Incorporating Mental Workload into Highway Design

by

Karim Habib

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ABSTRACT

Human error is a leading cause of collisions on highways. Thus, if the aim is to reduce collision rates and keep drivers safe, it is necessary to investigate the factors that influence human mistakes and develop mitigation strategies to prevent these errors from occurring. One crucial approach to achieving lower collision rates is to design highways that do not overwhelm drivers with high mental workloads since too many tasks that challenge drivers' workload levels lead to human error. Better design will allow drivers enough mental capacity to make proper decisions. However, there is a lack of research on the quantitative relationship between mental workload and objective safety measures, as well as an absence of information on how to explicitly incorporate workload demand in geometric design guidelines and manage highway speeds in complex road environments. To address this research gap, this thesis investigates the relationship between mental workload and highway traffic safety from a geometric design perspective. The geometric design attributes for horizontal and vertical curvatures were automatically extracted from LiDAR data. This data offered various highway geometric parameters such as degree of curvatures and deflection angles of horizontal curves, detection of the existence of vertical crest curves, changes in cross-section, intersections, and available sight distances. Then, the outputs from the self-report measures were related to collision data and highway geometric design parameters. The objectives were to: (1) examine and model the relationship between workload demand and collisions using safety performance function, (2) calibrate highway design guidelines using reliability analysis, (3) create a system advisory speed limit on horizontal curves that incorporates workload demand, and finally (4) update the current workload ratings by adding new factors to assess the impact of weather and in-car technologies on workload levels. The results from the safety performance function showed a statistically significant relationship between collisions and MWL. The probability of non-compliance from the reliability analysis revealed that the mental workload stopping sight distance satisfied 99% of the driving population. Then, based on the mental workload stopping sight distance, an advisory speed limit, which compensates for any restrictions in mental workload sight distance was proposed. Finally, the last objective resulted in mental workload ratings that were highly correlated to their counterparts in the literature. Additionaly, the new ratings incorporated several essential factors such as active transportation, severe weather conditions, and in-car assistance technologies. This thesis significantly contributes to the current body of work by providing a framework to transition from a subjective workload measure to safety, design, and operational transportation applications. These applications would provide engineers with the tools to evaluate their designs in terms of mental workload and identify the countermeasures to address challenging infrastructural designs.

PREFACE

There are four studies in the body of this manuscript. Three papers are peer-reviewed published, and one is under peer-review.

Peer-Reviewed Journal Publications:

1- Habib K, Shalkamy A, El-Basyouny K. Investigating the Effects of Mental Workload on Highway Safety. *Transportation Research Record*. 2019;2673(7):619-629. doi:10.1177/0361198119846474

2- Habib K, Gouda M, El-Basyouny K. Calibrating Design Guidelines using Mental Workload and Reliability Analysis. *Transportation Research Record*. 2020;2674(8):360-369. doi:10.1177/0361198120928075

3- Habib K, Tawfeek M H, El-Basyouny K. A system to determine advisory speed limits for horizontal curves based on mental workload and available sight distance. *Canadian Journal of Civil Engineering*. **e-First** https://doi.org/10.1139/cjce-2020-0482

Submitted Journal Publications:

4- Habib K & El-Basyouny K. Factors Influencing Driver Mental Workload on the Highways: an Expert Survey Study. Submitted

Ethics Approval

This thesis is an original work by Karim Habib. The fourth study received research ethics approval from the University of Alberta Research Ethics Board 2, Project Name “**Assessing Mental Workload Levels Imposed by Geometric Design of Highways**” Pro00104592, 02/11/2021.

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LIST OF ABBREVIATIONS

ABBREVIATION	**EXPANSION**
AADT	Average annual daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ASD	Available sight distance
GPS	Global positioning system
IRR	Incident rate ratio
LiDAR	Light detection and ranging
LKA	Lane keep assist
LSF	Limit state function
MWL	Mental workload
PLN	Poisson lognormal
PSD	Passing sight distance
PRT	Perception reaction time
SPF	Safety performance function
SSD	Stopping sight distance
TAC	Geometric Design Guide for Canadian Roads
TIN	Triangular irregular network
UBC	University of British Columbia

1 INTRODUCTION

1.1 BACKGROUND

Although the research, design, and construction of highways have evolved over recent decades, collisions continue to occur; every year, 1.3 million lives are lost globally (1). In 2018, more than 150 thousand victims were injured, while almost 10 thousand lives were lost on Canadian roads (2). As a result, there is a growing interest in North American cities to adopt Vision Zero, a campaign and collaborative network to eliminate fatal and major injury collisions (3-5).

Vision Zero acknowledges that humans make mistakes and seeks to find strategies and solutions to address road safety in a realistic and viable way. Road design is one crucial area that can incorporate knowledge of human capabilities. Modelling human factors could be the solution to ensure that the surrounding driving environment does not overwhelm drivers' abilities. Engineers and road designers should evaluate highway design complexity from a mental workload (MWL) perspective and link it to highway safety.

Human factors primarily describe the relationship between human users and machines, and studying human factors is a challenging task. This work requires collaboration and knowledge-sharing between psychology and transportation engineering to understand and model drivers' interaction with roadway infrastructure, including road design and traffic patterns. These connections can identify the highway infrastructure's mental workload demand (complexity) and tie it to collision rates.

Workload is the quantification metric of human factors, and the primary goal of any design process is to eliminate failure when humans handle any system (6). Various workload measures include psychological, performance, and subjective (self-report) measures. Examples of psychological measures are changes in pupil diameter, cardiac functions, eye fixations, blood pressure, and electrodermal response (7). Performance measures include primary-task measures such as performance speed, headway distance, and reaction times. Also, some examples regarding secondary-task measures are text reading or head-up display monitoring during driving (7). Finally, subjective measures include rating scale mental effort and activation scale, where respondents quantify the workload levels in terms of ratings. Among these measures, the subjective workload measure such as survey is an efficient tool to express the complexity of the driving tasks because respondents can give reliable assessments based on their experience. In addition, the subjective measure is feasible from a time and cost perspective and is easily understandable. Unlike psychological and performance measures that require specialized equipment, technical experience when measuring workload levels is not easily quantified. For example, we might detect an increase in heart rate or a decrease in driving speed when a driver is navigating a complex infrastructural situation. We might subsequently identify an increase in workload levels. But we would be unable to quantify this increase. As a result, an integrated combination of psychological, performance, and subjective workload measures is best to address workload levels.

On highways, the surrounding environment imposes MWL demands on drivers. The complexity of the surrounding environment (e.g., geometric design) should not exceed the drivers' MWL supply to ensure that the drivers have enough room to make proper decisions in a safe driving situation. Indeed, according to the Geometric Design Guide for Canadian Roads, drivers should not be challenged with more than one task at a time (8). The geometric design elements that impose MWL demand include horizontal curves, vertical curves, intersections, traffic complexity, and changes in the cross section (9-13).

It is necessary to acknowledge the various methods and experimental designs that address the changing MWL levels. Simulations, naturalistic driving data, test track studies showed strong potential in quantifying and predicting the impacts of MWL (14-16). A significant advantage of those studies is their ability to account for MWL resulting from the driving environment and human factors such as age and distraction. Undoubtedly, the study of MWL is a challenging task that needs various data input to address the many factors that impact the drivers' MWL levels.

Self-report (subjective) measures can quantify the mental workload levels of the driving surrounding environment by scale ratings. The scale ratings could be used to assess the highway geometric design, representing an example of the transition to transportation engineering application. The assessment ratings could be inputs into safety performance functions (SPFs), design guidelines, and advisory speed systems, helping us understand human factors' contribution in collisions and create designs that improve safety.

1.2 MOTIVATION

The incorporation of MWL in road design and safety is not well documented in the literature, despite human factors and driver behaviour being extensively studied. It is important to explicitly include them in safety modelling, particularly because human factors contribute to around 95% of collisions (18). An obvious example is the lack of formulations and quantifications of MWL in the design guidelines. During the design process, the impact of highway geometric design is evaluated according to the design engineer's judgment since there is no explicit formulation for the complexity of highway design elements (MWL demand).

The Geometric Design Guide for Canadian Roads provides a general statement as direction for designers to consider MWL in designs: "Designers should avoid designs that result in high workload with more than one task at a time (an intersection on a curve, a lane drop on a curve, lane changes while readings guide signs, or a railroad crossing near a stop sign).” The statement implies that high levels of MWL demand result from combining two or more geometric elements. However, the Geometric Design Guide for Canadian Roads (TAC) does not provide an assessment tool to evaluate or modify designs, representing a concerning gap in the design guidelines.

The literature is replete with simulation-based studies that identify many factors that impact drivers' MWL supply. However, the perceived difficulty of quantifying the impact of those factors makes them impractical for usage in the design process. It is still challenging for engineers to incorporate psychological measures such as eye-movement tracking, heart rate variability, and galvanic skin response into design guidelines because they are not easily transferable to real-life transportation applications due to the inconsistencies in the measurements (6). More work is needed to understand how these measures can be captured and incorporated to reflect how higher MWL levels can influence driver behaviour.

1.3 RESEARCH QUESTIONS & OBJECTIVES

The thesis attempts to answer four major research questions. The first question is, “What is the contribution of the geometric design MWL demand on highway safety?”. It explores the relationship between highway safety and MWL demand generated by the highway infrastructure to understand highway safety changes in response to different MWL levels. The second question “What speed limits are required to ensure safe highway driving environment?” and the third question “How to include MWL in the design process of highway?” both address the outcomes from the first question. If MWL demand due to the infrastructure impacts highway safety, it is necessary to develop countermeasures to ensure a safe driving environment for drivers. Where these countermeasures may include infrastructural modifications and speed management techniques. Finally, the last question is “What is the impact of other factors that are added to the geometric design elements on MWL levels? ”. It investigates the impact of the surrounding driving environment, such as the geometric design, existence of cyclists, weather conditions, and in-car technology.

Figure 1.1 summarizes the objectives of this thesis. The first objective formulates the relationship between MWL demand by the geometric design of highways and collisions using the safety performance function. This formulation allows researchers and engineers to understand the changes in the geometric design on highway safety. Meanwhile, it offers a scientific yet practical tool to assess the geometric design of highways.

Understanding the relationship between MWL and highway design can offer engineers and designers the basis for countermeasures to improve highway safety. These countermeasures could be either infrastructural by constructing new highways or operational by proposing advisory speed limits. In the first case, stopping sight distance (SSD) based on the complexity of the geometric design will be provided to ensure that drivers have enough room to make proper and safe driving decisions. The resulting MWL SSD will be tested against the general population of drivers to confirm the validity of the SSD values. As a result, each geometric element, or a combination thereof (horizontal curve combined with an intersection), will have a specific SSD that satisfies the driving population requirements to drive safely.

However, reconstruction of the existing highway infrastructure or providing MWL SSD could be costly. In this case, providing MWL speeds is a feasible and safe alternative to give drivers enough leeway to deal with the complexity of the infrastructure. Decreasing drivers’ speed is a well-documented strategy for negotiating high MWL demands. Those implementing the advisory speed may consider the complexity of the geometric design alongside the available sight distance. As a result, the change in speed levels may address both the MWL demand (complexity) and the available room for drivers.

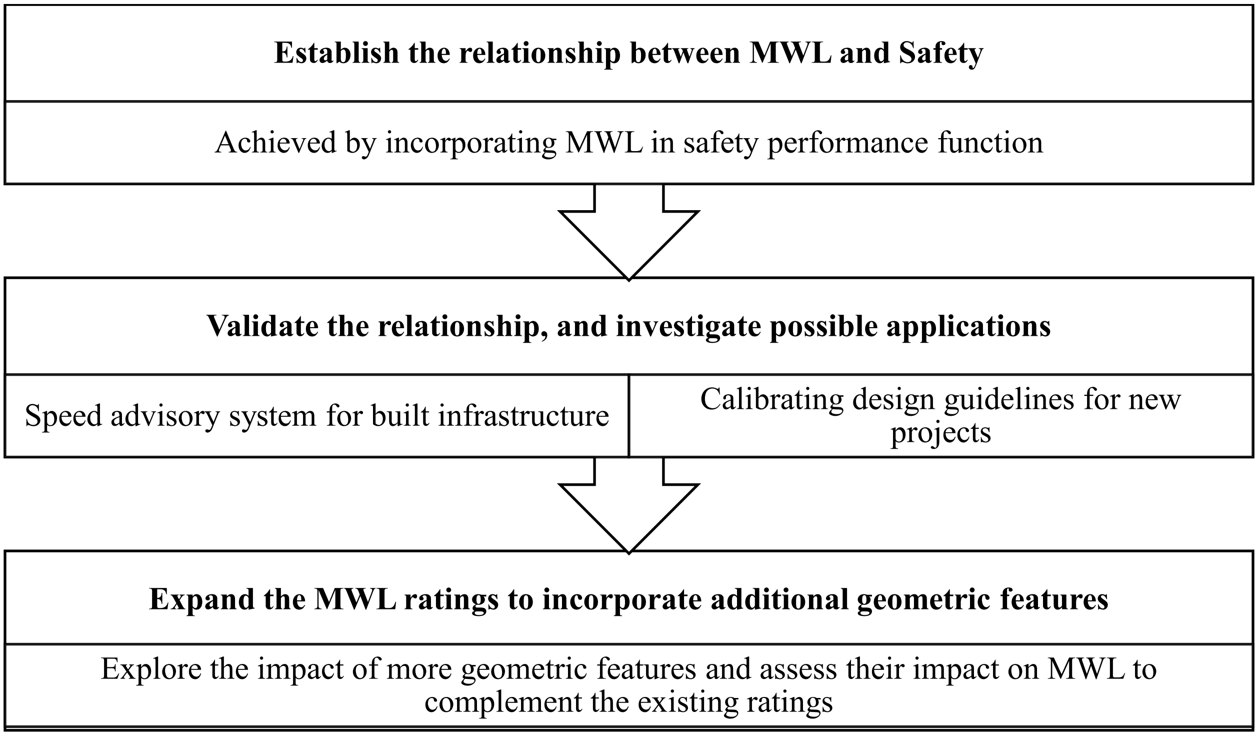


FIGURE 1.1 Summary of the thesis objectives

After achieving the listed objectives, this study explores some more recent factors and circumstances that highway drivers face via a survey of transporation experts. The survey is necessary to partially validate previous research on MWL ratings (9). In addition, adding more factors and their corresponding ratings address recent trends such as active transportation or in-car technologies.

In summary, the objectives contribute to a gap in the literature regarding the explicit inclusion of MWL demand in geometric highway design by considering the complexity of each highway segment differently. For example, a 2.5 second perception reaction time (PRT) for highway design is impractical because the complexity varies as the geometric design changes. Additionally, the research presented in this thesis facilitates a transition from subjective workload measure (survey) to transportation engineering applications such as SPFs, calibration of design guidelines, and estimation of PRT for different design elements.

1.4 THESIS SCOPE

The research in the body of this thesis focuses on Canadian and North American highway environments. For the first three studies, the Light Detection and Ranging (LiDAR) data collected on the highways of Alberta, Canada, were used to provide the studies with all input data required, such as the available sight distance (ASD) and highway geometric design attributes. The survey study collected ratings for the geometric design attributes from transportation experts in Canada and the US. Further, the collision data used was from the records on Alberta highways provided by Alberta Transportation. Then, the geometric design tied the collision records to the MWL demand. The identification of the MWL demand was achieved by using the subjective workload ratings of the geometric design extracted from LiDAR data.

The safety performance function was developed from a highway safety perspective to investigate the relationship between MWL and collisions. Safety performance functions are used to predict the long-term collision frequency and better understand the likelihood of a collision. The incidence rate ratio is developed based on the safety performance function factor coefficients to facilitate the interpretation of different variables such as the MWL.

Another statistical method used was a reliability analysis that assesses the risk linked to a given design. The reliability analysis was used to test for the sufficiency of the MWL SSD values for the population of drivers. As a result, the reliability analysis validates and calibrates the guidelines by incorporating the MWL design values to provide sufficient SSD.

The studies solve a gap in the design guidelines that overlook subjective workload measure ratings. Since the work presented here assumes that diverse geometric highway elements impose different MWL demands on drivers, varying SSD and PRT should be provided for those with distinct complexities (MWL demand).

1.5 THESIS STRUCTURE

This thesis aims to assess the impact of the mental workload demand by the geometric design of highways by 1) proving and quantifying the relationship between mental workload demand imposed by the highway road design and collision rates. If the connection is established and quantified, it is necessary to 2) calibrate the design guidelines to include mental workload when designing highways that mitigates human error. If changing the current infrastructure is infeasible, 3) advisory speed limits can ensure drivers have enough time to make proper decisions. Finally, 4) new assessments of the driving environment are developed to face highway design challenges such as cyclists on shoulders, partial in-vehicle automation, and changing weather conditions. This will offer the opportunity to further undertake future research that includes the changes in the highways and vehicles design.

The thesis is organized as follows: Chapter 1 presents a study that developed a safety performance function, modelling collisions based on the mental workload demand by the geometric design of highways. Then, Chapter 2 calibrates the design guidelines by incorporating mental workload requirements. This will guarantee sufficient stopping sight distance for drivers on a different combination of horizontal and vertical crest curves. Chapter 3 provides advisory speed limits for

41 different curves while considering mental workload demand and available sight distance. Finally, Chapter 4 expands the current knowledge on the impact of surrounding highway environments on drivers by surveying experts to provide an updated assessment for the highway design elements, surrounding environment, and in-car automation technology.

2 INVESTIGATING THE EFFECTS OF MENTAL WORKLOAD ON HIGHWAY SAFETY

This chapter formulates the impact of the MWL demand on safety using SPF.

2.1 INTRODUCTION

Driving is not only the physical activity of turning the steering wheel and applying pressure on the pedals; it is a highly visual and mental task that requires total concentration. Visual activities include scanning the road; detecting and reading traffic control devices, such as signs; communicating with other road users; and monitoring in-vehicle devices, such as the speedometer. As such, driving is clearly a demanding task where drivers are expected to have high levels of attention with the ability to continuously shift between multiple tasks in order to respond to different driving demands while processing large amounts of information in a dynamic road environment.

Driving demands can be caused by external or internal factors due to the road environment or as a result of built-in vehicle devices, respectively. While several studies investigate the relationship between internal factors and mental demand, few studies have focused on understanding the effects of external factors (i.e., road environment) on mental demand. However, in both cases, the driving demand requires drivers to be mentally engaged. It is clear that balancing mental demand by reducing driver workload at or near complicated alignment elements (such as curves, bridges, intersections, etc.) is crucial for safe driving. Hoedemaeker (19) defines MWL as the amount of information the driver needs to process in order to make a situation-dependent decision. Research evidence consistently shows that the risk of being involved in a collision could be highly associated with the driver MWL because of its effect on the performance and safety of driving (20). Dingus et al. (21) showed that failure of concentration was the first contributing factor to road collisions.

It was also noted that the majority of collision types involves loss or lack of driver's attention. In fact, driver inattention was found to contribute to 78% of collisions and 65% of near misses. The assessment of MWL should be an essential component in road safety as it represents the mental effort needed by a driver to process information from road geometry, traffic control devices, and other road users. Driver's MWL assessment is useful, especially when it is related to external factors such as geometry, traffic, and visibility (22).

Considering that managing the MWL of the driving task could improve the safety of drivers (23), the main objective of this chapter is to investigate the relationship between MWL and road collisions quantitatively. To achieve this overarching goal, this chapter focused on the following sub-objectives: i) identify a method to compute MWL based on external factors, ii) extract all of the road features that could potentially affect MWL for a select group of locations, and iii) conduct a cross-sectional study using a safety performance function that incorporates MWL as a model covariate. While enough evidence exists to support the reasonable conclusion that safety is affected by changes in MWL, there is no quantitative evidence of this effect. Therefore, quantifying the effect of MWL could improve the design process by, not only meeting the operational needs of the highway, but also ensuring that existing geometric layouts do not overwhelm drivers to the point that their safety is compromised.

2.2 PREVIOUS WORK

It is clear from the literature that there is a relationship between design consistency and collisions (24-25). It is worth noting that MWL is an important design consistency measure (9). Consequently, one might intuitively presume that a relationship between MWL and collisions exists, and several research studies make this assumption. However, a quantitative relationship between MWL and collisions has never been demonstrated. While many studies implicitly assume that MWL and safety are related, there is no hard evidence to that effect. The significance of design consistency stems from the fact that many collisions occur due to unexpected changes in road alignments as a result of sudden changes in cross-section, horizontal, and vertical curvatures, etc. Similarly, MWL is important because the complexity of specific locations may require closer attention, which is translated into more decision times and, as a result, requires longer sight distances than advised in design codes. Consequently, there is a necessity to study MWL as a contributing factor to collision occurrence for both normal and distracted drivers.

MWL is the demand time needed by the driver to perform a given task (9). A relationship between MWL and collisions was assumed because of the lack of adequate reaction time in complex situations for some age groups (26). Generally, many factors interfere with a driver's mental MWL capacity, such as using mobile phones, listening to music, and even driving in quiet electric cars (27-29). Built-in technological devices and traffic complexity pose challenges to a driver's MWL (30-32). Other factors such as geometric layout require high concentration and mental response levels. For instance, using a driving simulator, Cantin et al. (13) found a relationship between increased probe reaction time and the complexity of the situation or the task (intersection or maneuver) that shows that a higher MWL was required for complex driving situations. They also found that older drivers required more probe reaction time than younger drivers, relating age to MWL (13). In a different study that investigated the relationship between age and MWL, three age groups were compared with respect to reaction time. The group of older drivers always needed more reaction time, especially at more complex locations, such as horizontal curves, which translates into a reduced ability to deal with complex situations when a high MWL is required (17, 33). Roadside advertising was also found to adversely affect driver's attention and lateral control concerning visual workload; the effect was even more pronounced on rural roads (34).

Following the same logic, MWL was found to be higher on crowded (traffic dense) road sections (20). Even the type of road was found to affect driver's MWL. In a car-following situation, in comparison with longitudinal sections, drivers on curved segments drove with lower mean speed and did a higher number of corrections for wheel steering (35). Other geometric features, such as roundabouts, are problematic when dealing with MWL due to the high level of complexity associated with maneuvering, especially for heavy trucks. Roundabouts are more complex to deal with due to the continuity of flow, unlike signalized intersections, which are governed by signal times (36-37). In this respect, a study using corrections to wheel steering to measure the MWL of heavy trucks in roundabouts found that even in single roundabouts, a high level of difficulty maneuvering was detected (38). On vertical alignments, it was found that drivers' heart rate increased by 40% when driving on long downhill sections (about 3.5%). As a result, drivers were more likely to feel tired (39). The previous results were confirmed by another study that found more than 30% increment increase in heart rate when driving on 3-4% downgrade segments (40).

In summary, MWL capacity is affected by various factors. Driver's age and geometric layout are two of the most important factors that impact the MWL capacity. Most of the studies in the literature are simulation-based, and examine the impact of various factors on MWL capacity. For instance, comparing the performance of various age groups making decisions in different driving situations and different geometric layouts. To the best of our knowledge, no studies were able to find a quantitative relationship between MWL and collisions. Such quantification will help enrich our understanding of the impact of different geometric features on MWL. As a result, the main contributions of this study are i) to create MWL ratings based on information that is presented in Table 2.1 (9), ii) to utilize new data sources such as LiDAR data to extract different geometric features and assign them the corresponding MWL ratings iii) to quantify the relationship between MWL and collisions using a safety performance function.

2.3 METHODOLOGY

2.3.1 MWL and Design Process

A study by Messer in 1980 examined design consistency on highways from an MWL perspective (9). Mainly, the study developed a novel methodology to identify the MWL level needed for different geometric features as well as their combinations. MWL levels were represented by ratings ranging from 0 (for tangent section) to 7.7 (for sharp horizontal curve), where 0 represents the least complex situation and 7.7 representing the most complex one. The rating process was undertaken by a group of 21 design engineers and researchers who had expertise in human factors as well as highway and traffic engineering. The rating process was undertaken for 9 basic geometric features for 2-lane and 4-lane highways with design speeds ranging from 80-to-130 km/h. Then, based on the ratings given for different locations, each location was compared to the preceding and the following location in order to identify the design consistency based on the MWL needed (9). The study produced tables that show the MWL ratings for different geometric features as shown in Table 2.1.

TABLE 2.1. Workload Potential Ratings

<table>
<tr><th colspan="6">Horizontal Curves</th></tr>
<tr><th rowspan="2">Degree of Curvature (D°)</th><th colspan="5">Deflection Angle°</th></tr>
<tr><th>10</th><th>20</th><th>40</th><th>80</th><th>100</th></tr>
<tr><td>1</td><td>0.5</td><td>1.0</td><td>2.1</td><td>4.1</td><td>6.2</td></tr>
<tr><td>2</td><td>1.2</td><td>1.5</td><td>2.0</td><td>3.0</td><td>4.1</td></tr>
<tr><td>3</td><td>2.1</td><td>2.3</td><td>2.6</td><td>3.3</td><td>4.0</td></tr>
<tr><td>4</td><td>3.1</td><td>3.2</td><td>3.5</td><td>4.0</td><td>4.5</td></tr>
<tr><td>5</td><td>4.0</td><td>4.1</td><td>4.3</td><td>4.7</td><td>5.2</td></tr>
<tr><td>6</td><td>5.0</td><td>5.1</td><td>5.3</td><td>5.6</td><td>6.0</td></tr>
<tr><td>7</td><td>6.0</td><td>6.1</td><td>6.2</td><td>6.5</td><td>6.8</td></tr>
<tr><td>8</td><td>7.0</td><td>7.0</td><td>7.1</td><td>7.4</td><td>7.7</td></tr>
<tr><th colspan="6">Vertical Curves</th></tr>
<tr><th colspan="3">No. of Crest Curves in Prior 1500 meters</th><th colspan="3">Workload Potential Rating</th></tr>
<tr><td colspan="3">≤ 2</td><td colspan="3">1.9</td></tr>
<tr><td colspan="3">≤ 3</td><td colspan="3">3.0</td></tr>
<tr><td colspan="3">≤ 4</td><td colspan="3">4.0</td></tr>
<tr><td colspan="3">≤ 5</td><td colspan="3">5.0</td></tr>
<tr><td colspan="3">> 5</td><td colspan="3">6.0</td></tr>
<tr><th colspan="6">Intersections</th></tr>
<tr><th colspan="2">Highway</th><th colspan="2">Type of Approach</th><th colspan="2">Approach Stop or Yield or Controlled</th></tr>
<tr><td colspan="2" rowspan="2">Two-Lane high-design</td><td colspan="2">Unchannelized</td><td colspan="2" rowspan="2">4.0</td></tr>
<tr><td colspan="2">Channelized</td></tr>
<tr><td colspan="2" rowspan="2">Four-Lane Undivided</td><td colspan="2">Unchannelized</td><td colspan="2" rowspan="2">4.0</td></tr>
<tr><td colspan="2">Channelized</td></tr>
<tr><td colspan="2" rowspan="2">Four-Lane Divided</td><td colspan="2">Unchannelized</td><td colspan="2" rowspan="2">4.0</td></tr>
<tr><td colspan="2">Channelized</td></tr>
<tr><th colspan="6">Lane Drops (undivided highways)</th></tr>
<tr><th colspan="3" rowspan="2">Lane Drop Direction</th><th colspan="3">Workload Potential Rating for Prior Section Lengths</th></tr>
<tr><th>≤ 3.2 km</th><th>≤ 8.0</th><th>≥ 8.0 km</th></tr>
<tr><td colspan="3">4 to 2</td><td>2.5</td><td>3.0</td><td>3.9</td></tr>
<tr><td colspan="3">2 to 4</td><td>1.5</td><td>1.5</td><td>1.5</td></tr>
</table>

2.3.2 Horizontal and Vertical Feature Extractions

To estimate the potential MWL ratings at each location where there is a change in road geometry, certain geometric characteristics of horizontal and vertical alignment are required. Information on vertical alignment of the road was extracted using AutoCAD Civil 3D software and a MATLAB algorithm that was developed by Gargoum et. al (41). For vertical alignment, the presence, and locations of crest curves are probably more important compared to other features. The extraction process involved three stages, which are explained in Figure 2.1. The first stage was the generation of the centerline of the road and extraction of horizontal features. The second stage was creating a 3D surface for the road segment and overlaying the centerline of the road on the surface. The third stage included the generation of the roadway profile and identifying the location of vertical curves.

The first stage included extracting the road centerline. The developed MATLAB algorithm extracts the path of the data collection vehicle. This could be done by filtering the LiDAR points contained in the LAS file (file format designed to archive LiDAR point cloud data) with a zero scanner angle (these points lie on the road surface just perpendicularly below the scanner lens). The extracted points represent the path of the data collection truck, which is parallel to the road axis. This group of points was imported into Civil 3D and the “best-fit alignment” tool was utilized to generate the centerline of the road by fitting a line that is the best fit for this point group. Then, the "adding labels" tool was used to display characteristics of horizontal curves that include curve radius and angle of horizontal deflection.

In the second stage, a 3D surface of the road was created, and the centerline was overlaid in order to generate the road segment profile. The point cloud data (i.e. LAS file of the segment) was imported into Civil 3D, which reads x,y,z information for all points. This is followed by using the "create surface" tool to generate a 3D surface for the road by connecting all the points that are closest together making a Triangular Irregular Network (TIN) surface. Thereafter, the "best-fit" road centerline was overlaid onto the road surface in order to generate the road profile.

The final stage included generating the vertical profile. As Civil 3D assigns elevations from the created 3D surface to each point on the generated road centerline, the "create profile" tool was used to generate a longitudinal profile of the road segment. Because of the high density of LiDAR points, imperfections in the pavement surface are captured on the road profile. Thus, the "best-fit profile" tool was used to smoothen the generated profile in order to create best-fit longitudinal grade lines and vertical curves (without any imperfections) for the extracted road profile. Finally, the resulting road profile can be used to read any information related to location or curvature of crest curves. For horizontal curves, the horizontal curve radius and angle of horizontal deflection influence the MWL. Global positioning system (GPS) data were used to identify the locations of horizontal curves and verify horizontal curve radii obtained from LiDAR data. The generated horizontal alignment and vertical profile, along with the extracted information, are shown in Figures 2.2.a and 2.2.b.

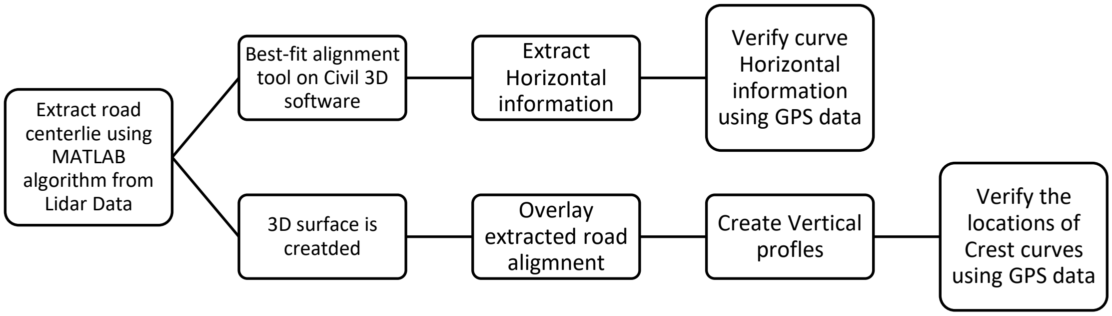


FIGURE 2.1 Flow chart showing the procedure of extracting geometric characteristics

2.3.3 Assigning MWL Ratings

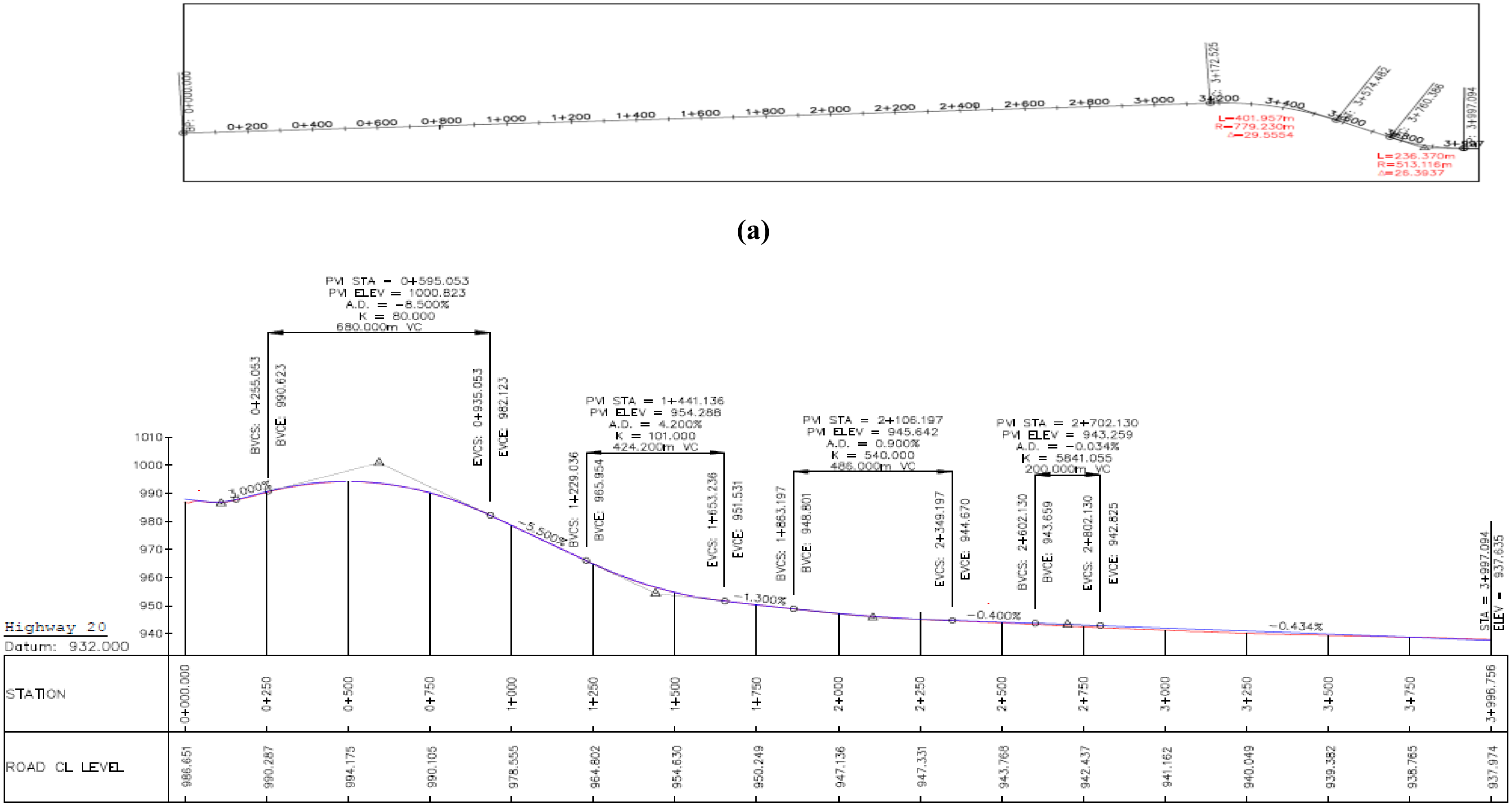
Once the geometric features were extracted, they were assigned ratings based on information in Table 2.1, taken directly from Messer's study (9). In this respect, it is important to note that the ratings of two or more geometric elements were combined together when the distance between the geometric elements was less than 457 meters. Messer suggested this distance because the unfamiliar motorists need time to recover from the experience of driving through the first unexpected feature before perceiving the next one (9). For example, if an intersection lies within 457 meters to a crest curve, then their ratings are combined. In this study, the ratings were assigned at the start of each study location with a buffer zone of only 457 meters both before and after the location's starting station (9). The example in this paper presents the ratings for a 3.6-km section, for the sake of presentation.

For this study, ratings were assigned for 46 two-lane, two-way highways in the Province of Alberta, Canada (42). Figures 2.2.a and 2.2.b show an example of the features extracted for one section using Civil 3D. The extracted features are used to calculate the MWL rating process based on Table 2.2.

Figure 2.2.a shows the horizontal features of the alignment. The alignment starts with a tangent from station 0+ 000 until station 3+172.525 where a horizontal curve starts and then ends at station 3+760.386. Another tangent extends between stations 3+574.482 and 3+760.386, where a second horizontal curve starts and finally ends at station 3+997.094. Additionally, the characteristics of the horizontal curves are labeled on each curve showing L the horizontal curve length, R the horizontal curve radius, and Δ the deflection angle of the horizontal curve. The extracted value of R is used to calculate the degree of curvature (D°), which is then used conjunctionally with the Δ to obtain the MWL ratings, as seen in Table 2.1.

Figure 2.2.b depicts the vertical characteristics of the alignment. Only the location of the crest curve is needed for the MWL rating assignment. However, a full extraction of the vertical profile features (i.e., crest and sag curves as well as the grades) are shown in Figure 2.2.b. The featured

alignment contains one crest and three sag curves. For example, the crest curve starts at station 0+255.053 and ends at station 0+935.053. The labels on the crest curve show the value of *K, length* of curve (*VC)*, station of the point of vertical curve, and the elevation of the point of vertical curve. In addition, the grades before and after the crest curve were computed. Similarly, the labels are shown for all sag curves.



STATION	0+000.000	0+250	0+500	0+750	1+000	1+250	1+500	1+750	2+000	2+250	2+500	2+750	3+000	3+250	3+500	3+750	3+996.756
ROAD CL LEVEL	986.651	990.287	994.175	990.105	978.555	964.802	954.630	950.249	947.136	947.331	943.768	942.437	941.162	940.049	939.382	938.765	937.974

(b)

FIGURE 2.2 Generated (a) horizontal alignment and (b) vertical profile

2.3.4 Collision Analysis

To investigate the relationship between MWL and safety, a SPF was developed. Let Y_i denote the number of collisions at highway segment $i (i = 1, \dots, n)$. It is assumed that collisions at the *n* segments are independent and that

$$Y_i | \theta_i \sim Poisson(\theta_i). \quad (1)$$

To address over-dispersion for unobserved or unmeasured heterogeneity, it is assumed that

$$\theta_i = \mu_i \cdot exp(u_i), \quad (2)$$

where

$$\ln(\mu_i) = \beta_0 + \beta_1 \cdot \ln(Length_i) + \beta_2 \cdot \ln(AADT_i) + exp^{\beta_3 \cdot WLI_i}, \quad (3)$$

where *Length* is a covariate representing segment length in km, *AADT* is the Average Annual Daily Traffic, *WLI* is the Workload Index: $\beta_0, \beta_1, \beta_2, \beta_3$ are model parameters and the term $exp(u_i)$ represents a multiplicative random effect. The Poisson Lognormal (PLN) regression model is obtained by the assumption

$$exp(u_i) \sim Lognormal(0, \sigma_u^2) \qquad \text{or} \qquad u_i \sim N(0, \sigma_u^2), \quad (4)$$

where σ_u^2 denotes the extra Poisson variance.

To obtain the full Bayes estimates it is required to specify prior distributions for the parameters. The most commonly used priors are diffused normal distributions (i.e., zero mean and large variance) for the regression parameters, and $Gamma(1, \varepsilon)$ for σ_u^{-2}, where ε is a small number, e.g., 0.01 or 0.001.

The incidence rate ratio (IRR), i.e., $exp(\beta)$, was calculated to facilitate the interpretation of the Workload Index. When a Poisson hierarchal model is used, the exponents of coefficients are equal to the incidence rate ratio, which is a measure of relative risk. For example, IRR(X_j) = exp(−0.1) = 0.90, this would indicate that a unit increase in X_j is estimated to reduce the mean crash rate by 10%. In this paper, X_j is a variable representing the Workload Index.

The posterior distributions needed in the full Bayes approach were sampled using the MCMC techniques available in WinBUGS (43). The BGR statistics, ratios of the Monte Carlo errors relative to the standard deviations of the estimates, and trace plots for all model parameters were monitored for convergence.

A posterior predictive approach (44-46) was used to assess the goodness-of-fit (adequacy) of the model. Such procedures involve generating replicates under the postulated model and comparing the distribution of a certain discrepancy measure, such as the chi-square statistic to the value of chi-square obtained using observed data. A model does not fit the data if the observed value of chi-square is far from the predictive distribution; the discrepancy cannot reasonably be explained by chance if the p-values are close to 0 or 1 (43).

A total of $n=46$ two-way, two-lane highway segments in the Province of Alberta were investigated for the purpose of developing a safety performance function relating the safeness of these highway segments to their traffic, their geometric, and their MWL characteristics. The crash data and traffic data were obtained from the Province of Alberta and covered the period between 2008 and 2012, while the LiDAR data was collected between 2013 and 2015.

2.4 DATA

2.4.1 Crash and Traffic Data

In order to investigate the relationship between MWL and the occurrence of road collisions, traffic and collision history data were assembled for all 46 locations. Traffic data and highway collision data from 2008 to 2012 was used for the studied sites.

2.4.2 LiDAR Data

LiDAR is a remote-sensing technology that uses laser lights to scan features and record reflected pulses that carry highly dense and accurate x,y,z measurements for these features. These measurements can then be used to generate accurate 3D models of objects. Since 2012, Alberta Transportation has collected LiDAR data of Alberta highways. Because of the high point density, the collected data for a given highway is saved in multiple LAS files. Each LAS file represents a segment of a 4-km length of the highway and the average segment file size is 600MB. The data was collected in normal traffic flow conditions and at posted speeds up to 100km/h. Provincial surveys at a speed of 90 km/h have point density ranges from 150 to 1000 points/m^2. As mentioned, a 4-km segment of Highway 20 in Alberta was used in this study as an example of the procedure for extracting the geometric features and assigning MWL ratings. The LAS file size of this segment was about 690MB and it contains more than 22 million points. Figure 2.3 shows a point cloud image of the selected segment. To assign ratings for the geometric features of the studied location, geometric characteristics of horizontal and vertical curves were extracted as described in the methodology.

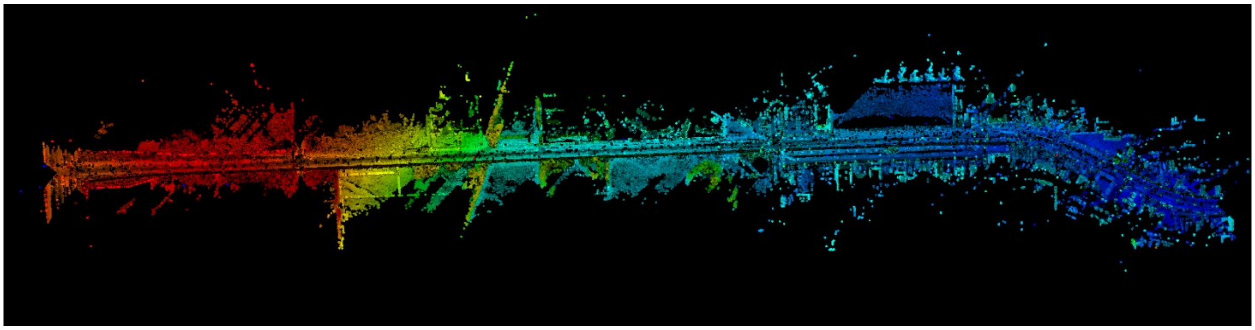


FIGURE 2.3. Point cloud data of the studied segment part of Highway 20

2.5 RESULTS & DISCUSSION

2.5.1 Mental Workload Ratings

Based on the procedure explained in the methodology, the results of MWL calculations are summarized in Table 2.2. In addition, Figure 2.4 shows the potential MWL ratings for the extracted horizontal alignment and vertical profile for a 3.6-km section. Figure 2.4 is the same as Figure 2.2 but with the MWL rating assigned on every change in the cross section. For example, at station 0+000, there is only one intersection, and it was assigned an MWL rating of 4.0 according to Table 2.2. The rating is represented by red a line at station 0+000. The same procedure is followed at all sections. Moreover, Figure 2.4 shows the start and end of the study location at stations 0+825 and 2+449, respectively. Furthermore, it shows the locations of highest and lowest MWL ratings at stations 0+791 and 2+680, respectively. Again, in this study only the MWL rating of the section preceding the study location was included in the model.

The rating process followed the procedure explained in the ‘Assigning MWL Ratings’ section. For instance, at station 0+000, there is only a single intersection. By checking Table 2.1, the intersection rating is 4. As a result, the total rating for station 0+000 is 4. Similarly, at station 0+791 there are three different geometric features which are an intersection, a crest curve, and a change in the cross section from 2-to-4 lanes. According to Table 2.1, the intersection has a rating of 4.0, while the presence of a crest curve has a rating 1.9, and the change in cross section from 2-to-4 lanes has a rating of 1.5. Consequently, a total score of 7.4 is computed for this section after adding all three ratings.

TABLE 2.2. Shows Ratings for Stations at Different Changes of Cross Sections

Station	Intersection?	Crest in Prev. 1500?	Horizontal Curve?	Cross section Change?	Total Potential Rating	Ranking From High Workload to Low
0+000	YES	NO	NO	NO	4.0	5
0+377	NO	NO	NO	YES 4 to 2	2.5	6
0+595	NO	YES	NO	NO	1.9	7
0+791	YES	YES	NO	YES 2 to 4	7.4	1
1+060	NO	YES	NO	YES 4 to 2	4.4	4
2+420	YES	NO	NO	YES 2 to 4	5.5	3
2+680	NO	NO	NO	YES 4 to 2	2.5	6
3+100	YES	NO	NO	YES 2 to 4	5.5	3
3+170	NO	NO	YES	NO	6.7	2
3+600	YES	NO	NO	NO	4	5

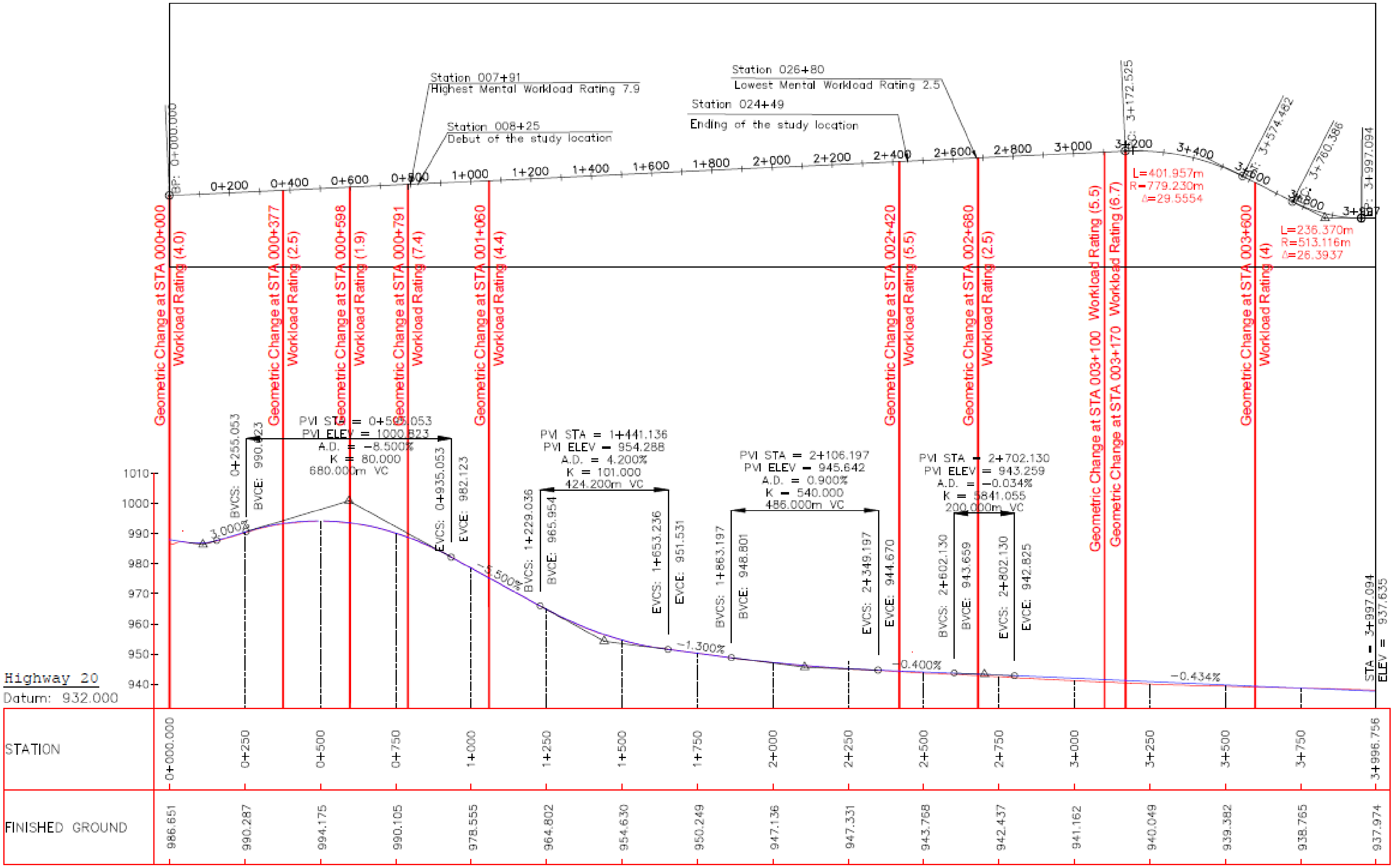


FIGURE 2.4 Potential workload ratings based on the extracted horizontal alignment and vertical profile

2.6 COLLISION ANALYSIS RESULTS

The posterior summaries in Table 2.3 were obtained via WinBUGS using two chains with 50000 iterations each, 10000 of which were excluded as a burn-in sample. Examination of the BGR statistics, ratios of the Monte Carlo error relative to the standard deviations of the estimates and trace plots for all model parameters indicated convergence (47-50).

To assess goodness-of-fit, the distribution of the chi-square discrepancy measure in replicated datasets was generated. The observed value of chi-square was located near the center of the replicated distribution, with an associated p-value of 0.524. As a result, the PLN model was found to perform well in terms of accommodating the variation in collision frequency across the highway segments.

Table 2.3 summarizes the parameter estimates and their 95% credible intervals for the PLN model. The table shows that the parameter estimates are significant, as the 95% credible intervals were bounded away from zero. Except for the intercept, the regression coefficients were all positive, indicating that factors such as segment Length, AADT, and the Workload Index are positively associated with the predicted collisions. The estimate of σ_u^2 was statistically significant, demonstrating the presence of over-dispersion in the data.

TABLE 2.3 Parameter Estimates, Standard Errors and Credible Intervals for PLN model

	Parameter	**Estimate**	**Standard Error**	**95% Credible Intervals**	
				Lower Limit	**Upper Limit**
Intercept	β_0	0.041	0.770	-1.495	1.559
Ln(Length)	β_1	0.360	0.114	0.138	0.585
Ln(AADT)	β_2	0.338	0.088	0.163	0.513
Workload Index	β_3	0.069	0.016	0.038	0.099
Variance	σ_u^2	0.026	0.013	0.007	0.056

The posterior estimate of the IRR and its 95% credible intervals for the Workload Index was calculated as 1.071 and (1.039, 1.105), respectively. These results indicate that the collision risk increased with workload. In fact, each time the Workload Index increased by one unit, the collision rate increased by 7.1%. This value was computed using the incidence rate ratio equation described in the methodology.

The above analysis resulted in an SPF that related the expected number of collisions to the AADT and most importantly, the Workload Index. However, using SPF might not be an intuitive task for some designers. Typically, design engineers need to choose between several alternative designs, and therefore, they need an effective, simple, and time-saving method to help them to make preliminary decisions. As a result, the SPF were used to produce design charts to facilitate the designers' task. Based on the results summarized in Table 2.3, the final model can be expressed as

$$Y = \text{collisions/5years} = \exp(0.041) * Length^{0.36} * AADT^{0.338} * e^{0.069\,\text{Workload Index}} \tag{5}$$

To calculate the number of collisions per 1-km, Equation (5) could be rewritten as

$$S = \text{collisions/5years/km} = \exp(0.041) * AADT^{0.338} * e^{0.069\,\text{Workload Index}} \tag{6}$$

where S represents the number of collisions/5years/km.

Figure 2.5 shows the design chart that translates the information in the SPF into a visual guide to easily predict the number of collisions for various AADT levels and MWL ratings. Figure 2.6 shows the values for the correction factor as a function of different highway lengths.

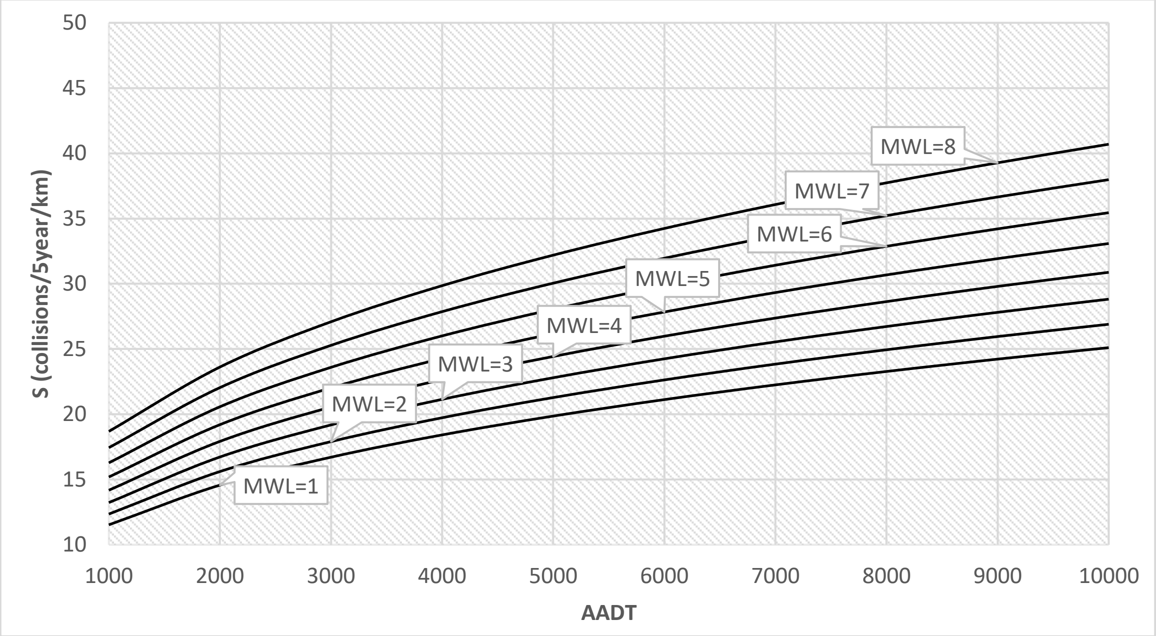


FIGURE 2.5 Design charts showing relationship between MWL, AADT, and collisions

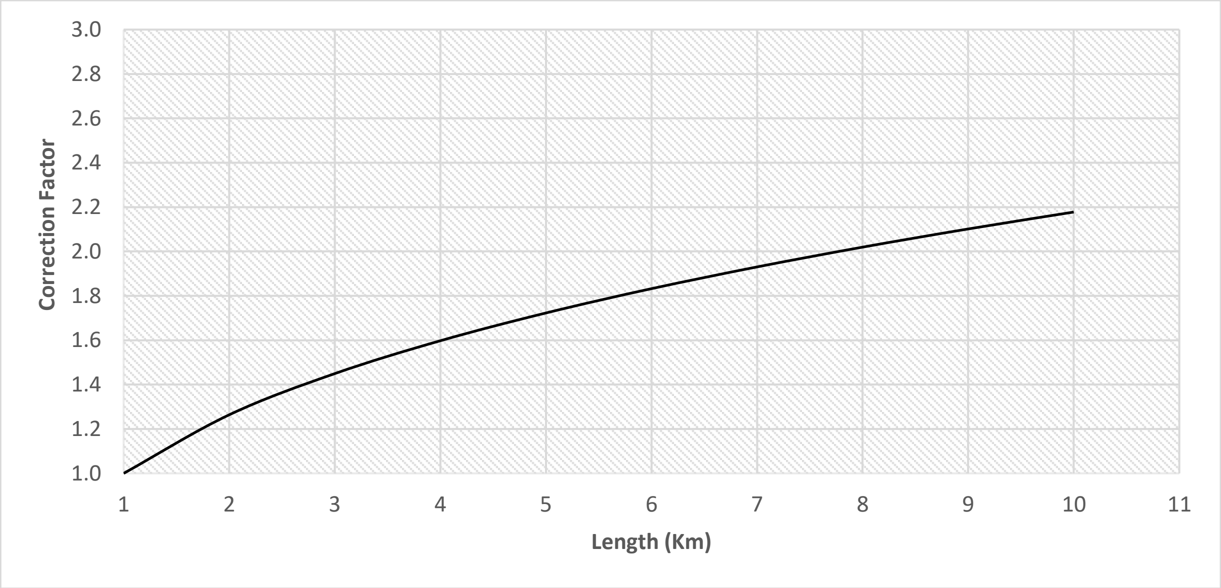


FIGURE 2.6 Correction factor for the road segment length

Figures 2.5 and 2.6 could be used by road agencies to evaluate their designs and predict the expected number of crashes related to varying MWL ratings. For example, in order to calculate the value of S at AADT=5000 and MWL=7, Figure 2.5 would be used. Entering the graph using an x-axis at 5000 AADT and intersecting the curve corresponding to MWL at a value of 7 would lead to an S value of 30 (read from the y-axis). Since the value of S is computed per 1 kilometer, Figure 2.6 could be used to correct this value for any length of segment. For example, if the segment under investigation is 4 kilometers long, then by entering Figure 2.6 with a value of 4 from the x-axis, a vertical line can be created until it reaches the curve leading to a y-axis value of 1.6, which is the correction factor incorporating that the length of the segment under investigation is 4 km. As a result, the final number of crashes for 4 kilometers would be the 30 from Figure 2.5 multiplied by 1.6 from Figure 2.6. The process could be repeated to find the impacts of changing the MWL index from 7 to any other value.

Finally, it is worth mentioning that these graphs are ready to use by engineers based on the data from the Province of Alberta highways. However, any jurisdiction might want to either calibrate the developed SPF (a calibration procedure is available as part of the 2010 Edition of the Highway Safety Manual) or use the adopted methodology in this paper to develop their own SPFs.

2.7 CONCLUSIONS

The main contributions of this study were to identify MWL ratings based on certain geometrical features. This was made possible by using the ratings developed by Messer based on inputs from 21 design engineers and researchers whose expertise was in human factors, as well as highway and traffic engineering. The second objective was to utilize new data sources, such as LiDAR, to extract different geometric features and assign them to the corresponding MWL ratings. Parameters for horizontal and vertical curves on two-lane, two-way highways were first extracted from LiDAR and GPS data using MATLAB algorithms, and the resulting features were summarized using Civil 3D. The third and final objective was to quantify the relationship between MWL and collisions using an SPF. The results, based on the developed SPF, emphasized the significance of including MWL as an explanatory variable. The findings highlighted the need to incorporate MWL during the design process in order to evaluate designs before final approval. To visualize the effects of changing MWL and AADT on collision, a design chart was produced as a quick reference for designers. It is important to note that the analysis of the MWL ratings were limited to those available in the tables developed by Messer (9). A possible limitation is the lack of ratings for other geometric features that were not considered by Messer, such as roundabouts. Moreover, very sharp curves with a degree of curvature (D°) greater than eight degrees were not considered by Messer, and consequently were not addressed in this chapter. As a result, future research should attempt to assign more MWL ratings to all possible geometric features in both rural and urban areas. Furthermore, work zones should be investigated as having a possible relationship to MWL (51). And, the current study could be replicated to study multilane highways. There is value in understanding the relationship between the change in MWL demand and collisions.

Based on the literature, several studies proved a relationship between changes in MWL supply and age. However, this relationship was not quantified. Future research should also investigate visual workload by examining the amount of information in advertising boards, traffic signs, and MWL. Moreover, a more in-depth investigation of the relationship between design consistency and crashes, based on MWL, is required. In this case, design consistency will consider a much larger number of factors, such as feature expectation, driver memory loss, average viewing distance, decision sight distance, and driver unfamiliarity factors (9). As a consequence, there may be an implicit relationship between MWL and self-explaining roads. Additionally, the relationship between MWL and environmental conditions, such as weather and darkness, should be investigated in the future work. Finally, distraction and driver experience were found to have a strong relationship with MWL. While distraction could be tackled by education and enforcement, this relationship needs to be quantified and incorporated into the design process. Such analysis will consider the majority of factors that could potentially interfere with a driver’s mental and visual capacity, including future changes to the drivers’ behaviour that might lead to distraction.

2.8 AUTHORS CONTRIBUTION

The authors confirm contribution to the chapter as follows: study conception and design: Karim Habib, Karim El-Basyouny, Amr Shalkamy; data collection: Karim Habib; analysis and interpretation of results: Karim Habib, Amr Shalkamy, Karim El-Basyouny; draft manuscript preparation: Karim Habib, Karim El-Basyouny, Amr Shalkamy.

3 CALIBRATING DESIGN GUIDELINES USING MENTAL WORKLOAD AND RELIABILITY ANALYSIS

The work in this chapter uses reliability analysis to investigate the adequacy of MWL SSD.

3.1 INTRODUCTION

Design guidelines provide deterministic values for design inputs, such as PRT and, consequently, SSD. Inadequacies can result since design guidelines assume that there are few differences in drivers' behaviour while traversing various alignment elements, specifically on horizontal curves. The literature shows that horizontal curves are relatively more dangerous than other highway portions (52). Research has shown that there were higher collision rates on horizontal curves compared to tangential sections (53). Furthermore, factors influencing operating speeds on highways were not the same for tangential and curved sections. This confirms the necessity to account for the diversities of the driving population since various geometric features (i.e., horizontal curves, vertical curves, intersection, etc.) are expected to affect drivers in varying ways. Additionally, different sharpnesses of curves and ASD can change drivers' speed choice and driving behaviour while navigating various road elements (54-55).

The failure to include human factors is a significant limitation of current design guidelines. The complexity of including human factors in the design process, such as MWL, drivers' ages, distraction, and fatigue, may contribute to the lack of research (8). While driver fatigue and distraction could be addressed through education or enforcement campaigns, the MWL demands imposed by highways are usually attributable to the design engineer's different geometric features that are design-dependent and controlled (56). It is, therefore, advisable to accommodate human capabilities, or as much of them as possible without increasing cost requirements, to ensure drivers conform to the designed facility. For example, providing sufficient PRT and, subsequently, an appropriate SSD will allow drivers ample time to take appropriate actions or make decisions, which will result in fewer errors.

It is essential to consider the different demands various geometric features place on drivers' MWL supply. Those differing MWL demands are mainly caused by varying complexities presented by the design elements; for example, an intersection is more complicated than a tangent section (9). These complexities will also require more SSD, so drivers will have more time to make appropriate decisions. Thus, it is necessary to explore ways to account for MWL in the estimation of SSD.

The main goal of this study is to translate these MWL levels into design guidelines to improve highway safety. In this respect, highways in the Province of Alberta, Canada, were studied. The necessary input data for this study were the available sight distance, which was obtained from LiDAR data using automated scripts. Then, a reliability analysis was used to account for the difference between ASD and the newly calculated SSD based on MWL. To achieve this goal, there was a need to i) convert the MWL ratings developed by previous research (9) into design attributes, such as design speed and MWL stopping sight distance (SSD_{MWL}), which was calculated based on MWL design speed (V_{MWL}); ii) investigate the credibility of these values by undertaking reliability analysis; and iii) compare the results from ASD, SSD_{MWL}, and SSD suggested by a recently novel method (57) based on the probability of non-compliance.

3.2 LITERATURE REVIEW

3.2.1 Mental Workload: Definition, Impacts, and Quantification

Mental workload is the rate of time needed by a driver to make decisions and perform a given driving task (9). In this respect, numerous factors can impact drivers' cognitive capabilities. Those factors vary from human factors to road environment factors. Also, all road users are influenced differently by changing levels of MWL demand. The road users in question may include conventional or autonomous car drivers, cyclists, or even pedestrians. The focus of this study is the geometric design environment and its relationship to MWL. Nevertheless, the literature review includes studies on different road users and different factors for the sake of completing the work.

Many factors affect a driver's supply of mental workload, such as age, driving environment complexity, and changes in infrastructure (13, 33, 17). Other factors can impact drivers' workload, such as using a cell phone, smartphone, and smartwatch (58-60). Moreover, engaging in activities, such as singing or even listening to music while driving, was found to affect drivers' performance (27, 61).

Consequently, the available MWL supply is a significant component for all road users. Drivers have different capabilities, and these cognitive capabilities are influenced by different factors, as explained before. These factors could be internal, dependant on the road user, or external, according to the road environment. The internal factors were summarized above, such as the age of drivers, fatigue, etc. while the external factors result from the design of the roads. For example, the geometric design of highways can exert high levels of MWL challenging drivers' MWL supply according to the level of complexity. In other words, a heavily traffic-dense, signalized intersection is more complex and cognitively taxing on a driver than a tangent section. As a result, including human factors in the design procedure is a must to guarantee MWL demands do not overwhelm drivers MWL capacity.

Several simulation-based studies explored the impact of road environment (design) and the MWL it poses on drivers such as a study by Bongiorno et al., who investigated the connection between MWL and road environment (22). This study included both dynamic and static objects that the drivers may face in a road environment. For instance, a parked vehicle is an example of a static object, while cyclists traveling near a driver in the same or opposite direction were considered dynamic objects. The MWL posed by all these objects was tested by calculating the eye fixation time where there is a directly proportional relationship between MWL levels and eye fixation time. A different study proved a relationship between the design of roundabouts and the levels of MWL (22). The existence and the configuration of work zones were also found to be directly related to higher levels of mental workload (62). Also, the placement and the inner distance between traffic signs placed demands on a driver's MWL (63). Moreover, proper road design is crucial, especially to ensure proper traffic movements, such as maneuvers, because they are also linked to drivers' workload (64). Furthermore, horizontal curves required a higher workload supply than straight sections (tangents) (65-66). Additionally, vertical curves influence drivers' decisions as they affect their perception of horizontal curves (67).

In summary, different design components contribute to changing MWL levels, such as horizontal curves, vertical curves, and roundabouts, as well as moving/static objects in urban and rural environments. All these road design components create fluctuating levels of MWL that pose challenges to drivers.

A study by Messer (1980) presented a complete methodology for calculating design consistency on highways based on degrees of MWL. This study provided detailed MWL ratings for nine different geometric features where ratings increase when the complexity of the geometric feature increases (9). These ratings ranged between 0 for the least complex highway section, which is a tangent section, and 7.7 for the most complex section, which is a very sharp horizontal curve, as shown in Table 3.1. All MWL ratings for horizontal curves and vertical crest curves are shown in Table 3.1. Also, Messer's study proposed an equation to calculate the MWL speed required for each geometric feature based on its level of complexity/MWL ratings. This speed differs from design speed as follows:

$$V_{MWL} = V_{design\,speed} + 8 * R_f \text{ (7)} \quad \text{and} \quad R_f \geq 2.0 \qquad (1)$$

where

V_{MWL} is the adjusted speed due to MWL demand (km/h); $V_{design\,speed}$ is the base design speed of the highway (km/h); R_f is mental workload ratings from Table 3.1.

Habib et al. assigned the above MWL ratings in Table 3.1 to a sample of 46 highway sections with different geometric features (or a combination of them) and developed a relationship between MWL demands and collisions using a safety performance function (68). The results indicated an increase of 7.1% in collisions for each 1-unit increase in MWL ratings on two-way two-lane highways in the province of Alberta, Canada.

TABLE 3.1 MWL Ratings (R_f) based on Different Degrees of Curvatures and Deflection Angles for Different Horizontal Curves and Number of Vertical Curves (9)

Horizontal Curves					
Degree of Curvature (D°)	**Deflection Angle°**				
	10	**20**	**40**	**80**	**100**
1	0.5	1.0	2.1	4.1	6.2
2	1.2	1.5	2.0	3.0	4.1
3	2.1	2.3	2.6	3.3	4.0
4	3.1	3.2	3.5	4.0	4.5
5	4.0	4.1	4.3	4.7	5.2
6	5.0	5.1	5.3	5.6	6.0
7	6.0	6.1	6.2	6.5	6.8
8	7.0	7.0	7.1	7.4	7.7

Vertical Curves	
No. of Crest Curves in Prior 1500 meters	**Workload Potential Rating**
≤ 2	1.9
≤ 3	3.0
≤ 4	4.0
≤ 5	5.0
> 5	6.0

3.2.2 Reliability Analysis and Road Geometric Design

Road geometric design guidelines, such as the American Association of State Highway and Transportation Officials (AASHTO) policy on geometric design of highways and streets, adapt a deterministic design approach that omits the uncertainty associated with design parameters (69). A drawback of this approach is that many design parameters, such as the operating speed and PRT, are stochastic. To account for this variability, design guidelines use rigid and conservative values for design parameters extracted from the broad range of expected values for design variables (70). Due to the use of deterministic values, the safety margin for the design outputs is unknown. Recently, several studies promoted the use of a probabilistic design approach using reliability theory to account for the uncertainty associated with road geometric design parameters.

The studied geometric design elements include stopping sight distance, passing sight distance (PSD), intersection sight distance, horizontal curves, and vertical curves. Navin (71) is one of the earliest to propose a process, based on reliability analysis, to evaluate the margin of safety and reliability index for SSD in the design of roadways. Second-order reliability methods (SORM) were used to determine the probability of noncompliance for trucks and cars on dry pavement. Sarhan et al. (72-73) and Ismail et al. (74) proposed a reliability-based method for the design of horizontal and vertical curves using SSD as a mode of failure. Easa (75) presented a reliability-based approach for the design of intersection sight distance in the AASHTO for three cases of no control, yield control, and stop control. The probability of non-compliance was estimated using a simple first-order probabilistic analysis method. Llorca et al. (76) studied the probability of failing to meet the PSD requirements of drivers and compared the results with Spanish guidelines. It was found that the design standards used deterministic PSD values, which resulted in up to a 30% probability of non-compliance. Recently, a few studies explored the calibration of road design guidelines using reliability analysis (77). Recent studies on the geometric design of roads advocate using a reliability-based design approach due to the high probability of failure associated with current design standards (e.g., AASHTO) (74-78).

In reliability analysis, a risk measure known as the probability of noncompliance (P_{nc}) is used to assess the probability that a proposed design might not meet the standard requirements (78-80). The stochastic nature of design parameters is accounted for by expressing input parameters in terms of their probability distribution. In this chapter, a reliability analysis is used to compare the difference in the probability of non-compliance obtained using SSD_{MWL} values and the 3D ASD obtained from LiDAR data and SSD recommended by Wood et al. (57).

In summary, studies have attempted to investigate the impact of several factors on drivers' MWL supply using survey or simulation-based techniques. These findings should be supplemented by statistical analysis, which will help relate the factors that affect MWL to collisions. This study performs further investigation based on the work conducted by Messer through undertaking a reliability analysis to understand the link between MWL and design compliance (9). A reliability-based approach is adopted to explore the effect of accounting for the drivers' MWL requirements on horizontal curves, evaluated through changes in the probability of non-compliance.

3.3 METHODOLOGY

3.3.1 Data Collection

LiDAR point cloud data were collected by Alberta Transportation between the years 2013 and 2015 using Tetra Tech PSP-7000, a multifunction pavement surface profiling vehicle. The vehicle is equipped with REIGL VMX 450 system and was used to collect data on multiple highways in Alberta, Canada. Figure 3.1 presents a 4 km point cloud from a provincial highway in Alberta. The data collection is performed at posted speed limits, and a collection speed of 90 km/h produces a density in the ranges of 150-to-1000 points/m^2. Data are saved in multiple .LAS files; each represents a segment of the highway.

3.3.2 Curve Attributes Extraction

A sample of 12 horizontal curves was extracted from LiDAR data. The attributes of the horizontal curves, required for this study, are the degree of curvature (D°) and the delta (Δ°) of the horizontal curves that are necessary to calculate R_f from Table 3.1. The horizontal curves ratings were increased by 1.9 due to the existence of a vertical curve preceding any horizontal curve within a distance of at most 1500 meters (9). For example, the MWL rating for curve one using a degree of curvature = 1.5° and deflection angle = 21° is equal to 1.3 (see Table 3.1). Then, 1.9 is added due to the impact of the vertical crest curve, which leads to a total value for R_f of 3.2. As a result, the V_{MWL} could be calculated by substituting 3.2 for R_f in Equation (1). A complete procedure for data extraction methodology and rating assignment is explained in these studies (41, 68). Table 3.2 shows a detailed explanation for the attributes needed as input for the reliability analysis. The degree of curvature was calculated based on the curve radius, which was extracted from the LiDAR data.

TABLE 3.2 Horizontal Curves Attributes, MWL ratings, Vertical grades, MWL Sight Distance, and Available Sight Distance

No.	Radius (m)	Degree of Curvature (D°)	Delta (Δ°)	MWL Ratings (horizontal & vertical)	Grade	MWL Sight Distance	Min. Available Sight Distance
1	1150	1.5	21	3.2	-0.026	278.904	221
2	1160	1.5	26.7	3.3	0.017	260.368	160
3	1160	1.5	51	4.3	0	297.996	200
4	860	2	20	3.4	0.001	271.133	140
5	700	2.5	42.1	4.2	0.018	285.058	179.8
6	850	2	27.3	3.6	-0.019	288.274	180.67
7	890	1.9	32.4	3.7	-0.004	282.522	160
8	1730	1	28	3.4	-0.01	277.087	243
9	1750	1	28	3.4	0.003	270.091	263
10	1900	0.9	14	2.6	0.004	247.354	183
11	1770	1	14	2.6	0	249.234	182
12	870	2	37.6	3.9	-0.008	290.738	160

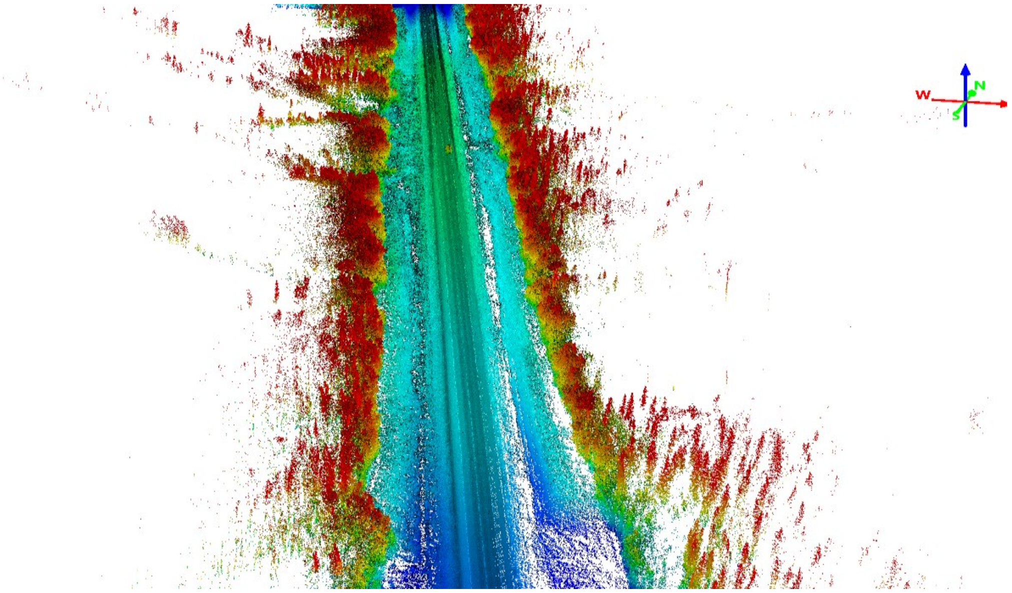


FIGURE 3.1 LiDAR point cloud sample of a 4 km section from Highway 40

3.3.3 Collision Data

The collisions data were collected between 2008 and 2014. These collisions were recorded at a buffer distance of 457 meters from the center point of each horizontal curve since drivers require 5-10 seconds to recover, perceive, and react to the following geometric feature (9). In this study, horizontal curves that did not intersect were chosen to investigate the impact of the horizontal curve only and eliminate any external influence on collisions from being adjacent to other curves.

3.3.4 MWL Calculations

Based on Equation (1), the SSD_{MWL} could be calculated, as shown in Equation (2). SSD_{MWL} is the mental workload stopping sight distance required by drivers to navigate through a complex or (a combination) of geometric features safely based on V_{MWL}.

$$SSD_{MWL} = 0.278 * V_{MWL} * PRT + \frac{{V_{MWL}}^2}{254(\frac{a}{9.81}+G)} \tag{2}$$

where V_{MWL} is the adjusted speed due to MWL demand (km/h), t is the perception-reaction time (sec), G is the road grade, and a is the deceleration rate (m/s^2).

3.3.5 Reliability Analysis

A reliability analysis was conducted to investigate the credibility of incorporating MWL values in the design procedure. Reliability analysis mainly concerns evaluating the risk linked to a specific design. In this chapter, different horizontal curves were studied by calculating different SSD_{MWL} for each curve depending on the degree of curvature ($D°$) and delta ($\Delta°$) from the MWL perspective. Then, a reliability analysis was performed to compare the difference in the probability of non-compliance (P_{nc}) obtained using SSD_{MWL} values, the 3D available sight distance, and SSD calculated based on Wood et al. (57) model. In reliability theory, the stochastic nature of design parameters is taken into account by expressing input parameters in terms of their probability distributions (79-80).

A limit-state function (LSF) represents the design equations as a difference between supply (e.g., available sight distance – ASD) and demand (e.g., SSD), and failure to meet design requirements occurs when demand exceeds supply (e.g., SSD > ASD). The P_{nc} is the chance that supply fails to accommodate demand (79). Equation (3) shows the limit-state function that defines our one mode of failure problem: the failure to meet the sight distance requirement. The probability of noncompliance is obtained using Equation (4). The integral in Equation (4), which cannot be solved analytically, was solved using the first-order reliability method (FORM).

$$LSF = ASD - [0.278 * V * PRT + \frac{V^2}{254\left(\frac{a}{9.81}+G\right)}] \tag{3}$$

where ASD is the available sight distance (meter), PRT is the perception and brake reaction time (second), V is the design speed (km/h), a is the deceleration rate (m/s^2), and G is the longitudinal grade in percentage.

$$P_{nc} = P(LSF \leq 0) = \int_{LSF \leq 0} \cdots \iint f(x)\, dx \qquad (4)$$

The probability distributions of the random variables (PRT, V, and a) were obtained from previous studies, as summarized in Table 3.4.

The approach followed in the methodology is primarily to explore the impact of applying guidelines that incorporate human factors represented by MWL demand by navigating the surrounding environment on highway safety. However, this work could be expanded to investigate the relationship between design factors and their impact on the P_{nc} and collisions.

R_t is a reliability analysis software developed at the University of British Columbia. In R_t, the different parameters of the limit state functions are first defined as continuous or constant variables. For the continuous variables (i.e., speed, PRT, and deceleration rate), the statistical distributions with their appropriate mean and standard deviation values are used as inputs. Also, the constant variables (e.g., grades, ASD, and MWL SD) are specified. The limit state function is then formulated in the functions section of the software. Finally, the reliability analysis is performed by running the analyzer while choosing the FORM method. Further information about the software can be found on the University of British Columbia (UBC) website and in the software manual (81).

TABLE 3.3 Vehicle Speed Distributions (82)

Radius	Mean (km/h)	Standard Deviation (km/h)
200	80.38	8.119
250	84.21	6.537
300	86.78	5.623
350	88.61	5.094
400	90.00	4.803
450	91.09	4.659
500	91.96	4.598
550	92.68	4.598
600	93.28	4.63
650	93.8	4.687
700	94.23	4.751
750	94.62	4.825
800	94.95	4.898
900	95.52	5.051
Tangent	100.66	9.443

Wood et al. (57) developed an updated SSD model that accounts for the distance between the front of a vehicle and driver eye ($L_{front-eye}$), which is not accounted for in the AASHTO SSD model, as shown in Figure 3.2. The reliability analysis was repeated based on Wood et al. (57) SSD model. PRT distribution values suggested by (57, 83) were used in the analysis as it accounts for distracted and undistracted drivers, different age groups, and was developed based on naturalistic data. As such, the PRT distribution resembles real driving circumstances. Equation (5) shows the limit-state function using Wood et al.'s model to express road users' SSD demand. The R_t software was used to find the P_{nc} using the two limit-state functions and parameter distributions (81). Richl and Sayed (82) used 11 speed-prediction models from several studies to estimate the average speed and standard deviation based on a curve radius, as shown in Table 3.3.

$$LSF = ASD - (\left[0.278 * V * PRT + \frac{V^2}{254\left(\frac{a}{9.81}+G\right)}\right] + L_{front-eye}) \quad (5)$$

TABLE 3.4 Probability Distributions of the Random Variables used in Wood et al.'s Model

Parameter	Mean	Standard Deviation	Distribution	Source
PRT	1.45 sec	1.07 sec	Lognormal	Wood et al. (57) and Green et al. (83)
V	See (Table 3.3)	See (Table 3.3)	Normal	Richl and Sayed (82)
a	4.2 m/s^2	0.6 m/s^2	Normal	Fambro et al. (84)
$L_{front-eye}$	2.36 m	0.128 m	Normal	Wood et al. (57)

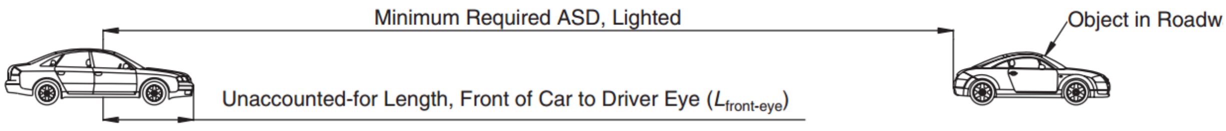


FIGURE 3.2 Unaccounted for length ($L_{front-eye}$) in AASHTO SSD Model (57)

3.4 RESULTS AND DISCUSSION

Table 3.5 shows the results of the reliability analysis on the 12 studied horizontal curves using the MWL sight distance and the ASD at all locations. Based on the AASHTO SSD model, on average, the probability of noncompliance (P_{nc}) dropped from 8.37% using the ASD to 0.668% when the SSD_{MWL} was used. The reduction in P_{nc} at all the study locations ranged between 0.15% and 21.12%, with an average of 7.7%.

Also, it was found that the reliability index using the ASD had a negative, statistically significant (at the 95% confidence level) correlation with the number of collisions with a correlation coefficient of -0.66. The P_{nc} using the ASD had a positive, statistically significant (at the 95% confidence level) correlation with the number of collisions at the study locations with a correlation coefficient of 0.61.

Using Wood et al.'s model, the probability of noncompliance (P_{nc}), on average, dropped from 9.09% using the ASD to 0.71% when the MWL SSD was used. The reduction in P_{nc} at all the study locations ranged between 0.16% and 23.025%, with an average of 8.38%. Moreover, the P_{nc} and reduction values found using Wood et al.'s model was higher than the P_{nc} and reductions using the AASHTO SSD model.

TABLE 3.5 Results of the Reliability Analysis

Results using the AASHTO model (suitable for night condition)

Curve Number	RI ASD	RI SSD_{MWL}	P_{nc} ASD	P_{nc} SSD $_{MWL}$	Reduction in P_{nc}	Number of Collisions
1	1.79	2.43	3.70%	0.760%	2.94%	0
2	0.96	2.37	16.83%	0.880%	15.95%	8
3	1.602	2.656	5.46%	0.395%	5.07%	11
4	0.79	2.676	21.49%	0.373%	21.12%	11
5	1.75	2.86	4.02%	0.214%	3.81%	4
6	1.56	2.78	5.67%	0.275%	5.40%	10
7	1.235	2.76	10.83%	0.290%	10.54%	6
8	2.12	2.46	1.70%	0.699%	1.00%	0
9	2.362	2.43	0.91%	0.758%	0.15%	0
10	1.342	2.211	8.98%	1.350%	7.63%	3
11	1.31	2.22	9.59%	1.330%	8.26%	2
12	1.22	2.46	11.21%	0.691%	10.52%	11
Average	1.50	2.526	8.37%	0.668%	7.70%	5

Results Using Wood et al. model (suitable for daytime condition) (57)

Curve Number	RI ASD	RI SSD_{MWL}	P_{nc} ASD	P_{nc} SSD_{MWL}	Reduction in P_{nc}	Number of Collisions
1	1.76	2.41	3.95%	0.801%	3.15%	0
2	0.91	2.35	18.15%	0.936%	17.21%	8
3	1.565	2.637	5.90%	0.417%	5.48%	11
4	0.725	2.656	23.42%	0.395%	23.03%	11
5	1.71	2.84	4.40%	0.226%	4.17%	4
6	1.52	2.76	6.46%	0.291%	6.17%	10
7	1.185	2.74	11.79%	0.310%	11.48%	6
8	2.093	2.436	1.81%	0.740%	1.07%	0
9	2.34	2.407	0.96%	0.800%	0.16%	0
10	1.3	2.186	9.67%	1.440%	8.23%	3
11	1.263	2.19	10.34%	1.410%	8.93%	2
12	1.165	2.439	12.20%	0.736%	11.46%	11
Average	1.46	2.504	9.09%	0.709%	8.38%	5

3.5 CONCLUSIONS AND FUTURE RESEARCH

The major objective of this study was to incorporate MWL into the design guidelines for horizontal curves, and subsequently the impact on highway safety. To understand the safety implications, a reliability analysis was conducted. Results of the analysis showed that providing the MWL sight distance on horizontal curves reduces the probability of failure to meet the stopping sight distance requirements of drivers by up to 23%, suggesting that incorporating MWL into the geometric design process improves the safety performance.

An important contribution of this work is the development of a new MWL rating that better expresses the complexity of different geometric design elements and their effects on driver workload. For example, the ratings developed by Messer expressed the influence of vertical crest curves according to their frequency, i.e., MWL demand increases with an increase in the number of vertical crest curves. To mitigate the adverse impacts that this might have on MWL demand, it might be prudent, if conditions allow, to decrease the number of vertical crest curves on new and existing alignments. Also, while the number of vertical crest curves is important, frequency alone cannot account for the variety in their flatness (rate of vertical curvature), affecting the ASD offered to drivers and impacting their sightlines. Therefore, additional research is required to develop a more robust rating for the impact of vertical curvature on mental workload. In addition, the inclusion of vertical grades in the reliability analysis is also worth further investigation (85). The literature indicates that there is a link between the MWL and vertical grades (39-40). This is both logical and intuitive since fewer steep grades and flatter crest curves will result in an increased ASD, which provides drivers with a capacity to safely and comfortably maneuver these locations while driving.

Future research should be conducted to investigate how various geometric features could impact MWL. More importantly, how the combination of different geometric features and their resulting levels of complexity could influence the MWL of drivers. Additionally, the reliability analysis could include more than one mode of failure in addition to MWL to investigate the effect of combining other design factors in combination with horizontal curves, for instance, road surface friction.

Future work on the use of a probabilistic approach in determining the ASSD on a curve, as suggested by Wood at al. (57) instead of using the minimum ASD, is required. This is important because the effect of restricted SSD is highly situational. For instance, the combination of a crest curve on an intersection was found to raise the collision rates when SSD is restricted. Conversely, a restricted SSD on crest curves without an intersection, did not experience an increase in collision rates (57, 85). This could be the reason why the safety impacts of SSD have not been quantitatively assessed to date (i.e., there are no available crash modification factors for SSD on curves). Also, the current calculations oversimplify the driving situation assuming that the car is always located in the middle of the lane, and the driver's sightline is in the middle of the car, which is not realistic. Moreover, the AASHTO assumes that the SSD is a result of the design speed, which is not accurate because drivers do not constantly follow the posted speed limits. As a result, a probabilistic procedure that incorporates all factors that could impact the situational SSD is needed to better understand drivers' behavior and the reasons that lead to their involvement in collisions.

Investigating the dynamic relationship between speed, PRT, and deceleration rates is another area for future work. Few studies investigated the impact of driver behavior during emergency braking (86-88). The studies lacked the sense of urgency required while braking because the obstructions faced by drivers were smaller than a vehicle. This is important because the real sense of urgent maneuver or braking can impact the mean deceleration rate. Also, the research on speed and PRT lacked the inclusion of several factors such as listening to music, using a cell phone, and distraction overall. These factors are directly related to MWL and can affect the mean speed and PRT. It is worth noting that Wood et al. (85) developed a prediction model that accounts for the dynamic relationship between speed, PRT, and deceleration rate using crash and conflict data. This is a new area of research with a huge potential to enrich our understanding of the 'true' failure mechanism. Additionally, future work may utilize naturalistic data to enrich the current knowledge of these relationships. These complex relationships will be further complicated when one considers the effect of new technologies such as collision warning systems (85) or as vehicles exhibit an increased level of automation.

Future research should explore the impact of offset and radius on the P_{nc}, the P_{nc} impact on collisions, and the relationship between these parameters and the mediating impact on collisions through the P_{nc} using structural equation modelling. This will help better understand the impact of the changes in SSD due to MWL on highway safety. Also, it will offer insight on which factors have a direct and indirect impact on collisions, which will offer an opportunity to better meet the MWL demand.

Finally, including human factors in the design process would help to conform road design to human abilities and guarantee a safe driving environment that adapts to human capabilities. This study advocates for the incorporation of human factors into design guidelines, which will serve Vision Zero and will have direct applications on automation.

3.6 AUTHORS CONTRIBUTION

The authors confirm contribution to the chapter as follows: study conception and design: Karim Habib; data collection: Karim Habib; analysis and interpretation of results: Maged Gouda, Karim Habib, Karm El-Basyouny; draft manuscript preparation: Karim Habib, Maged Gouda, Karim El-Basyouny.

4 A SYSTEM TO DETERMINE ADVISORY SPEED LIMITS FOR HORIZONTAL CURVES BASED ON MENTAL WORKLOAD AND AVAILABLE SIGHT DISTANCE

This chapter introduces a framework for developing advisory speed limits that incorporates MWL and ASD to compensate for the complexity of highway geometric design.

4.1 INTRODUCTION

The design of horizontal curves on highways needs to consider numerous parameters, including vehicle speed, curve radii, superelevation, friction, and longitudinal grades. However, human factors are not typically or even implicitly considered in the process of highway design, even though horizontal curves may have a substantial impact on mental workload. MWL is defined as the time and effort required to perform a given driving-associated task (9). For example, an earlier study by Messer (9) produced subjective MWL ratings for a set of horizontal curves based on a survey of 21 design engineers, research engineers, and human factor specialists. It was found that the MWL ratings of horizontal curves increase with a larger angle of deflection and a higher degree of curvature. A relationship between MWL and the frequency of collisions on two-way, two-lane highways was established by (68). The results of these studies indicate that human factors must be incorporated into the highway design to guarantee that horizontal curves do not overwhelm the drivers' cognitive abilities and to ensure safety.

One of the significant drawbacks in current highway design is that there are typically no efforts made to differentiate between the unique challenges presented by individual geometric features. For example, the PRT value for any highway location is typically fixed. This means that the PRT used to determine safe navigation of a horizontal curve is similar to that used for a tangent section even though needs and performance clearly change as drivers traverse the former, more complex sections of a highway (55). This design method assumes implicitly that drivers perceive all geometric features similarly and that they will react based only on the stopping sight distance (SSD; the sum of the distance travelled during perception-reaction time and the distance required for the vehicle to come to a complete stop). These simplifications are typically based on percentile values that include the responses of as many drivers as possible. However, by their nature, they ultimately ignore the diversity of the overall driving population.

Horizontal curves were associated with significantly increased visual demands in both on-road and test track studies (89-90). Horizontal road curvature affects driving performance, including mean speed, lane-keeping performance, and the ability to maintain headway (91). More importantly, evidence from the literature revealed that collisions occur more frequently on horizontal curves than on tangent sections (92).

Recent literature suggests that there is a link between available sight distance and highway safety (93-94). For example, Habib et al. 2020 (95) found that the probability of non-compliance dropped from 9.1 % to 0.7% when the MWL for SSD (MWL_{SSD}) was examined in conjunction with the ASD on horizontal curves. Likewise, a study by (96) revealed that collision rates increased 2.1-fold among ageing drivers, most notably on sections of highways with restricted SSDs. Collectively, these two studies demonstrated the impact of both MWL and ASDs on safety and emphasize the need to accommodate these factors in future safety applications for highway design. It may be difficult to incorporate MWL into the design of existing highways and it may not be possible to make changes to existing highways to accommodate MWL requirements. It may be more feasible to manage the operations of existing highways by proposing curve advisory speeds at relevant sections. To achieve this goal, this study proposes a means to determine advisory speed limits (ASLs) for horizontal curves that address PRT changes, thereby ensuring that the geometric design of these curves can be navigated safely by all drivers. The main objectives are (i) to assign

MWL ratings to different horizontal curves based on their geometrical attributes, (ii) to calculate the PRT associated with each horizontal curve based on MWL, and (iii) to propose new advisory speeds that will provide drivers with enough time to traverse these curved sections safely and without mental overload through balancing MWL and ASD.

4.2 LITERATURE REVIEW

4.2.1 Advisory Speed Limits for Curves

ASLs have been introduced to improve safety, operation, and congestion on major highways. For example, an ASL system was developed to mitigate traffic conflicts at work zones in Minnesota (97). The system was intended to reduce the speed of upstream traffic so that it matched the speed of the downstream traffic after a work zone. The results revealed a 25–35% reduction in the maximum speed differences at the morning rush-hour traffic peak. Another study featured a microsimulation model that tested the results of implementing varying speed limits (98-99) explored the utility of advisories posted on dynamic message signs for reducing driving speed in locations with the potential for collisions between vehicles and animals. The results indicated that the posted ASLs resulted in effective reductions in average driving speed and were most effective under dark conditions. These findings demonstrate how ASLs can promote safer driving conditions on highways.

Echaveguren and Vargas-Tejeda (100) developed an ASL system specifically for use on horizontal curves based on ball-bank indicator readings and consistency concepts in which driving speeds were determined as a function of lateral acceleration (i.e., a geometric characteristic). However, the surrounding geometric and background elements were not included in the development process. A simulation-based study identified the major issues that challenge drivers while negotiating horizontal curves as a failure of attention, misperception of speeds and curvature, and problems associated with lane positioning (101). These three challenges are all a function of the MWL demand associated with geometric features and reflect the MWL capacity of the drivers. These findings emphasize the need to include MWL as a factor when developing ASLs for horizontal curves.

4.2.2 Perception-Reaction Time

Results from several studies suggest that PRT values may vary in different situations. For instance, the results of one study revealed that the mean PRT for an unexpected object was 1.1 seconds, with the 95th percentile value at 2.0 seconds (102). Ismail and Sayed (74) developed a system based on a mean PRT of 1.5 seconds with a standard deviation of 0.4 seconds and assumed that the PRT followed a log-normal distribution. In another study, the average PRT at high speeds (i.e., 60 and 85 mph) was measured for 50 demographically diverse participants using a driving simulator and several driving scenarios. In this study, the average PRT, measured as the time taken to apply the brakes in response to the changing speed of the leading vehicle was 2.83 seconds (103). Despite these observed variabilities, the geometric design guidelines from the American Association of State Highway and Transportation Officials (104) uses a fixed value PRT of 2.5 seconds.

The Geometric Design Guide for Canadian Roads published by the Transportation Association of Canada suggested that 1.5 seconds may be a more appropriate value to use for PRT; this value represents the 90th percentile for young individuals driving over the crest of a hill during daytime hours who need to avoid a hazard that is partially blocking their lane. However, PRT depends on factors that include the nature of the stimulus (size, contrast, time of exposure, and motion, among others), expectancy, the number of available choices, and the complexity of the background (8). All of these factors can have an impact on the suggested PRT value of 1.5 seconds, which was determined to be appropriate only for reasonably alert drivers dealing with a hazard in their direct line of sight.

When the complexity of the situation increases, human factors can have a significant impact on the PRT. For instance, PRT was estimated in an on-road study in which drivers needed to initiate a lane change once a gore in the road became visible. The mean PRT in this case was measured at 10.5 seconds, with 20 seconds at the 85th percentile; the mean time required to affect a full lane change was 4.6 seconds (105). Thus, while 2.5 seconds is generally accepted as an appropriate measure of PRT, longer times may be needed when the complexity of the driving task or tasks increases.

4.2.3 Available Sight Distance

ASD is a critical component that contributes to road safety. If the ASD is less than the required SSD at any point on the highway, drivers may be unable to respond appropriately to avoid hazards. Research has shown that highway sections with restricted ASD requirements are particularly difficult for ageing drivers (SSDs calculated based on a PRT <5 seconds; 96) and were associated with higher collision rates.

It is important to recognize that the effects of restricted SSDs are highly situational (106). Locations that include an intersection together with a crest curve and SSD restrictions are likely to be the sites of frequent collisions (107). This result might relate to the increased complexity of the driving situation, as the combination of two aforementioned geometric elements would likely require additional ASD. For example, Habib et al. (95) examined the credibility of the SSD framework as provided by Messer (9) using reliability analysis. The results of reliability analysis, which compared the results of stopping sight distance based on MWL requirements versus the available sight distance, showed the applicability of Messer’s framework and its readiness for further applications. Also, this study showed that SSD based on MWL requirements (SSD_{MWL}) on 12 horizontal curves preceded by crest vertical curves was found to drop the probability of non-compliance to 0.7% (95). This means that the SSD_{MWL} will satisfy the needs of 99.3% of the drivers in the population versus only 90.9% that are accommodated with the existing ASDs. In this case, SSD calculations were based on the MWL demand by combining the complexities of both the horizontal and the vertical curves. This is a crucial step toward understanding the connection between design complexity and ASD on highways from the perspective of MWL.

4.2.4 Mental Workload (MWL) associated with Curves and Design

The TAC included further discussion on MWL and provided highway designers with several recommendations regarding the need to avoid challenging drivers with difficult tasks. The guidelines also noted that it was advisable to avoid situations that required simultaneous processing of a large amount of information, such as signs containing information on different destinations. The recommendations in this report were as follows:

> ***"Designers should avoid designs that result in high workload with more than one task at a time (an intersection on a curve, a lane drop on a curve, lane changes while readings guide signs, or a railroad crossing near a stop sign)."***

No further information was provided regarding the use of quantitative assessments or thresholds of MWL demand in the design of the geometric layout.

Horizontal curves are visually demanding (89). Easa and Ganguly (10) used a simulator to model the visual demands required for successful navigation of horizontal curves and tangent sections. The results of their study were in agreement with those of Messer 1980 and revealed that visual demands are affected by both the preceding and the current design element. Moreover, factors with significant impact on the visual demand include the curve radius, the curve direction, the angle of deflection, the frequency of crest curves preceding the horizontal curve, the relationship between the curve and its tangent, and lane width.

The combination of horizontal and vertical curves was also identified as visually demanding (108). This study identified significant effects associated with the inverse of both the horizontal curve radius and the vertical curvature. These results are also consistent with those previously reported by Messer 1980, in which the existence of a vertical curve just before another geometric feature leads to an increase in MWL demand.

Horizontal curves, especially those that are sharper in nature, present problems for drivers with respect to the choice of proper speed; this requires an increase in both MWL and visual demands. Additionally, vertical curves can change a driver’s perception of the nature of the horizontal curve (108), a factor that must be considered when designing these geometric elements. This problem could be alleviated by providing drivers with more time and space to react appropriately. In other words, this problem could be addressed by providing drivers with additional PRT which then translates into increased SSD.

This chapter proposes a new ASL that incorporates both MWL demands and ASDs associated with driving on horizontal curves. This was achieved by (i) extracting ASDs for horizontal curves from LiDAR data, (ii) extracting information on horizontal and vertical curves from LiDAR data, (iii) assessing the MWL demands associated with the horizontal curves, (iv) calculating PRTs based on the MWL demands associated with the combination of horizontal and crest curves (if present), and (v) developing ASLs based on the ASD on curves in combination with PRT measurements that were based on MWL demands.

4.3 METHODOLOGY

Messer 1980 presented the results of a survey of transportation experts and used this information to rate the complexity of nine basic geometric features and to identify elements of design consistency. In his study, the MWL complexity ratings were utilized to assess the complexity of different horizontal curves. Table 4.1 includes a summary of the MWL ratings for horizontal and vertical crest curves used in this study. Additional ratings and details on how they were developed and used can be found in (9) and (68).

The ratings shown in Table 4.1 represent the different levels of the MWL required to navigate different horizontal and crest vertical curves. If a given crest vertical curve precedes a horizontal curve by a distance of 1500 meters, the ratings of both curves were combined by adding the MWL score of the horizontal curve to the MWL score of the vertical curve based on Table 4.1. Moreover, tangent sections were scored with MWL ratings of zero because drivers are not required to engage in any complex decisions or actions while driving on these segments. Hence, the PRT is based solely on the requirements associated with SSD. However, drivers navigating a sharp horizontal curve, for example, would require more time to respond due to its higher degree of complexity, even if the ASD equalled the SSD as recommended by AASTHO. The PRT needed, in this case, could be determined as described in the formulae in Equations (1, 2, and 3).

In Equation (1), the MWL design speed (V_{MWL}) in km/h is calculated based on the addition of the design speed ($V_{design\ speed}$; km/h) and the R_f, which is the MWL rating listed in Table 4.1. This equation is only valid when the total value of the ratings is >2 MWL units, which would result in a V_{MWL} at least 16 km/h greater than the design speed. If the horizontal curve has an R_f rating ≤ 2, no changes are necessary for the determination of the MWL-based design speed. The term $R_f = 2$

is defined as the starting point; values of $R_f > 2$ will require additional design requirements to accommodate challenging MWL demands.

$$V_{MWL} = V_{design\,speed} + 8 * R_f \text{ (1)} \quad \text{and} \quad R_f \geq 2.0 \tag{1}$$

SSD based on MWL (SSD_{MWL}; in m is calculated as shown in Equation (2). This value is obtained by substituting V_{MWL} (km/h) in the equation used to calculate SSD. This leads to a new design requirement for SSD_{MWL} (m) that includes the added information from Equation (1). This adjustment is made to accommodate variations in drivers' cognitive abilities (95).

$$SSD_{MWL} = 0.278 * V_{MWL} * PRT_{2.5} + {V_{MWL}}^2/254(\frac{a}{9.81} \pm G) \tag{2}$$

In this equation, $PRT_{2.5}$ is a constant PRT value of 2.5 seconds, a is a deceleration rate of 3.4 m/s^2, and G is the longitudinal grade of the highway.

Using Equation (3), the MWL-associated PRT (PRT_{MWL}) is calculated using the V_{design} (km/h) and the new SSD_{MWL} (m). PRT_{MWL} is the time (seconds) needed by drivers to respond appropriately to the horizontal curves while experiencing a specific MWL.

$$PRT_{MWL} = (SSD_{MWL} - \frac{{V_{design\,speed}}^2}{254\left(\frac{a}{9.81} \pm G\right)})/(0.278 * V_{design\,speed}) \tag{3}$$

Equation (4) is a quadratic equation generated from the calculated SSD used to determine the ASL. The calculated ASL ($V_{advisory}$ in km/h) accounts for the PRT (in seconds) needed to accommodate the MWL and the ASD extracted from the LiDAR data for each horizontal curve.

$$V_{advisory}^2 + 0.278 * PRT_{MWL} * 254\left(\frac{a}{9.81} \pm G\right) * V_{advisory} - 254\left(\frac{a}{9.81} \pm G\right) * ASD = 0 \tag{4}$$

This entire process is summarized in the flowchart depicted in Figure 4.1.

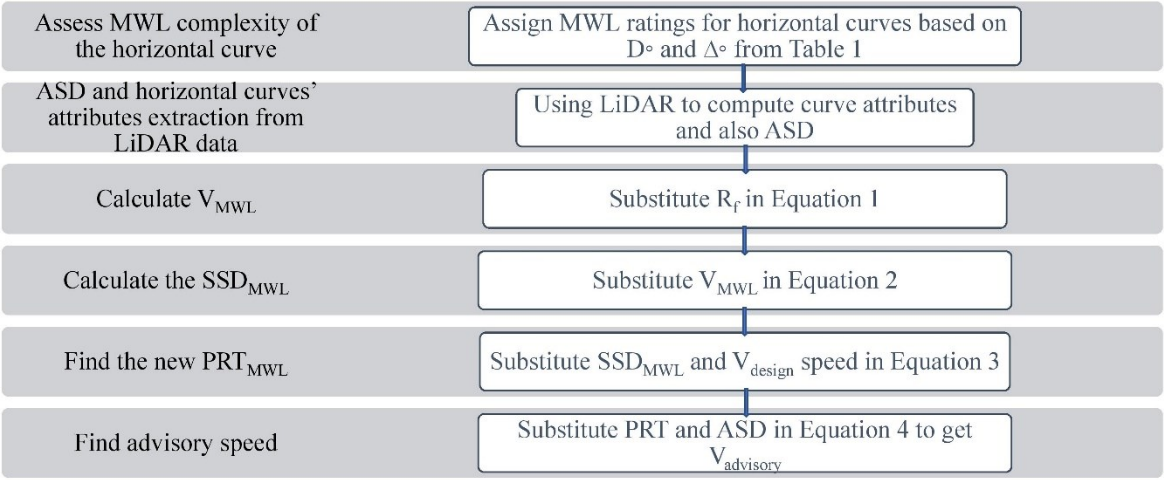


FIGURE 4.1 The procedure used to calculate $V_{advisory}$

TABLE 4.1 MWL Ratings of Different Horizontal Curves and Effect of Crest Vertical Curves

Horizontal Curves					
Degree of Curvature (D°)	**Deflection Angle (*Δ*°)**				
	10	**20**	**40**	**80**	**100**
1	0.5	1.0	2.1	4.1	6.2
2	1.2	1.5	2.0	3.0	4.1
3	2.1	2.3	2.6	3.3	4.0
4	3.1	3.2	3.5	4.0	4.5
5	4.0	4.1	4.3	4.7	5.2
6	5.0	5.1	5.3	5.6	6.0
7	6.0	6.1	6.2	6.5	6.8
8	7.0	7.0	7.1	7.4	7.7

Crest Vertical Curves	
No. of Crest Curves in the prior 1500 meters	**Workload Potential Rating**
≤ 2	1.9
≤ 3	3.0
≤ 4	4.0
≤ 5	5.0
> 5	6.0

LiDAR data were used in this study to obtain the geometric characteristics of the horizontal curves. Alberta Transportation collected these data, reflecting the current design of the provincial highway network. The data are at very high density (150–1000 points/m^2) and are stored in LAS format. Each LAS file contains data for up to a 4-km stretch and includes pavement, marking, signs, and vegetation, as well as other features. In this study, automated scripts were developed in MATLAB to compute the attributes of all the horizontal curves and to determine the ASD from the LiDAR.LAS files.

First, several parameters that define the horizontal curves, such as the deflection angle (Δ^{o}) and the degree of curvature ($D°$), were extracted from the LiDAR data (109). The same dataset was used to extract data regarding the vertical curves (41). The findings shown in Table 4.1 were used to assign equivalent R_f values based on the extracted curve parameters. A detailed explanation of the extraction procedure and the MWL rating assignments was presented in an earlier study (10). Finally, based on the R_f assigned to each curve, the PRT_{MWL} was calculated using the formulae shown in Equations (1, 2, and 3). The data for ASDs for these highways were extracted using MATLAB scripts and LiDAR data, as described in (110).

4.4 RESULTS & DISCUSSION

Data obtained for 41 curves were evaluated by calculating the $\mathrm{PRT}_{\mathrm{MWL}}$, extracting the ASD data, and then calculating the required $\mathrm{SSD}_{\mathrm{MWL}}$. It is worth mentioning that, according to the literature review, consideration of the impact of crest curves is essential. The results shown in Table 4.2 include the ASLs proposed for each of these 41 curves based on these calculations. This sample includes horizontal curves with various radii and deflection angles, as well as data from those that are adjacent and not adjacent to crest curves. The analysis of these horizontal curves generated information on various levels of associated MWLs in addition to different ASDs. The radii of these horizontal curves ranged from 460 to 1900 meters and the ASDs ranged from 122 to 1244.9 meters. This diverse sample led to a richer presentation and a stronger demonstration of the impact of both MWL demands and the ASDs on the ASLs.

As shown in Table 4.2, the results suggested no changes to the ASLs currently in place for 21 of these horizontal curves. This finding resulted from the residual ASD (ASD value > 185 meters), which compensated for the high MWL demands otherwise required to navigate these curves. The TAC currently advises an SSD of 185 meters for a PRT of 2.5 seconds. As a result, for any PRT_{MWL} >2.5 seconds, the SSD_{MWL} will need to be >185 meters. Consequently, there will be no need to decrease the speed limits in cases in which the ASD meets the MWL requirements. This is consistent with an intuitive conclusion, as one can drive as fast as 100 km/h on these roads so long a there is enough time and space to make appropriate decisions. Moreover, one curve (no. 10) had an ASD of 180 meters; although this value is less than the 185 meters required by the TAC, our analysis suggested slight reductions in the ASL. This was due to the absence of crest vertical curves and thus no added MWL demand for drivers.

Curve number 21 had a $D^{o} = 0.96$ and a resulting $R_f = 1.6$ (< 2) which indicated no increase in the required SSD_{MWL}. This finding demonstrates the impact of the crest curves on these calculations. As shown, the presence of one or two crest curves will result in an increase in the MWL demand by 1.9, resulting in a total MWL demand equal to 1.6 (for the horizontal curve) added to 1.9 (for the crest curve) equalling an MWL demand of 3.5 (i.e., >2). In this situation, a reduction in the ASL or an equivalent increase in the ASD will be required.

By contrast, we identified 20 curves that might benefit from reduced speed limits. Generally, successful navigation of these curves involves a high MWL demand, as they include both vertical and horizontal curves with restricted ASD (i.e., ≤185 meters). For example, our calculation suggested an ASL of 80 km/h for horizontal curve number 12 due to the existence of 3 crest curves within a distance of 1500 meters. This specific horizontal curve also included a very sharp turn with a radius of 700 meters; this resulted in a PRT of 8.33 seconds. The high PRT alone did not lead to a drop in the speed because the ASD was 260 meters (>185 meters), which was significantly higher than that required by the TAC. Nonetheless, this ASD was insufficient to compensate for the complexity of the geometric situation, which required at least 344.9 meters.

By contrast, curves numbered 11 and 14 have ASDs at 160 and 122 meters, respectively; both of these values are less than the 185 meters required by the TAC. Although these curves do not have high MWL scores, the comparatively low ASDs suggest that significant reductions in ASL might be of benefit to drivers. Similarly, curve number 23 has a restricted SSD of 140 meters while its SSD_{MWL} equals 248 meters.

As another example, curve number 36 is the sharpest of those considered in this sample, with a radius of 460 meters; it is also preceded by a crest vertical curve, which results in a PRT of 7.42 seconds. However, the extended ASD of 783.6 meters relieved what would otherwise result in a high value for MWL demand. Overall, no change in the ASL was recommended.

TABLE 4.2 Extracted Data and Advisory Speed Limits

No. of curve	Radius (m)	Crest ?	D(◦)	Δ(◦)	Hz Rating	Total Potential Rating	V_{MWL} (km/h)	SSD_{MWL} (m)	PRT_{MWL} (sec)	ASD (m)	$V_{Advisory}$ (km/h)
1	1150	1.9	1.50	21.0	1.3	3.2	125.6	266.3	5.50	221.0	85
2	1160	1.9	1.48	26.7	1.9	3.8	130.4	283.5	6.12	160.0	65
3	710	1.9	2.42	34	2.11	4.0	132.0	289.7	6.34	341.0	100
4	700	0	2.46	49	2.3	2.3	118.4	241.3	4.60	279.0	100
5	1160	1.9	1.48	51.0	2.5	4.4	135.2	301.3	6.76	200.0	70
6	870	1.9	1.98	37.6	1.94	3.8	130.7	284.7	6.16	160.0	65
7	860	0	1.99	20	1.5	0.0	100	182.9	2.50	140.0	85
8	700	0	2.46	42.1	2.3	2.3	118.4	241.3	4.60	179.8	80
9	900	1.9	1.91	29	1.7	3.6	128.8	277.7	5.91	301.0	100
10	850	0	2.02	27.3	1.7	0.0	100	182.9	2.50	180.6	95
11	860	1.9	2.00	50	2.25	4.2	133.2	293.9	6.49	160.9	60
12	700	3	2.46	62.5	2.8	5.8	146.4	344.9	8.33	260.0	80
13	1350	1.9	1.27	30.0	1.7	3.6	128.8	277.7	5.91	202.0	80
14	1780	1.9	0.97	10	0.5	2.4	119.2	244.0	4.70	122.0	60
15	1770	1.9	0.97	14	0.7	2.6	120.8	249.5	4.89	182.0	80
16	1900	1.9	0.91	14	0.7	2.6	120.8	249.5	4.89	183.0	80
17	1750	1.9	0.98	28.0	1.4	3.3	126.7	270.2	5.64	263.0	95
18	1160	1.9	1.48	38.0	2.1	4.0	131.6	287.9	6.28	205.0	75
19	1740	1.9	0.99	28.3	1.5	3.4	126.8	270.5	5.65	243.0	90
20	870	1.9	1.98	56.0	2.4	4.3	134.4	298.3	6.65	323.0	100
21	1800	0	0.96	31	1.6	0.0	100	182.9	2.50	884.0	100
22	1530	0	1.12	10	0.57	0.0	100	182.9	2.50	240.0	100
23	1600	0	1.07	50.0	2.6	2.6	120.4	248.1	4.85	140.0	65
24	1730	0	0.99	15.5	0.8	0.0	100	182.9	2.50	241.0	100
25	860	1.9	2.00	49.7	2.2	4.1	132.8	292.4	6.44	538.1	100

No. of curve	Radius (m)	Crest ?	D(◦)	Δ(◦)	Hz Rating	Total Potential Rating	V_{MWL} (km/h)	SSD_{MWL} (m)	PRT $_{MWL}$ (sec)	ASD (m)	$V_{Advisory}$ (km/h)
26	1000	1.9	1.69	16	1.2	3.1	124.8	263.4	5.40	200.8	80
27	1600	1.9	1.07	20.8	1	2.9	123.2	257.8	5.19	1244.	100
28	650	1.9	2.66	17.7	1.96	3.9	130.8	285.3	6.18	864.7	100
29	620	1.9	2.79	89.9	3.4	5.3	142.4	329.0	7.76	200.3	65
30	830	1.9	2.06	35.6	1.9	3.8	130.4	283.5	6.12	420.0	100
31	1000	1.9	1.70	54.5	2.5	4.4	135.2	301.3	6.76	906.3	100
32	900	1.9	1.92	48	2.2	4.1	132.8	292.4	6.44	982.2	100
33	900	1.9	1.91	48	2.2	4.1	132.8	292.4	6.44	438.2	100
34	740	1.9	2.33	23.6	1.8	3.7	129.6	280.6	6.01	341.2	100
35	690	1.9	2.49	35.6	2.2	4.1	132.8	292.4	6.44	540.9	100
36	460	1.9	3.72	22.3	3.1	5.0	140	319.7	7.42	783.5	100
37	880	1.9	1.96	14.5	1.35	3.3	126	267.7	5.55	321.3	100
38	680	1.9	2.51	16.8	1.8	3.7	129.6	280.6	6.01	301.1	100
39	660	1.9	2.59	19.1	2	3.9	131.2	286.5	6.22	763.1	100
40	730	1.9	2.35	41.4	2.21	4.1	132.8	292.7	6.45	178.4	70
41	550	1.9	3.12	19.1	2.4	4.3	134.4	298.3	6.65	181.0	70

4.5 CONCLUSIONS & FUTURE WORK

The observed relationship between MWL demand and collisions on the highways highlights the need to develop a more robust system to determine ASLs that considers both the PRT_{MWL} and the ASD (68). Restricted ASD on some highway segments due to intrinsic geometric features, vegetation, and other factors was associated with higher collision rates, especially among older drivers. It is important to recognize that many collisions are situational and can be directly attributed to specific geometric elements and associated restricted ASDs. This paper provides a method that can be used to determine ASLs that accounts for MWL demands associated with the geometric layout and that offers a procedure to calculate SSD and PRT based on MWL requirements. Moreover, ASDs were extracted from LiDAR data and utilized to remedy the problems associated with horizontal curves preceded by crest vertical curves, which are highway configurations associated with increased MWL demands.

The calculated values of PRT_{MWL} were uniformly greater than 5.0 seconds in combinations of crest and horizontal curves. This specific value is of great significance, as results from research into the human factors associated with highway design revealed that older drivers require at least 5 seconds to perceive and respond to road hazards (105). As a result, the use of the PRT_{MWL} value will ensure that all drivers have enough time to circumvent the complexities associated with the combined horizontal and vertical curves and will specifically accommodate the needs of an older population.

Operational solutions designed to address problems associated with our existing infrastructure are critically needed. The solutions presented here can improve safety on sharp horizontal curves that may have been constructed due to spatial or environmental restrictions. As such, a feasible alternative (i.e., a proposed speed advisory) can be considered rather than more costly reconstruction or rehabilitation of the existing infrastructure.

The calculated $\mathrm{PRT_{MWL}}$ is based on the $\mathrm{SSD_{MWL}}$ that was calculated as per Equation (1) as initially described by (Messer 1980). The same $\mathrm{SSD_{MWL}}$ was evaluated in a study performed by Habib et al. (95) who explored the validity of this parameter via a formal reliability analysis. In this study, the probability of non-compliance on curves dropped to almost 0.7% in the cases in which $\mathrm{SSD_{MWL}}$ was applied. This finding revealed that the $\mathrm{SSD_{MWL}}$ can accommodate the needs of drivers travelling on horizontal curves that are preceded by crest vertical curves. This finding also emphasizes the importance of the procedure presented in this paper, which ensures that the complexity of a given driving situation is accommodated so that drivers are less likely to be overwhelmed. Taken together, this work offers some insights into how human factors can be translated into improved design parameters.

This chapter presents a procedure that can be used to calculate the PRT required for safe driving based on the MWL demands associated with horizontal curves. This calculation can produce PRT values that might also be applied to different issues and outstanding questions in transportation engineering. Furthermore, the extraction of ASD findings using LiDAR data was a remarkably quick, feasible, and precise method that represents a novel application in transportation engineering. These findings may also serve to create a link between infrastructure design and the needs of future autonomous vehicles (111-112), where take-over requests may need human interference in the driving process, which includes a workload component (113-114)

Data from LiDAR scans can facilitate recovery of the geometric design features in a manner that can be translated into safety applications . For example, the extraction of the geometric elements of the highways could be used to create safety applications such as safety performance functions (95, 115). These applications will rely on the efficiency of using LiDAR data to effectively extract different highways infrastructure geometric elements such as 3D SSD (116), signs and marking (117), vegetation (118), light poles (119). As a result, the advancement of the LiDAR data processing and features extraction will contribute to improvements in highway safety.

One of the primary contributions of this study is the presentation of a method that can be used to adapt the ASL calculation procedure to develop a perceptual Curve Speed Warning application. This application might take the form of a vehicle-to-infrastructure communication program designed to promote driver safety, specifically on horizontal curves. A perceptual warning system is one that considers the individual driver's capacity to address a given safety concern (120).

Perceptual warnings are superior to kinematic warnings in terms of safety and driver expectations (120-121). The proposed ASL is a perceptual warning method that is estimated based on the calculated MWL and the ASD available to the driver at each curve. This warning enhances awareness of the surrounding highway features, which is particularly important when driving on highways with design limitations (e.g., limited SSD).

This study could be extended by including the impact of additional geometric elements on MWL demands (i.e., intersections, vertical curves, and others). These findings would lead to an improved understanding of the impact of different geometric elements both as single entities and in combinations. An extended application of MWL-based assessments will require the development of adequate MWL ratings for these additional geometric elements. Unfortunately, this information is currently missing from the existing literature. For example, there are currently no MWL ratings available for roundabouts or work zones. These ratings will also need to take into consideration the effects of external factors such as meteorological conditions and time of day; both of these factors contribute significantly to road and highway safety (122-124).

4.6 AUTHORS CONTRIBUTION

The authors confirm contribution to the chapter as follows: study conception and design: Karim Habib, Mostafa Tawfeek; data collection: Karim Habib; analysis and interpretation of results: Karim Habib, Mostafa Tawfeek, Karm El-Basyouny; draft manuscript preparation: Karim Habib, Mostafa Tawfeek, Karim El-Basyouny.

5 FACTORS INFLUENCING DRIVER MENTAL WORKLOAD ON THE HIGHWAY: AN EXPERT SURVEY STUDY

This chapter investigates the impact of different geometric design factors that impact drivers' MWL levels including an expanded list of factors such as the existence of cyclists, weather, and in-car assistance technologies.

5.1 INTRODUCTION

Human behaviour and cognitive processing play an enormous part in executing driving tasks, as a substantial amount of surrounding information needs to be processed to reach correct decisions. Since human error plays a role in 95% of all vehicular collisions, the ongoing study of human factors associated with the driving task is critical to ensure a safe and forgiving driving environment for all drivers. Building this knowledge accords with Vision Zero's aim to eliminate fatal and serious injury collisions by investing in infrastructure upgrades to change and improve road designs that increase road users' survivability.

When driving, a significant human factor metric is MWL, defined as drivers' time or effort rate to perform a given driving task. Many factors influence the degrees of MWL associated with a given driving task. For example, the complexity of the geometric design and driving situation may increase drivers' MWL, such as horizontal curves, intersections, or a combination of them. Adding the newly introduced factors to the geometric design, such as cyclists on the shoulder or at intersections, further challenges car drivers (125). Those challenges can even become more complex when inclement weather, such as rain, snow or fog, or other forms of limited visibility, is added to the driving context.

Climate change has had a significant influence on highway design and has contributed to increased concerns for vehicular safety. These latter concerns include the MWL demands associated with increased intensity and duration of fog (126), rain, and snow and the associated reduced visibility (127), lane obstruction (128), and decreased skid resistance (129-130). While lane obstruction might be addressed by increased attention to highway maintenance, reduced visibility and higher skidding potential require highway designs that incorporate increased SSDs, reduced speed limits, and intelligent transportation system solutions. Those issues must be addressed by taking the MWL perspective to provide the drivers with sufficient room to make proper decisions.

In addition to the effects of climate change, the impact of in-car technologies designed to assist drivers' vehicle operations must also be considered in light of MWL. Although technologies such as lane keep assist (LKA) and cruise control may lead to a safer and more comfortable driving experience, there is no clear understanding of the impact of these technologies on vehicular safety. For example, while MWL demands should decrease while using adaptive cruise control (131), the process of monitoring the device might counteract this otherwise positive feature. It will also be critical to compare the impact of different types of technologies (e.g., navigation provided by a head-up display instead of a conventional head-down screen) and the interactions of these technologies with the surrounding environment.

Yet, despite these added complications to the MWL for drivers, highway design has remained largely unchanged over time, with only incremental improvements. Highway design focuses on horizontal curvature, vertical curvature, and intersections. These elements and their placement along highways can entail high levels of complexity that challenge drivers and increase MWL demands. A complex geometric design that combines several elements (e. g., a vertical curve combined with an access) may represent a notably challenging driving environment, which increases with the presence of adverse environmental factors, such as snow, fog, or rain.

Developing updated, successful designs will require an appreciation and quantitative evaluation of these MWL demands so that all significant factors can be transposed into models and formulations for highway design and policy. As such, this study is a review article that investigates the changes in MWL in relation to highway design, beginning with the seminal research on this subject by Messer in 1980 (9). Our study will identify the contemporary challenges highway drivers face, determined by analyzing responses gathered through a survey of transportation experts. These results are then quantified from the perspective of MWL demand. We will then compare our results to those published by Messer (9), both to update these ratings based on the MWL demands and to explore the association of MWL to those aforementioned emerging factors. Crucially, the results will provide engineers with a vital tool to develop new designs to reduce MWL levels and assess existing infrastructure for designs that compromise safety. Such quantifications represent a notable gap in the current research literature and design guidelines; this study provides essential solutions to these design and planning issues.

5.2 LITERATURE REVIEW

This section reviews the research on factors that can influence MWL demands associated with highway driving, including automation, climate change, and geometric design. These elements represent the core subject matter addressed in our survey study and form the basis of comparison when assessing factors contributing to current MWL concerns.

5.2.1 Automation

One significant change in transportation that cannot be overlooked is the introduction of automation into the driving experience. The term automation should not imply that humans play no role in the driving process. By contrast, considering human factors and MWL demands is essential in two specific situations. The first situation involving significant MWL demands is the transition from fully automated to manual driving after a driver has been issued a take-over request. The second situation associated with increased MWL demands involves partially automated technologies, including cruise control and LKA systems. In both cases, drivers will need to intervene to ensure safe driving when the automated system fails to engage correctly or immediately after a take-over request has been issued.

Findings from several published studies have highlighted the impact of in-car assistance technologies on MWL demands placed on drivers. DeWinter et al. (132) reported that adaptive cruise control resulted in slight decreases in MWL demands placed on drivers. The study published by Ma and Kaber (29) confirmed these results and reported that adaptive cruise control resulted in decreased MWL demands even with concurrent cell phone use. Results from another study revealed that head-up displays, i.e. transparent displays of necessary data presented to drivers within their usual viewpoint parameters, permitted truck drivers to respond more effectively to urgent events compared to conventional head-down displays, i.e. displays of data that require drivers to look away from their usual viewpoints when driving (133). Interestingly, Stapel and colleagues (131) reported that the process of monitoring automated driving imposed a healthy MWL on drivers' MWL levels that keep them engaged without being overwhelming). Additionally, a strong relationship between the duration of a take-over request and performance after transitioning to manual driving, specifically in cases where the take-over request persisted for as long as 60 seconds after driving resumed, was identified (134).

More research is needed to provide a clear understanding of the impact of automation on MWL demands, especially where the use of one technology might preclude the effective engagement of another.

5.2.2 Severe Weather Conditions

Another growing and concerning factor in MWL is climate change, with more extreme weather events affecting driving conditions. Some research suggests, for instance, that the overall increase in ambient temperature may lead to driver stress and injuries (135). Climate change also directly impacts highway safety, mainly due to increased precipitation and storm conditions (136). Snow, in particular, directly relates to the rate of collisions on the road and has been associated with an increased number of non-fatal collisions (122, 137). Rain has a similar effect on highway safety as it results in both reduced visibility and decreased skid resistance. One recent study highlighted the increased risk of collisions involving multiple vehicles during periods of rainfall (138). A study in two Canadian cities revealed that rainfall increased the overall risk of collision by 70% (139). Results from another report showed increased wind speeds (140) are associated with a higher risk of collisions while driving (141) and causing trucks to overturn (142-143). Furthermore, smoke from wildfires resulting from climate change (144) can result in limited visibility, leading to collisions on the road (145).

In summary, those aspects of climate change resulting in unusual meteorological conditions pose novel challenges to highway drivers. Increased snow, rain, and fog may also limit the functionality of car sensors and other safety features (146-147). As a result, these changing weather conditions should be carefully considered when designing driving environments, including speed limits (148).

5.2.3 Geometric Design

As already noted, the surrounding environment contributes to changing MWL demands and can represent a significant challenge if drivers must deal with complex highway configurations. This is especially so when designs do not provide sufficient SSDs. Restricted sight distances may have a more profound impact on MWL demands than previously anticipated, especially in countries with ageing populations or where the prevalence of distracted and impaired drivers is high. Thus, it will be necessary to identify and quantify the impact of human factors on highway design to build safe and welcoming highways for drivers who face different personal situations and contexts.

Several studies have investigated the impact of different geometric elements on the MWL demands associated with highway driving. Horizontal curves on highways are recognized as visually demanding (89). Vertical crest curves add to that MWL demand because they change the perception of the horizontal curves that follow (10). The MWL demand increases with the increased degree of curvature and deflection angle of the horizontal curve (9). A prominent example of this issue is the case of roundabouts with small turning radii. Trucks have restricted turning capabilities and thus find these roundabouts to be challenging because of their sharp curves (38). Moreover, increases in traffic density and driving complexity (for example, work zone configurations) also increase MWL demands (63-64).

The 1980 study published by Messer (9) was the first to quantify the MWL demands imposed by the geometric layout of the highways using subjective workload measures, a study that is still foremost in the literature. He based his findings on survey data, which are subjective measures of MWL. Nonetheless, the results highlighted the MWL demands, and challenges associated with nine different geometric elements, including horizontal curves, crest curves, various intersections, and changes in the cross-section, among others. An example from this dataset is shown in Table 5.1.

TABLE 5.1 MWL Ratings for Various Combinations of Horizontal and Vertical Crest Curves (9)

Horizontal Curves					
Degree of Curvature (D°)	Deflection Angle°				
	10	20	40	80	100
1	0.5	1.0	2.1	4.1	6.2
2	1.2	1.5	2.0	3.0	4.1
3	2.1	2.3	2.6	3.3	4.0
4	3.1	3.2	3.5	4.0	4.5
5	4.0	4.1	4.3	4.7	5.2
6	5.0	5.1	5.3	5.6	6.0
7	6.0	6.1	6.2	6.5	6.8
8	7.0	7.0	7.1	7.4	7.7

Vertical Curves	
No. of Crest Curves within 1500 meters preceding the horizontal curve	Workload Potential Rating
≤ 2	1.9
≤ 3	3.0
≤ 4	4.0
≤ 5	5.0
> 5	6.0

Messer's paper remains the foremost study in the literature, not only because it was the first to undertake this type of analysis but because it now acts as a significant marker for similar current-day research. Notably, his study presented a methodology for design consistency based on MWL demands. A subsequent study performed by Habib et al. (68) confirmed Messer's (9) findings. They incorporated the values published by Messer (9) in a safety performance function used to explore the impact of MWL demands on highway safety (68). In addition, Habib et al. (149) used these findings to create an advisory speed system for horizontal curves on highways in the province of Alberta that incorporated the associated MWL demands. Messer's study also highlighted the significance of subjective MWL measurements, when combined with statistical tests such as reliability analysis, as a tool to calibrate the design guidelines (95). Collectively, these studies create a framework for implementing subjective measures in real-life transportation applications and form the basis upon which we draw our conclusions here.

Further, similar studies have been performed to assess the impact of the surrounding driving environment, such as the geometric design and weather condition, on driver MWL demands. Bongiorno et al. (22) reported that the surrounding environment in urban settings substantially impacted drivers represented by workload demands. As part of this study, the researchers categorized factors in the surrounding environment as either static objects, including parked vehicles, dumpsters, road signs, yards, and construction sites, or else as dynamic objects, including pedestrians, vehicles, cyclists, and motorcycles travelling in the same or opposite direction. Baldwin and Coyne (20) reported that decreased horizontal radii also increased MWL demands, and the combination of vertical and horizontal curves substantially impacts driver MWL demands. On top of these factors, the impact of the road geometry increases with increasing traffic density and places particularly critical MWL demands on ageing drivers (20, 150).

5.2.4 Summary

This literature review highlighted various factors, including automation, climate change, and geometric design, that influence driving, leading to potential critical safety issues if they remain unaddressed. In addition, the studies discussed here, most notably Messer's 1980 paper, form the basis upon which we consider how design has addressed MWL since that time and its contemporary challenges. In order to understand how the identified factors contribute to MWL demands, particularly in cases where two or more factors are combined, it will be necessary to quantify the impact of each one. One established method used to carry out quantification includes surveying transportation engineers. Therefore, this study obtained survey data from transportation engineers from varying educational and professional backgrounds utilizing this methodology. These engineers were asked to provide their opinions of MWLs associated with each factor in a scale-rating format. A rating system was designed that permits respondents to convey information around increases and decreases in driver MWL demands in a given situation. This addresses a gap in the literature where most of the previous studies identify the factors that impact drivers' MWL without offering any quantifications. This study presents quantifications necessary by engineers to design and evaluate their design and researchers to understand further the impact of changing workload demands on drivers concerning highway safety, design, and operations.

5.3 METHEDOLOGY

5.3.1 Survey Design

The survey was designed online and distributed via email to experts with documented work or research experience regarding geometric highway design, safety, operations, planning, and pavement design in Canada and the USA. The respondents represented various US states (Virginia, Florida, and Wyoming) and Canadian provinces (British Columbia, Alberta, Manitoba, and Ontario). The results shown in Table 5.2 provide a breakdown of the educational and professional backgrounds of the respondents based on publicly available information. As shown in Table 5.2, most respondents had design or research experience; some respondents had both design and research experience. These findings assure that our respondents represent a diversity of backgrounds.

TABLE 5.2 Qualifications of the Survey Respondents

Breakdown by professional sector		Highest academic degree	
Design	21/26 (80.8%)	**MSc**	21/26 (80.8%)
Research	20/26 (76.9%)	**PhD**	9/26 (34.6%)

The survey asked respondents to rate the degree of MWL demand associated with various geometric features and other factors using an 11-point scale (i.e., ratings of 0–10). The assumed speed was set at 100 km/h, and driving was assumed to be carried out in favourable weather conditions unless otherwise noted. Since recent literature examines the potential of automation to decrease (as well as increase) MWL demand, respondents were also asked to rate the impact of automation factors such as lane keep assist, cruise control, and adaptive cruise control on a scale of -10 to 10 (Tables 5.2 – 5.6). The findings presented in Table 5.3 – 5.6 were generated from responses to questions focused on external factors such as snow, rain, cyclists, and partial automation.

This survey was approved by the Ethics Department at the University of Alberta on November 2, 2020, ID number Pro00104592 and was renewed on October 2, 2021.

5.3.2 Statistical Testing

Reliability testing was used to test the internal consistency of the experts' responses statistically. Cronbach Alpha was calculated for the survey responses. The correlation between the MWL for horizontal and vertical crest curves (Tables 5.3 and 5.5) was calculated from this study and Messer's results (9) to validate the results further. The results from the correlation test will further validate the results from this survey.

5.4 RESULTS

Survey responses were collected from 26 transportation experts from Canada and the USA with research and design experience. Evaluation of the survey responses' internal consistency revealed a Cronbach alpha value of 0.9 for the scale (0 to 10) and 0.86 for the scale (-10 to 10). Those results denote strong internal consistency for the survey responses. SPSS software ® version 28 was used for the analysis. The mean and standard deviation values for the different geometric elements and the surrounding factors are shown in Tables 5.3 – 5.6.

5.4.1 Ratings for MWL Demands Associated with Horizontal Curves

The average ratings for MWL demand while driving on horizontal curves are shown in Table 5.3.

TABLE 5.3 Average MWL Demands for Horizontal Curves

Mean Ratings					
Degree of curvature (D◦)	**for Deflection Angle (Δ◦)**				
	10	**20**	**40**	**80**	**120**
1	0.9	1.5	2.7	4.2	5.6
2	1.6	2.1	3.3	4.6	5.7
3	2.4	3.2	4.1	5.2	6.3
4	3.5	4.1	5.0	6.0	7.1
5	4.5	5.1	6.0	6.8	8.0
6	5.3	5.9	6.7	7.7	8.5
7	6.0	6.6	7.5	8.3	9.0
Standard Deviation					
1	1.1	1.3	1.4	1.7	2.3
2	1.4	1.4	1.4	1.5	2.0
3	1.6	1.6	1.4	1.4	1.8
4	2.3	2.0	1.6	1.5	1.7
5	2.6	2.2	1.8	1.4	1.4
6	2.6	2.2	1.6	1.4	1.3
7	2.7	2.1	1.7	1.3	1.1

The results shown in Table 5.3 can be compared to those presented in Messer's ratings in Table 5.1 in reference (9). These results correlated strongly with one another (correlation of 0.92). These results confirm the findings initially presented in 1980 by Messer (9).

5.4.2 Ratings of MWL Demands Associated with Intersections

Building on Messer's findings (9), this study conducted a more detailed evaluation and generated a rating system focused on different road intersections. The ratings focus mainly on MWL demands associated with signalized or stop-sign controlled divided and undivided intersections.

TABLE 5.4 Average MWL Demand Associated with Different Intersection Configurations

Intersection type	Average MWL rating	Standard Deviation
Signalized divided intersection	3.6	2.0
Signalized undivided intersection	4.7	2.2
Stop-sign controlled divided intersection	6.0	2.0
Stop-sign controlled undivided intersection	6.5	2.0

Table 5.4 provides ratings for MWL demands based on the intersections' layouts and traffic control types. Note that the ratings shown here focus only on the geometric layout along with signalling, as the remaining details are typically site-specific. For example, the survey did not address the type of left-turn permitted at each intersection (i.e., open or controlled), nor did it consider traffic volume. To address these site-specific issues, details on the nature of particular traffic patterns and information on annual average daily traffic would be required. These factors can be included in future transportation design and operation applications evaluations. This survey, however, addressed only general MWL demands based on geometric layout only. The approach used here models safety performance functions in the Highway Safety Manual (151), where additional details regarding the number of protected lanes remain optional. Additional information on the layout of specific intersections and traffic volumes could be combined with the average ratings included here to better understand and value various transportation applications.

5.4.3 Impact of Vertical Curves Preceding Horizontal Curves and Intersections on MWL Ratings

In contrast to Messer's survey (9), this study examined the impact of a sag curve in combination with both horizontal curves and intersections. MWL demand ratings describing the influence of vertical crest and sag curves were determined separately for intersections and horizontal curves to identify any potential differences. Several previous publications documented changes in driver perception of geometric elements when combined or preceded by vertical curves (152-154). The results of this analysis are presented in Table 5.5.

TABLE 5.5 MWL Demands on Roadways in which Vertical Curves Precede Horizontal Curves and Intersections

Number of vertical curves[1]	**followed by a horizontal curve**				**followed by an intersection**			
	Crest		Sag		Crest		Sag	
	Mean Rating	St. Dev.	Mean Rating	St. Dev.	Mean Rating	St. Dev.	Mean Rating	St. Dev.
1	2.5	1.6	1.9	1.4	2.9	1.4	2.0	1.3
2	3.7	1.7	2.8	1.5	3.9	1.3	2.8	1.6
3	5.0	2.1	4.1	2.2	5.2	1.5	3.9	1.9
4	6.2	2.3	5.0	2.5	6.3	1.7	5.0	2.3
5 or more	7.0	2.3	5.7	2.7	7.1	2	5.7	2.6

[1] Number of vertical curves preceding a horizontal curve or intersection within a distance of 1500 meters (9)

The average MWL demands required on roadways in which one or more vertical crests precede either horizontal curves or intersections correlate strongly (= 0.99), with ratings of vertical crest curves published by Messer (9). The findings presented in Table 5.5 include additional details, such as the impact of vertical sag curves followed by horizontal curves and intersections on driver MWL demands.

5.4.4 Ambient Factors

This subsection presents a review of the ratings provided for various weather conditions and other factors that can influence the MWL demands associated with driving on horizontal curves and intersections. These additional factors include other users of the roadway and driving assistance technology, as outlined in Table 5.6.

TABLE 5.6 MWL Demand Associated with Ambient Factors Combined with Horizontal Curves and Intersections

Major Geometric Element		**Horizontal curve**		**Intersection**	
		Mean Rating	Standard Deviation	Mean Rating	Standard Deviation
Cyclists	**(on the shoulder of the roadway)**	4.9	2.1	4.1	1.8
Night	**(non-illuminated)**	5.7	1.7	5.1	1.8
Fog	**medium**	7	1.8	6.5	2
Rain	**(requiring windshield wiper use)**	5.9	2	5.4	2.1
Snow	**(medium)**	6.6	1.8	6.2	2.2
Use of cruise control		-2.8	2	N/A	N/A
Use of adaptive	**Cruise control**	-2.8	1.6		
Use of LKA system devices		-2.8	1.9		

Of the various weather conditions (i.e., medium fog, rain, and medium snow), the survey revealed that the appearance of fog while driving on horizontal curves and intersections was perceived as having the highest impact on MWL demands; rain and medium snow followed. Cyclists and a lack of night-time illumination were also considerable effects on driver MWL. Interestingly, using in-car technologies, including conventional and adaptive cruise control and LKA systems, while driving on horizontal curves resulted in an overall decrease in the perceived average MWL demand (all values -2.8).

5.5 DISCUSSION

The goal of this study was to quantify the impact of MWL demands on highway drivers based on the subjective ratings of survey responses from transportation experts with various backgrounds; these results confirm Messer's study (9). The findings are validated via a partial comparison with Messer's ratings represented by a high correlation between the horizontal and vertical curves ratings. Moreover, the internal reliability of the survey results showed high consistency amongst the experts' responses.

Our survey not only establishes degrees of change to road design but advances knowledge in the field by focusing on ratings for MWL demand imposed by newly introduced factors, including weather, cyclists, and in-car driver assistance automation technology. Furthermore, our study relates these factors to the geometric elements of highway design, such as horizontal and vertical curves. These are significant advances in the research understanding of these issues, intended to support transportation planners, roadway designers and urban traffic safety authorities.

Certainly, the results agree with the literature regarding the magnitude of the ratings. For example, the complexity of the horizontal curves increases with an increase in the degree of curvature (decrease of horizontal radius) and rise of the deflection angle, as revealed by Messer (9, 10, 155, 156). Similarly, vertical curvatures increase the MWL demand when combined with other geometric elements such as horizontal curves and intersections (10, 65). The results from this survey agree with the literature regarding the existence of cyclists on the shoulder. Studies (126, 157) show that drivers slow down in intersections and horizontal curves when driving close to cyclists. The increase in MWL demand on highways due to fog, non-illuminated night-time, snow, and rain is documented in the literature (158-161). The significant effect is the decreased visibility due to those particular weather conditions.

This survey represents the first step toward the full process of synchronizing human factors in highway design and operation management processes. The results are in line with those published previously by Habib et al. (95), where a reliability analysis was performed to evaluate the sufficiency of Messer's MWL stopping sight distance on horizontal and vertical crest curves, resulting in the validation of the MWL ratings results (9). It is essential to recognize that changes to human behaviour, for example, changes in acceleration and deceleration distributions, could be updated and combined with the results from this study and the original Messer analysis (9) using the reliability analysis presented by Habib et al. (95).

The study aimed to overcome some limitations in the subjective ratings by minimizing the bias or over/under evaluation of MWL levels by surveying transportation experts (162). Surveying experts with a broad spectrum of transportation experience ensured high reliability, represented by the value of Cronbach alpha = 0.9 and 0.86. Limitations and future work may include the development of more subjective ratings for novice drivers and different genders. In addition, establishing a quantified relationship between subjective and psychological workload measures will significantly add to the literature. Ultimately, linking the psychological workload measure to collision data will be the goal. That link was achieved between collision and subjective workload measures, and an SPF was created (68).

5.6 CONCLUSIONS

This study identified the hierarchy of MWL demands due to various factors that may impact drivers on highways. The results quantified those factors using subjective workload measure (survey), and the magnitude of the results agreed with the findings from the literature as discussed earlier in the discussion section. The outcomes of this study are vital for creating a transition from subjective workload measures to real-life transportation engineering applications. Those applications may vary from safety, traffic management, equity and emerging technologies.

Human factors continue to play essential roles in an automated driving environment. Drivers must be able to control the driving task when the automated systems fail, or drivers have reason to distrust signals from the system (155). Additionally, the design of the take-over request itself is important as there must be enough time for drivers to absorb information and respond to signals from the surrounding environment. The design of safe and effective transitions from automated to fully manual driving will rely on a complete understanding of the complexity of the surrounding environment.

Ultimately our study indicates that there have been no significant foundational or transformational changes since Messer’s study to address MWL in geometric design. Changes that have been implemented have been incremental at best, suggesting that MWL has not been a significant consideration. As our population ages, there is little to suggest that drivers’ are improving their skills, and engineers should therefore be designing to make roads more user-friendly. Our study can act as a way to quantify the MWL factors and incorporate these considerations into road planning.

There is a need for additional studies focused on quantifying factors that increase driver MWL demand on all roads in urban environments. Drivers in urban settings typically encounter highly complex situations on a frequent and continuous basis, including roundabouts, road intersections, rail intersections, public transit systems, cyclists, pedestrians, and even scooters. Each situation involves a substantial focus on complex details. For example, safe transit through road intersections requires increased MWL demands, including accommodation for sun or snow glare combined with cyclists, pedestrians, and transit priority lanes. In this case, a modified design might permit drivers to be challenged with only one task and will provide sufficient room for appropriate actions and responses.

The work presented here contributes to including equity in highway design. By understanding the capabilities of different driver populations and the impact of each highway design element, future research may ensure that the geometric design of highways and their MWL demand will not exceed the drivers' population MWL supply. If it does happen, countermeasures could be implemented, such as advisory speed limits giving drivers more time to adjust their behaviour (162). In this case, highways may welcome all drivers with different driving capacities, either in manual or automated driving situations.

Thus, this study might extend to assess the impact of the surrounding environment on cyclists and pedestrians since they face different MWL challenges given their vulnerability compared to passenger car and truck drivers. For instance, physical effort increases cyclists' MWL levels, unlike car drivers (163). An improved understanding of how accommodation for vulnerable road users affects MWL demand is a critical foundation for designing equally forgiving and challenging environments for all road users. This might be accomplished by balancing the MWL demands among all road users. It will also be necessary to explore the MWL capacity of all road users, including senior drivers, cyclists, and pedestrians. New road designs must be developed that accommodate the needs of all users, including those with varying capabilities.

5.7 AUTHORS CONTRIBUTION

The authors confirm contribution to the chapter as follows: study conception and design: Karim Habib; data collection: Karim Habib; analysis and interpretation of results: Karim Habib, Karm El-Basyouny; draft manuscript preparation: Karim Habib, Karim El-Basyouny.

6 CONCLUSIONS

6.1 SUMMARY

This thesis covered the incorporation of mental workload into highway safety, design, and operations. Moreover, a survey for mental workload demand was developed to cover the geometric design of highways, including cyclists' presence, partial in-vehicle automation, and changing climatic weather conditions. The research material presented herein followed a logical flow where the relationship between mental workload demand and collisions was proved and formulated using safety performance functions. After clearly outlining the nature and contribution of mental workload demand on collisions, a calibration for design requirements was undertaken using the reliability analysis to address the mental workload demand component while designing highways. Also, a system advisory speed limit was created that incorporated mental workload and available sight distance to advise drivers on the safest speed. Last, this study presented a further validation for Messer's ratings and, given the need to take factors into account that have more recently surfaced, offered an upgrade to Messer's survey.

The first study explored the relationship between the MWL demand imposed by geometric road design and collision rates on Alberta highways. It is worth mentioning that the segmentation was undertaken and provided by Alberta Transportation, resulting in homogenous highway segments. Moreover, no correlation was found between the AADT and workload index in the developed SPF (correlation = 0.1). More so, the SPF developed in Chapter 1 was compared with a previously developed SPF that used the geometric characteristics of horizontal curves, such as length of curve, curve radius and superelevation. The estimates of the SPF models parameters were different in the MWL SPF and the geometric characteristics SPF (164). For example, the AADT parameter estimate was 0.36 and 0.63 for the MWL SPF and the PDO SPF. This difference shows how incorporating a MWL index can explain impact of the geometric design on collisions, especially when there was a weak correlation between AADT and MWL.

The safety performance function identified the impact of creating designs that include one or more geometric elements—for example, combining a horizontal curve with an intersection or combining a vertical curve with changes in a cross section or intersection. Such a combination of various geometric elements may demand that drivers deal with different driving tasks simultaneously and require more time to react appropriately. The incorporation of the MWL in the safety performance function was represented by ratings provided from a survey.

Once the influence of the changing MWL levels on highway safety was understood, two different applications were created to tackle the safety issues regarding the high MWL levels. The first application was an advisory speed system that accounts for the MWL complexity of the geometric design and drivers' available sight distance. The resulting speed limits ensure that the infrastructure does not overwhelm drivers, giving them enough leeway to drive safely through the geometric elements. Meanwhile, when constructing new highways or implementing infrastructural changes, the complexity of the geometric design must be informed by considerations that satisfy the users. In this respect, the second application provides stopping sight distance based on the MWL demand of the geometric design for one or a combination of more geometric elements.

The last study surveyed transportation experts to subjectively assess the MWL in terms of various highway geometric elements, such as horizontal curves, vertical curves, and signalized and unsignalized intersections. These experts evaluated further factors, such as the presence of cyclists on shoulders, representing a novel change to the highway driving environment. It was also necessary to assess the impact of now widely used in-car assistance technologies such as lane keep assist, cruise control, and adaptive cruise control on drivers' MWL levels. As a result, those ratings provide a powerful tool for designers and researchers to evaluate the impact of various factors on their designs and drivers' reaction to them.

6.2 RESEARCH CONTRIBUTION

The novelty and contribution of this thesis include a full methodology to incorporate human factors in transportation applications starting from survey design and analysis, using the proper statistical methods, and ending by developing and interpreting the application developed. Additionally, LiDAR data is a rich data source processed using previously developed and validated MATLAB scripts to accurately and automatically provide research inputs such as available sight distance, horizontal curve parameters (degree of curvature and deflection angle), and detection of vertical curvature.

This first study successfully incorporated the subjective ratings for the geometric design MWL demand, which explicitly considered human factors in highway safety, providing designers with reliable quantification. This is a starting step to further model other factors that may impact drivers' MWL, such as signing whose amount of information may impact drivers' MWL resources.

The second and third studies provided a framework for developing calibration for design guidelines and advisory speed systems. Those studies presented a transportation statistical testing for the outcomes of the subjective workload measures. They then suggested stopping sight distance and advisory speeds to overcome the complexity of different designs.

The last study in this thesis provided ratings for various surrounding environmental factors such as the geometric layout, climatic weather conditions, the presence of cyclists, and in-car assistance technologies. These new factors help to clarify the impact on the driving task and can be incorporated into the design and operational process.

From a practical perspective, this thesis provides design and safety engineers with the tools necessary to assess and design safe highways. SPF helps safety engineers to find the proper countermeasures for locations of concern. Moreover, the thesis offers SSD and PRT values for different geometric elements or combinations.

Here, it is crucially important to mention that the research in this thesis contributes to the core of including equity in highway design. Providing different design requirements according to diverse population needs promotes equity in highway design. In the reliability analysis, the distribution for the perception reaction times for the stopping sight distance could be represented by considering different populations' capabilities, including old, young, distracted drivers, and more.

6.3 RESEARCH LIMITATIONS

The work in this thesis was done on Alberta highways which is a possible limitation to this work. A recommendation is to apply this work in other locations. Also, surveying different groups in different countries can capture drivers' behavioural and cultural differences. This will help us understand how to design and manage highways for diverse populations based on their differing capabilities and behaviours.

In addition, the province of Alberta experiences extremely low temperatures in winter and has low-rolling terrain. Alternately, the province of British Columbia has higher winter temperatures and mountainous terrain in nature, making the geometric highway design and operations in both regions different. In this respect, using geometric design and collision data from other provinces may deepen the understanding of the impact of geometric design on highway safety.

Regarding the reliability analysis, the inclusion of drivers' behaviours, was to combine these with the survey results as inputs for analysis. However, developing more behavioural distributions is necessary to accommodate different segments of the population, achieving the goal of equity in highway design.

6.4 FUTURE RESEARCH

Regarding the development of the safety performance function, future work could address the development of different safety performance functions that model the collisions for different driver groups and varying weather conditions. The psychological measures could potentially be used to model collisions and compared to the output of this thesis. Understanding the impact of the infrastructure on various driver groups directly addresses equity in highway safety.

From an equity perspective, the available sight distance and advisory speed systems for different geometric elements should consider the complexity of infrastructure and the capabilities of the driving population. For instance, advisory speed limits for the ageing population at restricted stopping sight distance locations may be different than for younger drivers.

The ratings developed in the fourth study are based on a subjective assessment by transportation experts. Those ratings may be used to calibrate or understand the output of psychological measures. Simulation-based and naturalistic driving data may be helpful to understand changes in drivers' MWL levels when driving on different highways.

Future work includes investigating the workload demand of vulnerable road users such as cyclists and pedestrians in urban and rural settings. Each road user has different challenges and different levels of vulnerability. The introduction of connected vehicles could significantly decrease the workload levels for road users if they receive early information regarding the infrastructure and traffic patterns.

Human factors will play a crucial role in the transition from automation to manual driving in the automated driving environment. In separate cases, a take-over request occurs due to system failure, or else drivers could issue these requests. Here, humans must control the vehicle and resume driving, and human factors play a part in guaranteeing that drivers can continue driving safely.

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APPENDIX A

For Chapter 1, The following table presents descriptive statistics for the SPF data.

Descriptive Statistics for the SPF Data

	Collisions per 5 Years	AADT	Segment Length (km)	WLI
Mean	55	3101	3.12	4.6
Standard deviation	20.9	1972	1.74	2.4

For Chapter 3, the next table offers descriptive statistics for the advisory speed system data.

Descriptive Statistics the Developed Advisory Speed System Data

	MWL Rating	SSD_{MWL} (m)	ASD (m)	$V_{advisory}$ (km/h)
Mean	3.3	269.6	366.3	87.7
Standard deviation	1.4	38.9	275.1	14.1