environmental improvements, given the elimination of the human driver from autonomous vehicles.

Keywords: Autonomous Vehicles, Perception-Reaction Time, Stopping Sight Distance, Highway Design, LiDAR.

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List of Abbreviations

AASHO: American Association of State Highway Officials

AASHTO: American Association of State Highway and Transportation Officials

AHS: Automated Highway System

DARPA: Defense Advanced Research Projects Agency

DSD: Decision Sight Distance

GM: General Motors

GPS: Global Positioning System

HSO: Horizontal Sightline Offset

LiDAR: Light Detection and Ranging sensor

NHTSA: National Highway Traffic Safety Administration

PRT: Perception Reaction Time

SSD: Stopping Sight Distance

Chapter One

Introduction

In the last couple decades, major efforts have been exerted to increasing safety on roadways and reducing crashes. Engineers have been restlessly developing driving systems that gradually reduce and eventually eliminate the need for a human driver, thus reducing the human error associated with most vehicle crashes (Stanton and Young, 1998). The National Highway Traffic Safety Administration (NHTSA) “2015” fact sheet highlights the fact that human error is the main cause of 94% of motor crashes in the US. Drivers’ conditions such as fatigue, drowsiness, alcohol and drug abuse, stress and anger, or illness and medication cover 25% of those drivers who are involved in vehicle crashes in New Jersey, according to the Fatal Accident Investigation unit of the state.

Over the course of the past few years, autonomous vehicles in general, and driverless vehicles in specific, have been gradually introduced to the highway network. The journey of fully autonomous vehicles underwent several levels of driver assistance systems, from basic levels of cruise-control and self-parking to fully automated vehicles requiring no human intervention even for the trickiest situations. The Society of Automotive Engineers (SAE) has identified six levels of vehicle automation, ranging from Level 0 to Level 5. Level 0 is the zero autonomy level; the driver performs all the driving tasks. Level 1 of autonomy is assisted driving where the human driver receives assistance in performing steering or acceleration/deceleration (Eldada, 2017). In Level 2, entitled partial automation, the driver assistance system strictly performs steering as well as acceleration/deceleration rather than assisting the human driver who performs all remaining dynamic driving tasks, such as monitoring the driving environment and taking over in unusual situations. Level 3, conditional automation, indicates that the self-driving function is limited, with the automated driving system performing all aspects of the dynamic driving task. However, the human driver is still expected to take over whenever the system requests an intervention (NHTSA). High automation is expected in Level 4 where the system still performs all driving tasks and still sends requests for human intervention, however the human driver is not expected to respond (Eldada, 2017), hence the system is better equipped than that in level 3 to handle critical situations. Finally, level

5 is that of full automation where the system performs all the driving tasks under all roadway and environmental conditions without sending any requests for human takeover (Eldada, 2017).

Google's driverless vehicle pursuit has so far led the development of autonomous vehicles. Their autonomous vehicle hit the roads in 2009 and has already traveled 7 million miles on city streets in various states in the US (Waymo). Their fully autonomous vehicle becoming available to the public as of 2015, through the "Early Rider" program that allows civilians, in certain states of the US, to ride an autonomous vehicle and then provide feedback to Waymo's team (Waymo). Nissan has also tested its prototype of a fully autonomous vehicle on the streets of Tokyo planning to release the technology for real-world use in 2020. Another auto manufacturer, Volkswagen, has displayed its I.D. Vizzion concept car at the Geneva motor show in March 2018. With level 5 autonomy, the latter car is intended to enter production in 2022. Ford also promised to have fully autonomous vehicles, classified as SAE-Level 4 vehicles in operation by 2021. In March 2018, following more than a year of testing, General Motors (GM) announced their plan to "commercialize the first production-ready vehicle" built to operate with no driver, no steering wheel, no pedals or any manual controls. Given the rapid progression in vehicle automation, it is logical to expect that the highway network will soon be governed by level 5, fully autonomous vehicles. By eliminating the need for a human driver, the automation of vehicles will also reduce delays and increase mobility, knowing that human behavior contributes to the bulk of delay suffered on roadways, specifically at intersections (Khoury and Khoury, 2018). Highways will go through a transitional period serving mixed vehicle fleets, including human drivers and driverless vehicles simultaneously, before reaching a 100% level 5 autonomous vehicle fleet. As long as humans still drive vehicles, highways will still be designed according to current American Association of State Highway and Transportation Officials (AASHTO) standards to accommodate for worst case scenarios – human errors. Such standards account for human driver factors to derive the highway geometric design equations. Once the entire vehicle fleet comprises fully automated vehicles, design standards bound by human drivers' factors will consequently be revised. The establishment of highway design standards dates to the early 1900s when the first cars were being produced. Highway engineering textbooks, since, presented design guidelines for horizontal and vertical curves, drainage systems, pavements, lane widths, street intersections and other aspects of highway design. A key design parameter that has always been the subject for research is the stopping sight distance (SSD), which is directly related to the human driver. The SSD concept dictates the safe distance a human driver needs to stop before hitting an obstacle and accounts for the perception reaction time of most drivers. The SSD was defined in 1914 by Blanchard without performing any experiments or assigning any values. Going through several amendments and studies, AASHTO came up with the current model, which comprises both the human driver's perception reaction time and braking time. Throughout the development of their model, AASHTO relied on several experiments studying human drivers' behavior in efforts to determine the two mentioned components of the SSD.

Clearly, the SSD is directly related to the human driver. It is also the foundation of other highway geometric design elements, such as lengths of sag and crest vertical curves and sideline offsets/clearances around horizontal curves. The eventual transformation of the vehicle fleet to fully autonomous vehicles will logically require significant changes to the highway design process. Such changes to the design process will result in measurable financial savings in highway projects. Thus, it is necessary to quantify the extent of such impacts due to the full deployment of autonomous vehicles. This study will assess the highway design formula that are directly or indirectly affected by the human reaction time. The human driver-related values will be substituted with new values based on the responses of autonomous vehicles in situations similar to ones that human drivers encounter. The newly established models will then be used to redesign an existing road for autonomous vehicles solely. Later, the technical and economic effects of the design project will be assessed and quantified.

Chapter Two

Background

2.1. Development of Highway Geometric Design Elements

Highway and street design for motor vehicles was first mentioned in Blanchard and Drowne's Textbook on Highway Engineering published in 1914. Before that, building highways meant choosing adequate bituminous material that best suited horse-drawn carriages. Early references on principles of highway engineering included design sections of vertical alignments and horizontal alignments for automobiles. Design specifications included determining grade, curvature, widths, super-elevations and other factors. The concept of sight distance was mentioned in Blanchard's book without assigning specific values. The latter highlighted the relationship between traveling vehicles' safety and having a sufficient sight distance at sharp curves.

The SSD model was further developed in subsequent research. The first numerical reference to SSD was given in 1916 by Agg. He stated that there should always be a clearance of at least 250 feet[1] of the view ahead, when designing rural highways. He also advised that whenever there are steep grades, sharp curves and hills, grades should be flattened or avoided. With this statement being the only reference to SSD in Agg's book, the 250 feet distance was not justified in his work. In 1924, Agg further developed the SSD reference in the third edition of the previously mentioned book. He increased the SSD distance from 250 to 400 feet, in addition to, relating the concept of SSD to roadway characteristics, such as horizontal and vertical alignments. In 1926, Brightman reinforced the concept of providing adequate SSD and advised providing 500 feet of sight distance, which was adopted by the American Association of State Highway Officials (AASHO) two years later as a minimum requirement. In 1935, Baldock defined SSD as the "distance travelled during the reaction time of the operators plus the braking distance", which still is current definition today. He also referred to Oregon's method of calculating SSD, which relates speed and perception reaction time to SSD, which still holds today. The only difference is the assumed 0.5 seconds driver's perception reaction time rather than the experimental 2.5 seconds used in today's model. Later that year, Wiley dedicated a section

[1] 1 foot = 0.305 meters

on sight distance, defining it as the maximum distance at which two vehicles are mutually visible. He then indicated that the sight distance is set by experience to be around 600 feet for both horizontal and vertical curves. Another reference to SSD was given in the mid-1930s by the State of Ohio through its, then, Department of Highways. It specifically referred to the sight distance on vertical curves and presented three values for minimum sight distance: 1000 feet on two-lane, 1500 feet on three-lane and 800 feet on four-lane highways. Finally, the current model adopted by AASHTO, adopts a perception reaction time of 2.5 seconds following an experiment performed by Johansson and Rumar on 321 alert drivers, in addition to other groups that were tested under different circumstances. Table 1 groups the historical development of the SSD model since 1914 and summarizes all the changes it has gone through.

Table 1 – Development of SSD Model (Hall and Turner, 1989)

Source (Author/Year)	Perception-Reaction Time (sec)	Sight Distance (feet)	Sight Distance (meters)
Agg, 1916	-	At least 250	76.3
Agg, 1924	-	400	122
Michigan, 1926	-	500	152.5
Oregon, 1935	0.5	1,500 @ 80 mph	457.5 @ 128.8 km/h
Wiley, 1935	-	600	183
Ohio, 1937	-	1,000 (two lanes) 800 (four lanes)	305 (two lanes) 244 (four lanes)
Conner, 1937	-	500 (four lanes)	152.5 (four lanes)
HRB, 1937	3	-	-
Bateman, 1939	-	800 (Horiz C)	244 (Horiz C)
Agg, 1940	<1	-	-
AASHO, 1940	3 @ 30 mph 2 @ 70 mph	200 @ 30 mph 600 @ 70 mph	61 @ 48.3 km/h 183 @ 112.7 km/h
AASHO, 1954	2.5	-	-
AASHO, 1965	2.5	-	-
AASHTO, 1970	2.5	-	-
AASHTO, 1984	2.5	200 @ 30 mph 850 @ 70 mph	61 @ 48.3 km/h 259.3 @ 112.7 km/h
NCHRP, 1984	2.5	-	-

2.2. Evolution of Autonomous Vehicles

Remotely controlled driverless cars emerged in the early 1920s with the release of Pontiac's phantom auto (Lafrance, 2016). From then on, the concept has been under constant development. GM released its vision of automated highways in 1939 (Weber, 2014). Norman Bel Geddes, designer of the GM exhibit Futurama, imagined automated highways with traffic control towers, safe intersections and automatic lighting. By the 1960s, visions of driverless vehicles smart enough to sense, process, and react emerged. Yet, the ability to imitate the human driver remained a challenge (Weber, 2014). In the 1980s, the US released plans of executing a prototype of an Automated Highway System (AHS). Provisions of the AHS involved a system of in-road magnets that helped control the vehicles movements. In addition, vehicle sensors, tested by Honda, automatically allowing lane changes and avoiding road obstacles (Lipson and Kurman, 2016). Between the 1980s and the 1990s, the German Ernst Dickmanns tested several prototypes of autonomous vehicles that could steer themselves using sensors and intelligent software. From 2004 to 2007, the Defense Advanced Research Projects Agency (DARPA) conducted three challenges involving autonomous vehicles. The challenges comprised teams racing a specific distance using driverless vehicles fully under autonomous mode. In 2009, Google's Self-driving project was established. Driver assisted vehicles appeared, where the driver needed to take over in tricky situations. Up until June 2018, Google's fleet of autonomous vehicles had covered over 7 million miles on autonomous mode, without any manual interference (Waymo). In 2015, Google released the first customized model of a driverless car, after testing the autonomous system on ordinary vehicles such as Toyota and Lexus to allow human driver intervention in case of emergencies (Waymo). The car "firefly" was designed with customized sensors and systems without pedals or steering wheel, prohibiting any manual interference. The car performed its first trip on public roads with a blind passenger in its seat without any incidents (Waymo).

Several systems have been under testing and development to facilitate autonomous vehicles operations along highways, and more specifically, at intersections to improve efficiency and traffic operations (Khoury and Khour, 2018 and Rios-Torres, 2016). To achieve a high degree of safety and accuracy in driverless vehicles, several sensors and radars are used to instantly map the road ahead. One main component of current driverless vehicles is the Light Detection and Ranging sensor (LiDAR). LiDAR is a remote sensing method that depends on light to measure variable distances to Earth. Consequently, LiDAR allows the generation of three-dimensional information about the terrain all-around the sensor. Proceeding from the concept of LiDAR, Waymo[2] created its own LiDAR sensor that did not only detect objects or pedestrians all around the vehicle, but also determine the direction pedestrians are facing. This customized sensor guarantees a more detailed view and safer operations. Waymo's self-driving car hardware comprises 3 customized LiDARs that ensure uninterrupted surround vision, efficient and fast zooming and high-resolution input. In addition, Waymo's driverless car has a custom vision system enabling the car to visualize the surrounding imitating human behavior. It consists of 8 vision modules that include multiple sensors and an additional super high resolution multi-sensor module that allows 360-degree color-detecting vision.

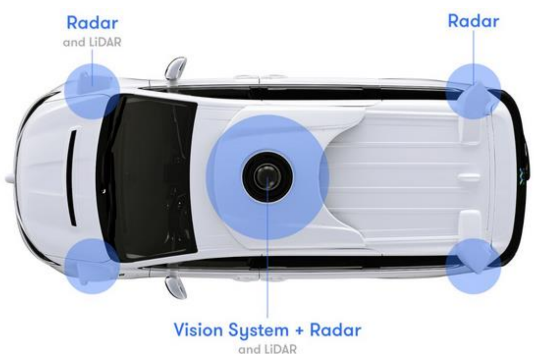

Figure 1 – Waymo's driverless vehicle, vision system

This system detects small objects from long distances at high speed under any lighting condition. The driverless car also relies on a radar customized by Waymo that provides a continuous 360-degree view of objects and vehicles that are usually hidden from the human eye. This radar is highly effective in rain, fog, or snow and is much more sensitive to the slow motion of objects such as pedestrians or cyclists. Finally, the system includes an audio detection system that recognizes sounds such as police and emergency sirens up to 100 feet away and a GPS that adds to the vehicle's thorough understanding of its physical location. As of 2018, the company partnered with Jaguar to build 20,000 self-driving vehicles (Waymo). Several automobile companies have already started

[2] Waymo is the autonomous car development company that took over the Google Self-Driving Car Project. It was previously managed by Google Inc. It is now managed by Google's parent company, Alphabet Inc.

developing full autonomous vehicles with their sensors and LiDARs. Big companies such as Nissan, Ford, GM and Volkswagen have already promised that driverless vehicles will be on roads or in production between 2020 and 2022.

2.3. Criticizing Highway Geometric Design Elements

Stopping Sight Distance (SSD) and Decision Sight Distance (DSD) are critical in calculating the required lengths of horizontal and vertical alignments and the locations of various highway signs. The development of safe, efficient and practical alignments suitable for all highway users requires behavioral studies of a wide variety of drivers, to determine a representative driver reaction time for use in SSD and DSD calculations. Driver's performance characteristics accounted for in AASHTO design policies include: time to detect and recognize, perception-reaction time, decision and response time, time to brake and accelerate, maneuver time and when applicable, time to shift gears (13).

In 1971, Johansson and Rumar studied the expected brake reaction time of drivers in unexpected situations. They conducted four experiments to assess the reaction time of 321 drivers and the results were used by AASTHO to determine the standard for perception time. When computing SSD, AASHTO recommends 2.5 seconds as a safe design criterion for brake reaction time. This standard accounts for highway geometric complexities and the deteriorated responses of older drivers, exceeding the 90th percentile of reaction times of all drivers. AASHTO also recommends safe values for the DSD needed to make an instantaneous or a complex decision, knowing that the driver perception time is commensurate with amount of information. Maneuver times incorporated in DSD are also based on several experiments that resulted in five categories of maneuvers. Each category presents a different reaction time to account for speed and path/direction change on different categories of streets and highways.

Highway design models are constantly altered because of changes in vehicles, drivers, and the driving environment. Fambro and Fitzpatrick (1997) suggested that the parameters of the current SSD model are not representative of the actual driving environment. They reassessed the model, citing no evidence that longer SSD results in fewer accidents. They suggested a new and simpler model, based on driver performance. Their model includes more realistic parameters validated with field data and representing safe driver behaviors. Neuman (1989) suggested a new design approach for SSD. He concluded that functional highway classification should be the basis for determining SSD design policies and values. The proposed approach relies on several elements that differ from AASHTO's considerations. The study identifies five highway system classifications: low-volume road, two-lane primary rural highway, multilane urban arterial, rural freeway and urban freeway. Compared to the current AASHTO model, the resulting model shows lower SSD values on low-volume roads and higher values on rural and urban freeways. Wood and Donnell (2017) revised the SSD model in a different context to improve accuracy and safety of the model. Their goal was to improve the reliability of the SSD model by accounting for lighted versus unlighted nighttime conditions. They introduced a new variable to the model that measures the distance between the front of the vehicle and the driver's eye. This variable improves the accuracy of SSD provided in lighted roadway conditions.

Glennon (1989) criticized AASHTO's SSD model and other sight distance models for being too conservative. He also mentioned that the current model is simplistic and does not account for human visual limitations. Harwood et al. (1989) reassessed the parameters of the SSD model and evaluated its effect on horizontal and vertical alignments if trucks were used as design vehicles instead of passenger cars. They suggested that trucks with conventional braking systems require longer SSD than 1984 AASHTO's recommendation. They analyzed different scenarios and performed sensitivity analysis to see by how much SSD, and consequently lengths of vertical curves and horizontal sightline offsets, change if trucks with conventional brakes are the design vehicle.

Finally, Washburn's published online course (2018) studied autonomous vehicles and their potential effects on traffic flow and geometric design. Since autonomous vehicles are equipped with LiDARs and vision sensors, the vehicles will recognize obstacles better that humans do, but their line of sight could still get obstructed at horizontal curves. It concludes that if autonomous vehicles could see through the crest of the vertical curve, higher grades could be used for the same design speed.

All the mentioned studies updated the current parameters of the SSD model only to improve accuracy and safety of the model and not to investigate any effect of a new trend or technology on the highway geometric design elements. Except for Washburn's online course that briefly tackles the effect of autonomous vehicles on geometric design, the literature includes no research investigating changes in highway design given the complete elimination of human driver-related parameters. When conventional vehicles are replaced by autonomous driverless vehicles, elements affected by human factors need to be reassessed, including SSD and DSD models. In this research, we aim to re-evaluate these models in addition to the driver's eye height and angle of headlight beam. The research also assesses the effect of changes in the mentioned models on the following design elements: horizontal sightline offset, length of sag vertical curve and length of crest vertical curve. Since humans will be replaced by software and robots, the perception reaction time is expected to decrease significantly, thus reducing length requirements for building safe highways. This research provides new parameters for the same highway design formulas in addition to a lifecycle cost analysis showing a decrease in project cost of building highways for driverless vehicles.

Chapter Three

Methodology

The SSD and the DSD models are directly based on the driver's PRT. They are key elements in designing vertical and horizontal alignments. These models will be revised in this section to capture the effect of autonomous vehicles on highway design elements. The driver's eye height and the degree of illumination of the headlight beam are also key elements in designing crest and sag vertical curves, respectively. The latter concepts will also be reassessed.

3.1. SSD Model

The current SSD equation is a sum of two distances: the distance traveled during PRT and the distance traveled during braking (AASHTO). The distance traveled during braking, irrespective of the driver, is related to the vehicle properties. In this research, the dynamic properties of autonomous vehicles and conventional vehicles are assumed to be identical; thus, the braking distance will logically remain the same. The distance traveled during PRT is the product of the design speed of the vehicle and the PRT of the driver (a constant value of 2.5 seconds (AASHTO)).

3.1.1. Current Model Equations for Human Driven Vehicles

The current SSD model equations are retrieved from AASHTO's "A Policy on Geometric Design of Highways and Streets", 6th edition, chapter 3 pages 4 and 5 respectively.

a. SSD on Level Roads: (In Metric units)

$$SSD = 0.278Vt + 0.039\frac{V^2}{a} \qquad \text{(Eq. 1)}$$

b. SSD on Grade: (In Metric units)

$$SSD = 0.278Vt + \frac{V^2}{254\left[\left(\frac{a}{9.81}\right) \pm G\right]} \qquad \text{(Eq. 2)}$$

Where, V (km/h): is the design speed.

t (2.5 seconds): is the driver's PRT.

a (3.4 m/s^2): is the deceleration rate.

G (decimal): is the roadway grade.

3.1.2. Proposed Model Equations for Autonomous Vehicles

After extensive machine simulations and computational efforts, the braking reaction time of computer/machine from the moment an obstacle is recognized to the moment the brakes are applied, was found to be in the order of 0.5 seconds (Urmson, 2006). Assuming full autonomous vehicles, a braking reaction time of exactly 0.5 seconds is chosen to replace AASHTO's driver's reaction time of 2.5 seconds. Equations 1 and 2 are maintained in the proposed SSD model equations, with the new computer's perception reaction time changed from 2.5 seconds to 0.5 seconds.

3.2. DSD Model

The main purpose behind the DSD is to provide the driver enough distance in complex situations to recognize a potential danger in a cluttered environment ahead, identify the threat behind it and take the suitable decision (McGee, 1978). This decision may involve bringing the vehicle to a complete stop, changing lanes, or decreasing speed. The model classifies five avoidance maneuvers with different maneuver times. Avoidance maneuvers A and B provide the stopping decision time on rural roads and urban roads, respectively. Avoidance maneuvers C, D and E provide distance for speed, path or direction change on rural, suburban and urban roads, respectively. Larger maneuver times indicate more complex situations.

3.2.1. Current Model Equations for Human Driven Vehicles

The current DSD model equations are retrieved from AASHTO's "A Policy on Geometric Design of Highways and Streets", 6th edition, chapter 3 page 8.

a. Avoidance Maneuvers A and B: (In Metric Units)

$$DSD = 0.278Vt + 0.039\frac{V^2}{a} \qquad \text{(Eq. 3)}$$

b. Avoidance Maneuvers C, D, and E: (In Metric Units)

$$DSD = 0.278Vt \qquad \text{(Eq. 4)}$$

Where, t (seconds): is the maneuver time, shown in Table 2.

Note that the times shown for avoidance maneuvers C, D, and E, in Table 2, include both the pre-maneuver (reaction) plus the maneuver times. AASHTO specifies that 3.5 to 4.5 seconds of the latter times comprise the maneuver times, while the remaining portion is the pre-maneuver time.

Table 2 – Maneuver Times for the Different Avoidance Maneuvers (AASHTO)

Maneuver times:		
Avoidance Maneuvers A and B:	Pre-maneuver time:	t_A = 3 s t_B = 9.1 s
Avoidance Maneuvers C, D, and E:	Total pre-maneuver time and maneuver time:	t_C = 10.2 s → 11.2 s t_D = 12.1 s → 12.9 s t_E = 14 s → 14.5 s

3.2.2. Proposed Model Equations for Autonomous Vehicles

Being equipped with LiDAR sensors that can process 1.33 million points per second of the surrounding environment, what human drivers considered complex situations will be normal situations to automated vehicles. Instead of customized reaction times for each avoidance maneuver type of the DSD model, the same braking reaction time of 0.5 seconds remains applicable. For the avoidance maneuvers A and B, the DSD model becomes the SSD model, given identical reaction times, as shown in Table 3. Since the maneuver distances provided for avoidance maneuvers C, D and E depend on the driver, the DSD model for the latter maneuvers cannot be updated by replacing the pre-maneuver time only. The maneuver distances need to be investigated as well. The updated model for avoidance maneuvers C, D and E are not tackled in this research.

3.3. Length of Crest Vertical Curve

3.3.1. Current Model Equations for Human Driven Vehicles

The current model equations are retrieved from AASHTO's "A Policy on Geometric Design of Highways and Streets", 6th edition, chapter 3 page 151.

a. When Sight Distance is less than Length of curve (S<L):

$$L_{crest} = \frac{AS^2}{100(\sqrt{2h_1}+\sqrt{2h_2})^2} \quad \text{(Eq. 5)}$$

b. When Sight Distance is greater than Length of curve (S>L):

$$L_{crest} = 2S - \frac{200(\sqrt{h_1}+\sqrt{h_2})^2}{A} \quad \text{(Eq. 6)}$$

Where, S (m): is the sight distance.

h_1 (1.08 m): is the height of eye above the roadway surface.

h_2 (0.6 m): is the height of object above roadway surface.

A (percent): is the algebraic difference in grade.

3.3.2. Proposed Model Equations for Autonomous Vehicles

In autonomous vehicles, the eye of the driverless vehicle is the LiDAR sensor itself, constantly scanning its surrounding. In the new model, the eye height used in computing length of crest vertical curves is replaced by height of the LiDAR sensor mounted on top of the car. The height is measured from the roadway surface to the center of the lens. For safer computations, the total height of the LiDAR will be considered.

The Google self-driving project started their experiments of driverless vehicles and LiDAR testing on a Toyota Prius Car model and a Lexus RX450h model (Waymo). The mentioned vehicles have heights of 1.470 m and 1.685 m respectively. After Waymo taking over the project, the company manufactured its own customized car with a body like that of smart cars. The height of the Waymo self-driving vehicle is considered equal to that of a Smart car, 1.555 m. In addition to the car height, the height of the LiDAR is 0.284 m. Based on different car types, there are two possible values for h_1 as shown in Table 3.

Table 3 – Calculating h_1 for autonomous vehicles

Lexus Car	Waymo Car
Height of car roof = 1.685 m	Height of car roof = 1.555 m
Height of LiDAR = 0.284 m	Height of LiDAR = 0.284 m
Height of support = 0.3 m	Height of support = 0
h_1 = 1.68+0.284+0.3 = 2.27 m	**h_1 = 1.84 m**

Note that as h_1 decreases, L_{crest} increases. Thus, it is safer to assume that all autonomous passenger vehicles navigating roadways are either two-passenger vehicles (Waymo driverless car) or passenger minivans (Chrysler Pacifica Hybrid). Both vehicles have larger heights than smart cars. Autonomous trucks and buses will have larger heights as well. Knowing that vehicles with larger heights can navigate smaller crest vertical curves, this research will use a minimum h_1 of 1.7 m. Equations 5 and 6 are maintained in the proposed model equations for length of crest vertical curves, with the height of LiDAR above roadway surface, 1.7 m, replacing the height of driver's eye, 1.08 m. In addition, the "S" value is replaced by the sight distance of an autonomous vehicle rather than the sight distance of a human driver, whether this distance is SSD or passing sight distance (PSD).

3.4. Length of Sag Vertical Curve

3.4.1. Current Model Equations for Human Driven Vehicles

The current model equations are retrieved from AASHTO's "A Policy on Geometric Design of Highways and Streets", 6th edition, chapter 3 page 158.

a. When Sight Distance is less than Length of curve (S<L):

$$L_{sag} = \frac{AS^2}{200(H+S\tan\beta)} \qquad \text{(Eq. 7)}$$

b. When Sight Distance is greater than Length of curve (S>L):

$$L_{sag} = 2S - \frac{200(H+S\tan\beta)}{A} \qquad \text{(Eq. 8)}$$

Where, S (m): is the light beam distance taken to be equal to the SSD.

H (0.6 m): is the height of headlight above roadway surface.

β (1 degree, Figure 2): is inclined angle of headlight beam.

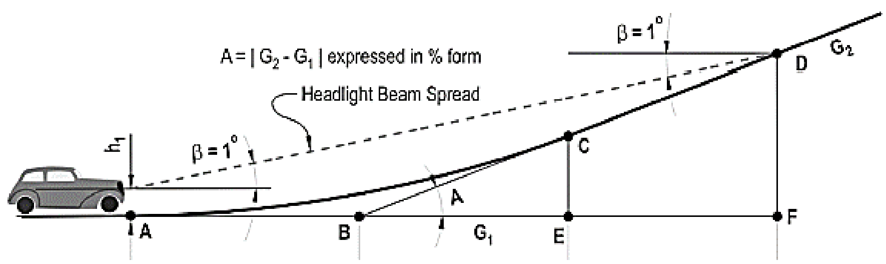

Figure 2 – Inclined angle of headlight beam of a vehicle, with respect to sag vertical curve (Tonias and Tonias, 2016)

3.4.2. Proposed Model Equations for Autonomous Vehicles

One of AASHTO's standards focus on nighttime operations for the design of a sag vertical curve. Visibility at night depends on both, the height of the driver's eye and the roadway illumination. The height of the vehicle's headlight and the inclined angle of the headlight beam in conventional vehicles are main parameters used in calculating the length of sag vertical curves. For autonomous vehicles, the LiDAR operates similarly in night and day conditions. In equations 7 and 8, the height of the headlight is replaced by the height of the sensor above the roadway, calculated to be 1.7 meters. Similarly, the inclined angle of the headlight beam is replaced by the inclination of the vertical field of view of the LiDAR, measured from the horizontal axis of the vehicle. The field of view, according to LiDAR's manufacturer, is 26.8 degrees. A schematic of the field of view of LiDAR is shown in Figure 2 which is retrieved from the LiDAR user's manual. We note that this value represents a 100th percentile value of the LiDARs because the technology is not vehicle-dependent. No reference was found in the literature discussing the inclination of the LiDAR's field of view from the vehicle's horizontal axis; thus, a 13.4-degrees-angle is assumed, which is half the total angle of view.

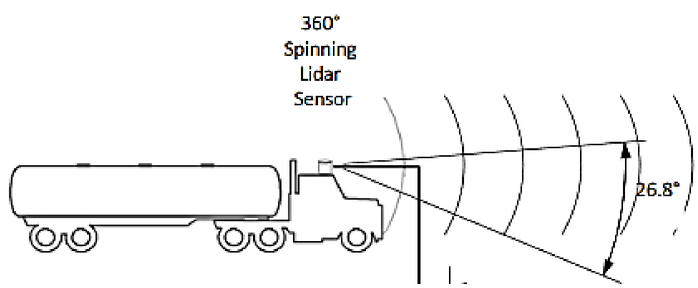

Figure 3 – Vertical field of view of LiDAR sensor

3.5. Model Applications

Using the models for each of the SSD, DSD, and length of sag and crest vertical curves, computations were performed to compare the current model values to the future model values. The results are shown in Tables 4 through 6. SSD differs with the design speed as well as the grade. Under all circumstances, the proposed model yields smaller SSD requirements, as shown in Table 4. The future SSD values that will replace the DSD values of the current model also yield smaller requirements regardless of the avoidance maneuvers (Table 5). Table 6 displays the rate of vertical curvature, K, calculated by dividing equations 5 and 7 by the algebraic difference of the grades. It also varies with the design speed. Using the future model equations for length of crest vertical curve, K values for crest curves are smaller, yielding smaller curve lengths. K values for sag vertical curves are also smaller. The benefits of reducing the vertical curve lengths are assessed in Chapter 5.

Table 4 – Comparing SSD Values at different design speeds

	SSD (m)							
	Level		Grade (Downgrades %)					
Design Speed (km/h)	0% Current[3]	0% Future	3% Current	3% Future	6% Current	6% Future	9% Current	9% Future
20	20	10	20	8	20	8	20	9
30	35	15	32	15	35	17	35	18
40	50	25	50	25	50	28	53	30
50	65	40	66	38	70	41	74	45
60	85	50	87	53	92	58	97	64
70	105	70	110	71	116	77	124	85
80	130	85	136	91	144	99	154	109
90	160	110	164	113	174	124	187	137
100	185	130	194	138	207	151	223	167
110	220	155	227	166	243	182	262	201
120	250	185	263	196	281	215	304	238
130	285	215	302	228	323	250	350	277

[3] OLD values are retrieved from AASHTO, 6th edition.

Table 5 – Comparing DSD Values for selected design speeds

		DSD (m)				
	Future	Current: Avoidance Maneuver				
Design Speed (km/h)	DSD = SSD (m)	A	B	C	D	E
50	40	70	155	145	170	195
70	70	115	325	200	235	275
80	80	140	280	230	270	315
100	130	200	370	315	355	400
130	215	305	525	390	450	510

Table 6 – Comparing Rates of Vertical Curvature for Sag and Crest Vertical Curves at different design speeds

	Sag Vertical Curve			Crest Vertical Curve	
Design Speed (km/h)	Rate of Vertical curvature, $K_{Current}$ Design (Rounded after calculation)	Rate of Vertical curvature, K_{Future} Design (Rounded after calculation)	Design Speed (km/h)	Rate of Vertical curvature, $K_{Current}$ Design (Rounded after calculation)	Rate of Vertical curvature, K_{Future} Design (Rounded after calculation)
20	3	1	20	1	1
30	6	1	30	2	1
40	9	1	40	4	1
50	13	1	50	7	2
60	18	1	60	11	3
70	23	2	70	17	6
80	30	2	80	26	9
90	38	3	90	39	14
100	45	3	100	52	20
110	55	4	110	74	28
120	63	4	120	95	40
130	73	5	130	124	54

3.6. Further applications of the future SSD model

While the previous section evaluates the changes in current models due to the direct relationship between them and the driver's perception reaction time, height of driver's eye and degree of headlight beam, this section evaluates the indirect effect of the latter parameters on current models. The Horizontal Sight line Offset (HSO) is the geometric design element affected indirectly by the change in driver's perception reaction time through sight distance. The model's equation below shows a direct relationship between HSO and sight distance, taken to be equal to the SSD:

$$\text{HSO} = R[1 - \cos(\frac{28.65S}{R})] \quad \text{(Eq. 9)}$$

Where R (m): is the radius of the curve

S (m): is the SSD

To evaluate the effect of driverless vehicles on horizontal alignments, two random values of HSO are chosen to model a real-life obstruction. In this example, HSO is taken to be 5 meters and 15 meters. Then, the required radius of horizontal curve is calculated using both current and future values of SSD presented in table 4. Figure 4 shows that the required radius satisfying SSD requirements for the same design speed decreases between the current model and the future model. The solid lines indicate that the radius is obtained using future SSD values in equation 9. The dashed lines represent values obtained using the current SSD model. The two lower curves represent HSO of 15 meters while the two upper curves represent that of 5 meters. For the same design speed, a smaller radius is sufficient for constructing a safe horizontal curve, as indicated by the red arrows on Figure 4. With larger HSO, which translates into an obstruction being farther from the mid ordinate, a smaller sight line is sufficient and hence a smaller curve.

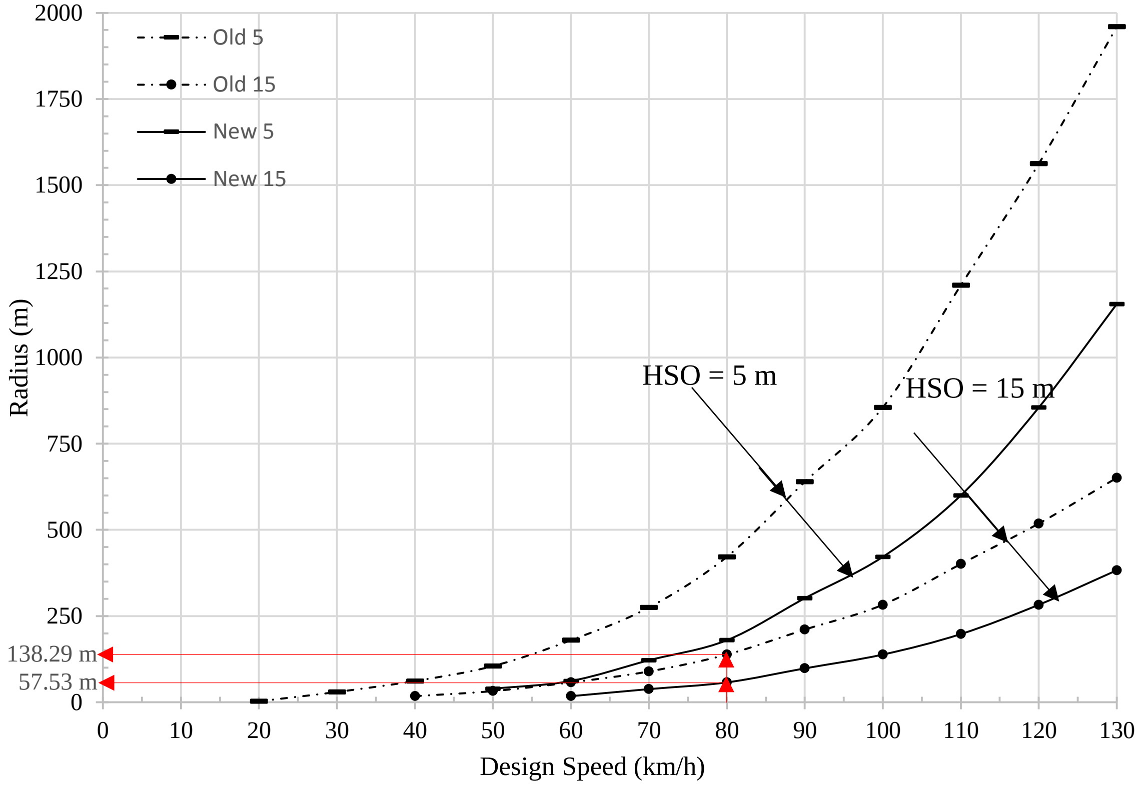

Figure 4 – Current & Future values of radius of horizontal curve vs. design speed

Chapter Four

Sensitivity Analysis

4.1. SSD vs. PRT

Noting that the proposed value of PRT, t = 0.5 seconds, is rather a conservative value, this section evaluates the effect of choosing a higher or a lower value than 0.5 seconds. Figure 5 shows the variation of SSD with respect to design speed, at different values of perception reaction time. The variation of SSD between two consecutive increments of time, the latter chosen to be 0.25 seconds, is at most 10 meters. Note that the SSD values used in figure 5 are design values, rounded up after calculation. The decrease in PRT and the resulting decrease in SSD values translate into a fractional decrease in calculated values of K and almost a negligible change in lengths of crest and sag vertical curves. The effect on HSO is more notable where the required radius of horizontal curve decreases for the same HSO with lower reaction time (Figure 6).

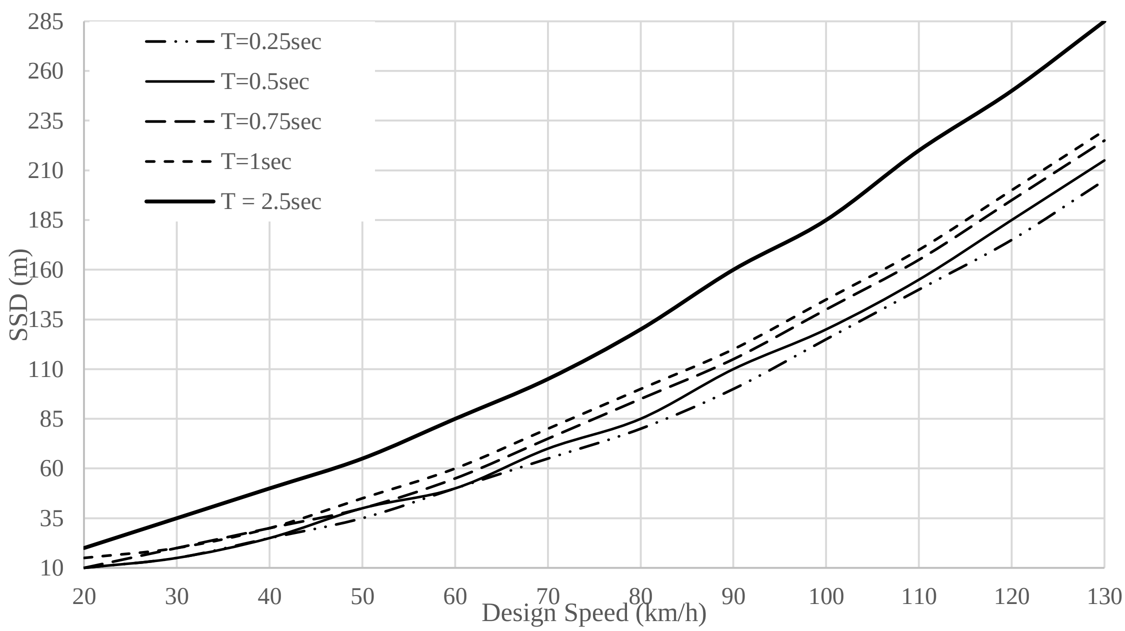

Figure 5 – Variation of SSD at different reaction times

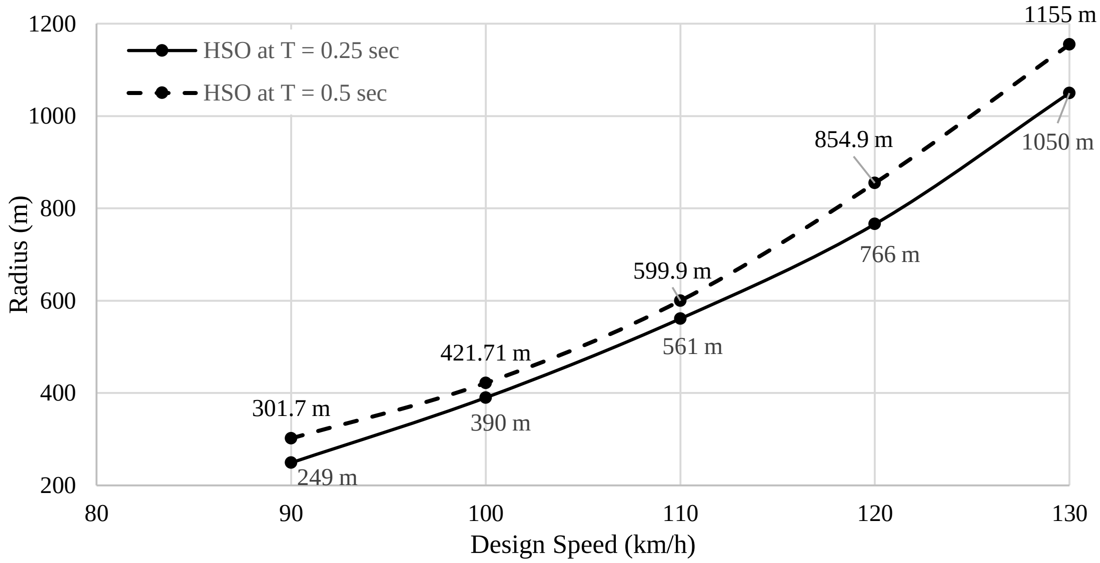

Figure 6 – Variation of minimum required radius of horizontal curve at different HSO values

4.2. Eye height vs. length of vertical curve

The value of h_1 in equations 5 and 6 chosen to be 1.7 m, is a conservative value. The effect of altering the value of h_1 is discussed below. At a specific design speeds, 70-km/h and 100-km/h, and algebraic grade difference, 9%, chosen for this discussion, figure 7 shows that shorter lengths are required for increased h_1 values. The decrease in length of vertical curves becomes more notable at higher speeds.

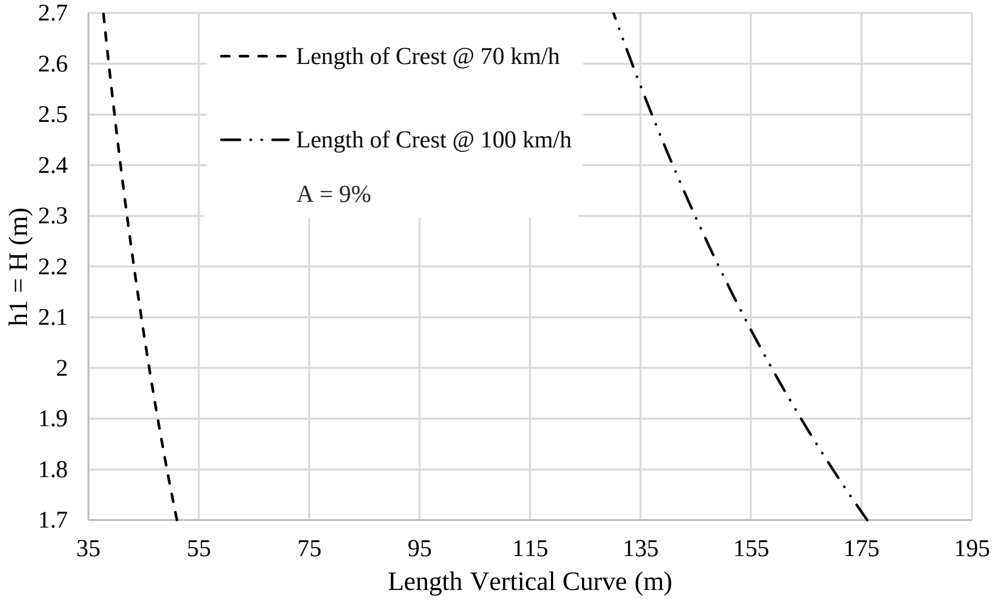

Figure 7 – Variation of Length at different values of h_1

4.3. Inclined angle of headlight beam vs. Length of vertical curve

LiDAR's field of vertical view provides vision of 26.8 degrees vertically. In case this field is increased, the inclination of the LiDAR's field of view from the vehicle's horizontal axis assumed to be 13.4 degrees, will also increase. As a result, the length requirements for sag vertical curve decrease negligibly (figure 8) since $K_{calculated}$ decreases in fractions.

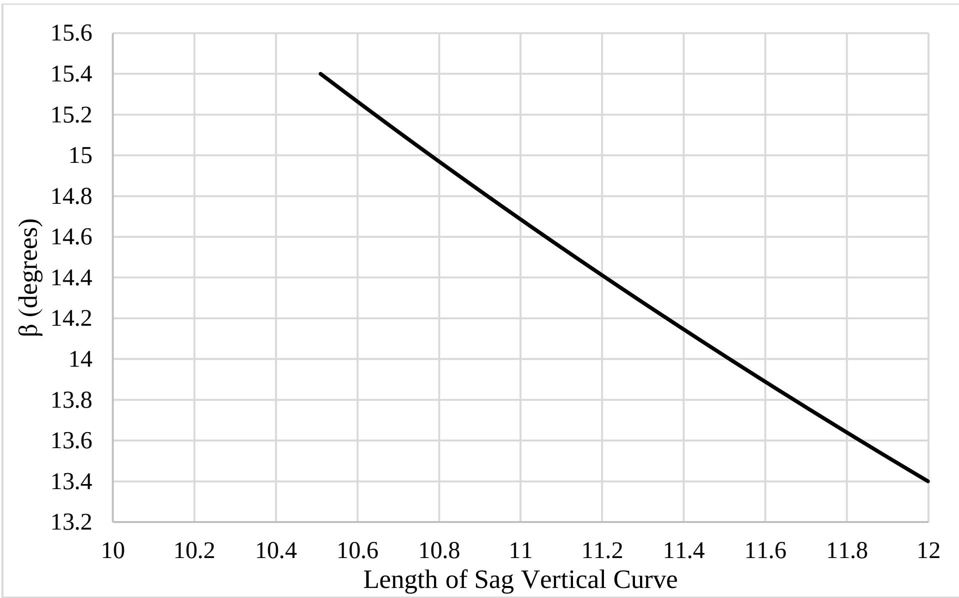

Figure 8 – Variation of length at different illumination angles

Chapter Five

Application

To test the effects of the future proposed models on real-life designs, a roadway designed according to the current AASHTO standards was retrieved from a leading engineering company in Lebanon. The roadway will be redesigned in this section using the proposed models. The design consists of two intersecting local rural mountainous roads in Hasbaya, Lebanon. Horizontal and vertical alignments were initially designed using AASHTO 2011 roadway design standards. Table 7 summarizes the specifications of the roads which will be also used in the tested design.

Table 7 – Designed Roadway Specifications

Road 1	Road 2
# of lanes: 2 lanes, 1 per direction	# of lanes: 2 lanes, 1 per direction
Lane width = 3.6 m	Lane width = 3.6 m
Shoulder width = 1.4 m	Shoulder width = 1.4 m
Design Speed = 50 km/h	Design Speed = 40 km/h
Undivided	Undivided
Roadway Length = 3,141 meters	Roadway Length = 1,781 meters

With the natural mountainous topography, the following design will test the proposed models of crest and sag vertical curves discussed in sections 3.3.2 and 3.4.2. Since both these models include SSD as a parameter, the SSD model will be indirectly tested as well. The initial design was performed using AutoCAD Civil3D, which allows the engineer to select the design criteria file of preference. In the proposed models, the design criteria files are updated to replace the rate of vertical curvature of the current model by that of the future model summarized in table 6. The software then inputs the K values and recalculates the lengths of vertical curves by multiplying K values by the algebraic difference in grades, which remain identical between the company's design and the tested design. For consistency, the horizontal alignment also remains unchanged.

According to the roadway specifications presented in table 7, the future K values to be imported to the software are selected from Table 6 as follows:

For road 1, minimum K_{sag} = 1 and minimum K_{crest} = 2

For road 2, minimum K_{sag} = 1 and minimum K_{crest} = 1

5.1. Results

To compare the differences between both designs, the lengths of vertical curves of each roadway segment are extracted and shown in tables 8 and 9 for roads 1 and 2 respectively. We note that the minimum K values presented earlier yield smaller lengths of curves than the ones used under Future Standards in tables 8 and 9. However, for passenger's comfort, AASHTO recommends a minimum length of vertical curve of 0.6 multiplied by the design speed for crest curves (1), and the maximum between 0.6V and $\frac{AV^2}{395}$ for sag vertical curves. This minimum value was used whenever the length resulting from minimum K values was smaller.

Table 8 – Comparing lengths of vertical curves of current and future designs, Road 1

			Current Standards – Design		Future Standards – Design	
	Curve Nature	A (%)	K (m/%)	Length of curve (m)	K (m/%)	Length of curve (m)
Crest Vertical Curves						
Curve 1	Crest	2.9	33.4	98.3	10.2	30.0
Curve 2	Crest	9.7	30.0	292.2	3.1	30.0
Curve 3	Crest	2.2	30.3	67.2	13.5	30.0
Curve 4	Crest	3.2	30.0	96.1	9.4	30.0
Curve 5	Crest	2.0	30.0	59.8	15.0	30.0
Curve 6	Crest	3.3	30.0	98.4	9.1	30.0
Curve 7	Crest	4.9	31.5	152.9	6.2	30.0
Curve 8	Crest	1.6	30.0	46.7	19.3	30.0
Curve 9	Crest	3.5	30.7	108.3	8.5	30.0
Curve 10	Crest	1.1	30.0	33.5	26.9	30.0
Sag Vertical Curves						
Curve 1	Sag	12.5	14.0	175.8	6.4	80.0
Curve 2	Sag	2.9	27.6	80.0	10.4	30.0
Curve 3	Sag	3.0	13.0	39.5	9.9	30.0
Curve 4	Sag	2.6	30.0	76.7	11.7	30.0
Curve 5	Sag	10.4	22.8	236.9	6.4	66.0
Curve 6	Sag	4.6	22.0	100.4	6.6	30.0

Table 9 – Comparing lengths of vertical curves of current and future designs, Road 2

	Curve Nature	A (%)	Current Standards – Design K (m/%)	Current Standards – Design Length of curve (m)	Future Standards – Design K (m/%)	Future Standards – Design Length of curve (m)
Crest Vertical Curves						
Curve 1	Crest	4.1	23.1	95.1	5.8	24
Curve 2	Crest	9.8	23.4	228.3	2.5	24
Curve 3	Crest	8.7	23.3	203.8	2.7	24
Curve 4	Crest	7.3	23.0	167.9	3.3	24
Sag Vertical Curves						
Curve 1	Sag	3.4	17.0	57.1	7.1	24
Curve 2	Sag	7.4	10.3	76.6	4.0	30
Curve 3	Sag	6.4	13.3	85.0	4.1	26
Curve 4	Sag	19.9	9.6	191.2	4.0	80

5.2. Discussion

The decrease in lengths of vertical curves shown in tables 8 and 9 has environmental and economic effects. Environmentally, the amount of cut and fill required to execute the designed roads decreases when using the future standards. Table 10 provides a comprehensive comparison of the volumes generated by AutoCAD Civil3D. Figure 9 displays the comparison in a schematic of crest vertical profiles of the current design, the proposed design, and the natural ground profile.

Table 10 – Comparison of Cut and Fill volumes

	Road 1		Road 2	
	Cut (m^3)	Fill (m^3)	Cut (m^3)	Fill (m^3)
Current Standards	123,973.89	3,754.83	144,969.54	8,113.21
Future Standards	120,279.68	1,936.39	133,853.75	4,282.01
Decrease (%)	2.98	48.43	7.67	47.22

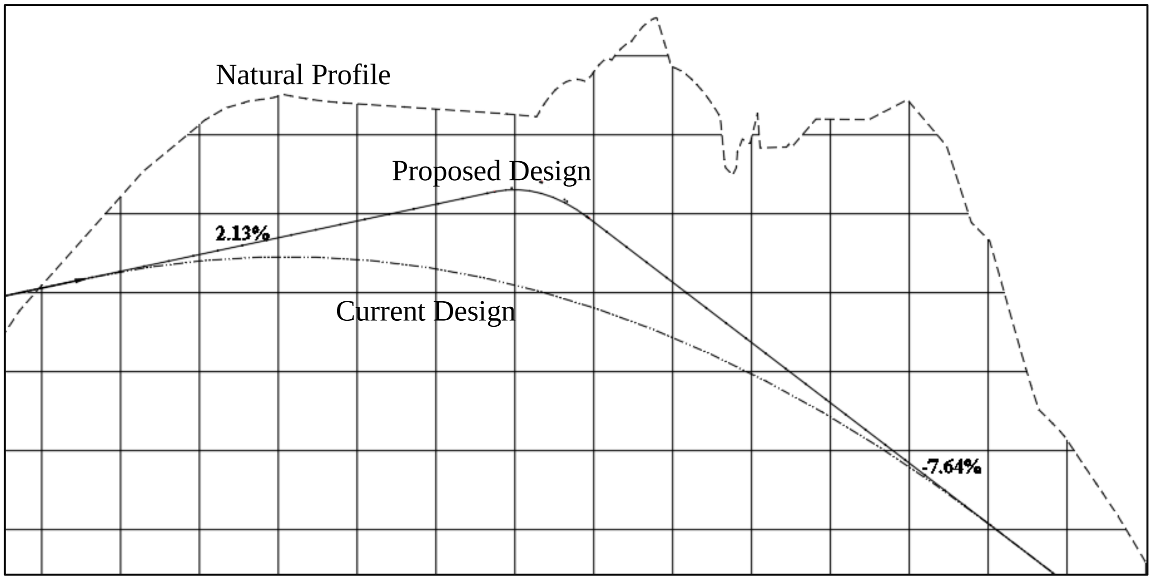

Figure 9 – AutoCAD schematic of crest vertical profiles: current, proposed and natural profiles

The crest vertical curves represented are curve 2 of table 9. The natural terrain is almost a crest curve of steep slopes. Noting that the entrance and exit grades are equal for both designs (set by the design company), the difference between the designs is clearly visible, with the proposed design requiring less cut than the current design.

Economically, an activity with a smaller volume to cut and fill is accomplished faster and cheaper given the same productivity rate. Also, if the fill material differs from the cut material, i.e. the fill material is to be purchased, a smaller volume will cost less. Figure 10 displays the discussed economic effect by showing the difference between the current sag vertical curve and the proposed curve. For curve specifications, refer to table 9, sag vertical curve 4. The future models for SSD and for lengths of sag and crest vertical curves tested in this application proved to be applicable and effective. The decrease in volumes to be cut will result in a reduced footprint upon the execution of the design. That and the decrease in volumes to be filled will cost less in terms of hours required to complete the work and material required for filling.

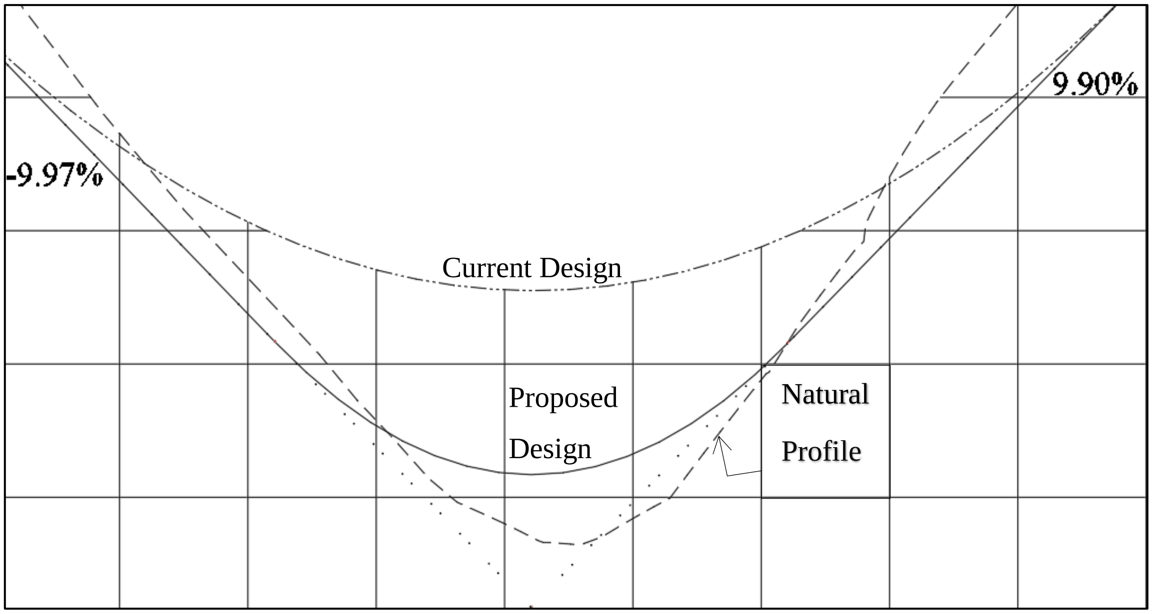

Figure 10 – AutoCAD schematic of sag vertical profile: current, proposed and natural profile.

Chapter Six

Discussion and Conclusion

Highway geometric design elements are subject to constant development and criticism. The models involving direct relationship with human factors underwent several updates to enhance their accuracy and increase roadway safety. This study evaluates the effect of having fully autonomous vehicles navigating roads on highway geometric design elements. The effect of complete elimination of the human driver is investigated and design standards are reassessed resulting in proposed models that will replace the current models for the following design elements: stopping sight distance, length of crest vertical curve and length of sag vertical curve. The suggested changes result in cheaper road designs with reduced environmental footprint. After updating the affected models, a roadway designed according to current standards was redesigned according to the proposed future standards of this research. The results validated the proposed economic and environmental effects through the reduced cut and fill volumes of the new design.

Further studies could investigate the operational effect of autonomous vehicles on roads. Knowing that driverless vehicles follow defined trajectories, volumes of autonomous vehicles might require less space than equal volumes of conventional vehicles. Another area of study could relate to road signs and markings, taking into consideration the LiDAR and cloud systems associated with driverless vehicles, which allow the generation of 3D maps that remain in the vehicle's memory. Traffic operations at intersections are also affected knowing that queueing theory and phasing of signals consider unexpected behaviors of drivers. In conclusion, while this study focuses on specific design elements, the replacement of conventional vehicles by autonomous vehicles will reform all elements of highway design, leading to environmental friendly and less costly roadways.

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