Canadian Journal of Civil Engineering

A System to Determine Advisory Speed Limits for Horizontal Curves based on Mental Workload and Available Sight Distance

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2020-0482.R1
Manuscript Type:	Article
Date Submitted by the Author:	16-Feb-2021
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Keyword:	Horizontal Curves, Advisory Speed Limits, Mental Workload, Available Sight Distance, LiDAR data
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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A System to Determine Advisory Speed Limits for Horizontal Curves based on Mental Workload and Available Sight Distance

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ABSTRACT

This study proposes a framework that accounts for mental workload and available sight distances to estimate advisory speed limits on horizontal curves. To achieve this goal, automated scripts were used to extract data on horizontal curve elements (i.e., the degree of curvature and the deflection angle), to detect crest vertical curves, and to compute the available sight distance from remote sensing data collected on highways in Alberta, Canada. Mental workload ratings were then assigned to each horizontal curve to calculate the perception-reaction time needed by drivers to maintain control of their vehicles while negotiating these curves. Finally, a curve advisory speed was calculated based on the available sight distance and the mental workload perception-reaction time needed to ensure a safe driving environment. This study presents a unique approach that incorporates human factors, including the responses of drivers based on their perception of the driving environment, in the development of speed advisory systems.

Keywords: Horizontal Curves, Advisory Speed Limits, Mental Workload, Available Sight Distance, LiDAR data

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INTRODUCTION

The design of horizontal curves on highways needs to take into account 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). MWL is defined as the time and effort required to perform a given driving-associated task (*Messer 1980*). For example, an earlier study by (*Messer 1980*) 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 (*Habib et al. 2019*). 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 perception-reaction time (PRT) for any highway location is typically a fixed value. 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 (*Shallam and Ahmed 2016*). 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 traveled during perception-reaction time and the distance required for the vehicle to come to a complete stop). These simplifications are typically based on percentile

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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 (*Woolridge et al. 2000; Tsimhoni and Green 2001*). Horizontal road curvature affects driving performance, including mean speed, lane-keeping performance, and the ability to maintain headway (*Jeong and Li 2017*). More importantly, evidence from the literature revealed that collisions occur more frequently on horizontal curves than on tangent sections (*Liu and Subramanian 2009*).

Recent literature suggests that there is a link between available sight distance (ASD) and highway safety (*Ibrahim et al 2012; Lanzaro et al. 2020*). For example, (*Habib et al. 2020*) 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 (*Gargoum et al. 2018a*) revealed that collision rates increased 2.1-fold among aging 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 the changes in PRT, 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

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time to traverse these curved sections safely and without mental overload through balancing MWL and ASD.

LITERATURE REVIEW

Advisory Speed Limits (ASLs) 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 (Kwon *et al.* 2015). 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 (Allaby *et al.* 2007) and (Hardy *et al.* 2006) 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 2013) developed an ASL system specifically for use on horizontal curves that was 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 (Charlton 2007). 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.

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Perception-Reaction Time (PRT)

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 (*Fambro et al. 1998*). (*Ismail and Sayed 2009*) 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 (*Fitzpatrick et al. 2012*). Despite these observed variabilities, the geometric design guidelines from the American Association of State Highway and Transportation Officials (*AASHTO 2011*) uses a fixed value PRT of 2.5 seconds.

The Geometric Design Guide for Canadian Roads published by the Transportation Association of Canada (TAC) 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 (*TAC 2017*). 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

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required to effect a full lane change was 4.6 seconds (*Campbell 2012*). 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.

Available Sight Distance (ASD)

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 aging drivers (SSDs calculated based on a PRT <5 seconds; *Gargoum et al. 2018a*) and were associated with higher collision rates.

It is important to recognize that the effects of restricted SSDs are highly situational (*Potts et al. 2019*). Locations that include an intersection together with a crest curve and SSD restrictions are likely to be the sites of frequent collisions (*Harwood et al. 2014*). 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. 2020*) examined the credibility of the SSD framework as provided by (*Messer 1980*) 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% (*Habib et al. 2020*). 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.

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Mental Workload (MWL) associated with Curves and Design

1) MWL in design

The TAC (2017) 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.

2) Mental Workload (MWL) on Vertical and Horizontal curves

Horizontal curves are visually demanding (Wooldridge et al. 2000). (Easa and Ganguly 2005) 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 (Easa and He 2006). This study identified significant effects associated with the inverse of both the horizontal curve radius and the vertical curvature. These results are also

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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 (*Easa and He 2006*), which is 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 manuscript 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 Light Detection and Ranging (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.

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 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 (*Messer 1980*) and (*Habib et al. 2019*).

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The ratings shown in **Table 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 1** (Habib *et al.* 2019). 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 equaled 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 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.

$$V_{MWL} = V_{design\ speed} + 8 * R_f \text{ (Messer 1980)} \quad \text{and} \quad R_f \geq 2.0 \quad (1)$$

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 (Habib *et al.* 2020).

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

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In this equation, $PRT_{2.5}$ is a constant PRT value of 2.5 seconds, a is a deceleration rate of 3.4 m/s², 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.

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

Equation 4 is a quadratic equation generated from the calculated SSD that is 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.

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

This entire process is summarized in the flowchart depicted in **Figure 1**.

Figure 1 The procedure used to calculate $V_{advisory}$

TABLE 1 MWL ratings of different horizontal curves and effect of crest vertical curves

LiDAR data were used in this study to obtain the geometric characteristics of the horizontal curves. Alberta Transportation collected these data which reflect the current design of the provincial highway network. The data are at very high density (150–1000 points/m²) 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°) and the degree of curvature (D°), were extracted from the LiDAR data (*Gargoum et al.*

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2018b). The same dataset was used to extract data regarding the vertical curves (Gargoum *et al.* 2018c). The findings shown in **Table 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 (Habib *et al.* 2020). 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 (Shalkamy *et al.* 2020).

RESULTS AND DISCUSSION

Data obtained for 41 curves were evaluated by calculating the PRT_{MWL} , extracting the ASD data, and then calculating the required SSD_{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 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 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

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requirements. This is consistent with an intuitive conclusion, as one can drive as fast as 100 km/h on these roads so long as 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 $D^0 = 0.96$ 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

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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 2 Extracted Data and Advisory Speed Limits (ASLs)

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 (Habib *et al.* 2019). 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 directed 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 as a means to remedy the problems associated with horizontal curves preceded by crest vertical curves, which are highway configurations that are 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 (Campbell *et al.*

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2012). 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 PRT_{MWL} is based on the SSD_{MWL} that was calculated as per Equation (1) as initially described by (Messer 1980). The same SSD_{MWL} was evaluated in a study performed by (Habib et al. 2020) 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 SSD_{MWL} was applied. This finding revealed that the SSD_{MWL} can accommodate the needs of drivers traveling 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 study 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 (Kockelman et al. 2017;

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Gouda et al. 2021) where take-over requests may need human interference in the driving process which includes a workload component (Yoon and Ji 2019; Zhang et al. 2019)

Data from LiDAR scans can facilitate recovery of the geometric design features in a manner that can be translated into safety applications (*Habib et al. 2019*). For example, the extraction of the geometric elements of the highways could be used to create safety applications such as safety performance functions (*Habib et al. 2019; Garcia et al. 2012*). These applications will rely on the efficiency of using LiDAR data to effectively extract different highways infrastructure geometric elements such as 3D SSD (*Ma et al., 2019*), signs and marking (*Smadja et al. 2010*), vegetation (*Yang et al. 2015*), light poles (*Yu et al. 2014*). 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 (*Tawfeek and El-Basyouny 2018*). Perceptual warnings are superior to kinematic warnings in terms of safety and driver expectations (*Tawfeek and El Basyouny 2018; Tawfeek and El Basyouny 2019*). The proposed ASL is a perceptual warning method since it 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

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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 (Gouda and El Basyouny 2020; Bongiorno et al. 2017; Hancock et al. 1992; Lenné et al. 1997).

ACKNOWLEDGMENTS

The authors would like to thank Alberta Transportation for providing the data used in this study. The contents do not necessarily reflect the official views or policies of Alberta Transportation. The contents of this paper reflect the views of the authors who are solely responsible for the facts and the accuracy of the data presented herein.

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Figure 1 The procedure used to calculate $V_{advisory}$

TABLE 1 MWL Ratings of Horizontal Curves and the Effect of Preceding Crest

Vertical Curves (Messer 1980)

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		

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≤ 3	3.0
≤ 4	4.0
≤ 5	5.0
> 5	6.0

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1 **TABLE 2** Extracted Data and Advisory Speed Limits (ASLs)

No. of curve	Radius (m)	Crest?	D(°)	Δ(°)	Hz Rating	Total Potential Rating	V _{MWL} (km/h)	SSD _{MWL} (m)	PRT _{MWL} (seconds)	ASD (m)	V _{Advisory} (km/h)
1	1150	1.9	1.50	21.0	1.3	3.2	125.6	266.308	5.50	221.00	85
2	1160	1.9	1.48	26.7	1.9	3.8	130.4	283.589	6.12	160.00	65
3	710	1.9	2.42	34	2.11	4.0	132.08	289.760	6.34	341.00	100
4	700	0	2.46	49	2.3	2.3	118.4	241.368	4.60	279.00	100
5	1160	1.9	1.48	51.0	2.5	4.4	135.2	301.392	6.76	200.00	70
6	870	1.9	1.98	37.6	1.94	3.8	130.72	284.759	6.16	160.00	65
7	860	0	1.99	20	1.5	0.0	100	182.978	2.50	140.00	85
8	700	0	2.46	42.1	2.3	2.3	118.4	241.368	4.60	179.80	80
9	900	1.9	1.91	29	1.7	3.6	128.8	277.770	5.91	301.00	100
10	850	0	2.02	27.3	1.7	0.0	100	182.978	2.50	180.67	95
11	860	1.9	2.00	50	2.25	4.2	133.2	293.910	6.49	160.90	60

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12	700	3	2.46	62.5	2.8	5.8	146.4	344.966	8.33	260.00	80
13	1350	1.9	1.27	30.0	1.7	3.6	128.8	277.770	5.91	202.00	80
14	1780	1.9	0.97	10	0.5	2.4	119.2	244.081	4.70	122.00	60
15	1770	1.9	0.97	14	0.7	2.6	120.8	249.551	4.89	182.00	80
16	1900	1.9	0.91	14	0.7	2.6	120.8	249.551	4.89	183.00	80
17	1750	1.9	0.98	28.0	1.4	3.3	126.72	270.294	5.64	263.00	95
18	1160	1.9	1.48	38.0	2.1	4.0	131.6	287.990	6.28	205.00	75
19	1740	1.9	0.99	28.3	1.5	3.4	126.8	270.579	5.65	243.00	90
20	870	1.9	1.98	56.0	2.4	4.3	134.4	298.388	6.65	323.00	100
21	1800	0	0.96	31	1.6	0.0	100	182.978	2.50	884.00	100
22	1530	0	1.12	10	0.57	0.0	100	182.978	2.50	240.00	100
23	1600	0	1.07	50.0	2.6	2.6	120.4	248.178	4.85	140.00	65
24	1730	0	0.99	15.5	0.8	0.0	100	182.978	2.50	241.00	100
25	860	1.9	2.00	49.7	2.2	4.1	132.8	292.425	6.44	538.1	100
26	1000	1.9	1.69	16	1.2	3.1	124.8	263.479	5.40	200.88	80
27	1600	1.9	1.07	20.8	1	2.9	123.2	257.864	5.19	1244.9	100

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28	650	1.9	2.66	17.7	1.96	3.9	130.88	285.345	6.18	864.76	100
29	620	1.9	2.79	89.9	3.4	5.3	142.4	329.077	7.76	200.35	65
30	830	1.9	2.06	35.6	1.9	3.8	130.4	283.589	6.12	420.02	100
31	1000	1.9	1.70	54.5	2.5	4.4	135.2	301.392	6.76	906.36	100
32	900	1.9	1.92	48	2.2	4.1	132.8	292.425	6.44	982.28	100
33	900	1.9	1.91	48	2.2	4.1	132.8	292.425	6.44	438.21	100
34	740	1.9	2.33	23.6	1.8	3.7	129.6	280.672	6.01	341.25	100
35	690	1.9	2.49	35.6	2.2	4.1	132.8	292.425	6.44	540.93	100
36	460	1.9	3.72	22.3	3.1	5.0	140	319.718	7.42	783.55	100
37	880	1.9	1.96	14.5	1.35	3.3	126	267.728	5.55	321.35	100
38	680	1.9	2.51	16.8	1.8	3.7	129.6	280.672	6.01	301.17	100
39	660	1.9	2.59	19.1	2	3.9	131.2	286.519	6.22	763.17	100
40	730	1.9	2.35	41.4	2.21	4.1	132.88	292.722	6.45	178.4	70
41	550	1.9	3.12	19.1	2.4	4.3	134.4	298.388	6.65	181.09	70

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