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Project Title

Proposing New Speed Limit in Mountainous Areas Considering the Effect of Longitudinal Grades, Vehicle Characteristics, and the Weather Condition

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Research Needs

Based on Green book (AASHTO 2011), design speed is a factor of horizontal curve radius. Then, the speed limit will be assigned based on the speed design considered in the design phase (speed limit is typically 5-7 mph less than design speed). The procedure of assigning an appropriate speed limit is a vital task regarding the safety due to the high rate of crashes on horizontal curves. The crash rate on horizontal curves is about 1.5-4 times greater than on an otherwise-similar straight section (Aram, 2010). Horizontal curves create two threats for the vehicles: (1) skidding and (2) rollover toward the outer direction of the curve. Green book (AASHTO 2011) considers a point-mass model to estimate the appropriate speed limit based on the radius of horizontal curves; however, there are some serious problems in using point-mass model:

(1) The effect of longitudinal grade is ignored (the method belongs to flat terrain),
(2) There is no trace of vehicle characteristics such as type, weight, and dimensions (in fact, vehicle has been assumed just as a point in the method),
(3) Side friction factors are still based on the studies of the 1930s,
(4) Adverse weather conditions are not considered.

Longitudinal grades (especially downgrades) make a difference in the distribution of weight on tires and axles, and change the dynamic performance of vehicles regarding the forces and accelerations that act on a horizontal curve. Longitudinal grades also cause an increase in side friction demand and a decrease in available side friction (Bonneson, 2000; Kordani and Molan 2015). The Green Book (AASHTO 2011) method is considering an unsprung (rigid) model for the vehicles which is independent of vehicle dimensions and features such as suspension system. This fact will be more critical for heavy vehicles (especially, in articulated vehicles) due to their specific dynamic features, while the point-mass model might work pretty acceptable for passenger cars. Fig. 1 has illustrated the location of the center of gravity (CG) in different components of an articulated vehicle on a horizontal curve combined with a downgrade (Eck and French 2002) to make a clear view of the problem.

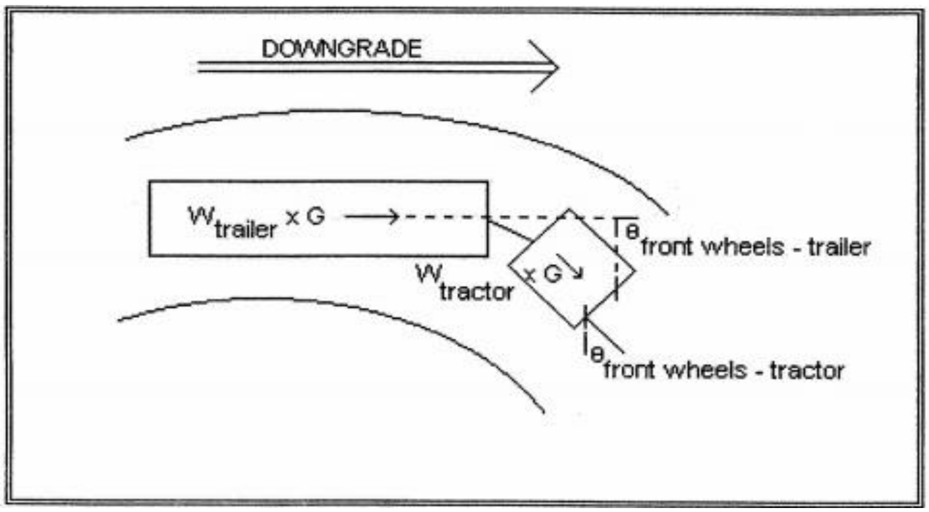


Fig 1. The condition of center of gravity in tractor and trailer of an articulated vehicle on combined horizontal curves with vertical alignments (Eck and French 2003)

Many researchers have recommended that a more sophisticated model should be introduced for analyzing the vehicles on horizontal curves (Psarianos et al. 1998; Kontaratos et al. 1994; Bonneson 1999). Studies by Varunjikar (2011), Molan and Kordani (2014) revealed that the transient bicycle, steady-state bicycle, and multi-body simulation models are better alternatives than the point-mass model for horizontal curve analysis. Excluding the variables related to weather condition is another drawback of the current method. It should be mentioned that the impact of the weather condition can be categorized in terms of its effect related to the friction (between tires and the pavement), wind, and the visibility (sight distance). Reviewing the previous studies, there have been only a few studies which considered the influence of the parameters related to the weather condition during vehicles cornering (Kordani et al. 2014; Hassan et al. 1996; Shin and Lee 2014).

Therefore, according to the discussions done in above, a new study is required to be conducted utilizing a new method to investigate the effect of these variables on vehicles safety on horizontal curves, and consequently include them into the procedure for defining new speed limits.

Research Objectives

(1) This research seeks to investigate the relationship between the speed limit and the missing variables in the point-mass model
(2) Proposing new values for the speed limit values considering geometric features, vehicle characteristics, and the weather condition
(3) The exclusive effect of each these variables on safety will be studied
(4) As a subjective in the study, the most dangerous segments of mountainous areas will be investigated in Wyoming

As a summary of the objectives in this research, the effect of variables ignored by the point-mass model will be discovered (running simulation modeling) to increase the accuracy in assigning speed limit values in mountainous areas. The main hypothesis is that all these variables will affect the safety of vehicles. Therefore, they must be considered in speed limit studies. Finally, a safer and more consistent atmosphere (between users and environmental variables) will be provided for the traffic on mountainous areas based on the result of this research.

Research Methods

The first step of the project will be done preparing a comprehensive literature review for the topic based on the previous efforts regarding proposing new speed limits for roads.

Then, the most dangerous segments will be investigated in Wyoming using the conventional "Rate Quality Control (RQC)," and the "Crash Severity (CS)" methods. The equations needed for the RQC, and CS methods are illustrated by Equations 1, and 2:

$$Rc = Ra + K\ (Ra / M)\ 0.5 + (1 / 2M) \qquad \text{Equation. 1}$$

Rc = Critical rate for a segment
Ra = Average accident rate for all segments
M = Average exposure (100 million vehicles miles of travel on a segment)
K = A probability factor determined for the desired level of significance (usually = 1.645)

$$EPDO = 541.74\ (F) + 29.18\ (A) + 2.5\ (B) + 6.06\ (C) + PDO \qquad \text{Equation. 2}$$

EPDO = Number of equivalent PDO (property damage only) collisions
F, A, B, C = Fatal, Type A, B, and C crash injuries

Afterward, the study will rank the sites based on RQC and CS analyses to recognize the most hazardous mountainous locations in Wyoming. Note that Equation 2 is consistent with the cost estimations presented in Table 1.

Table 1. Comprehensive Costs of crashes (FHWA 2009)

Injury Severity of Crash	Average Economic Cost
Death	$4,008,900
Incapacitating Injury (A)	$216,000
Non-incapacitating Injury (B)	$79,000
Possible Injury (C)	$44,900
No Injury (PDO)	$7,400

The primary method will be conducted using CarSim and TruckSim simulation modeling which are among the most popular dynamics simulation packages in the vehicle industry. Any variable related to road geometry and vehicles characteristics can be defined by software users in TruckSim (Stine et al. 2010). The hazardous locations in Wyoming will be modeled in two phases:

- The first phase can be called as the "ideal (or perfect) condition modeling." This part of the work models a road with no grade (flat terrain) in a good weather condition (no wind) on dry pavement ($\mu = 0.9$) for a typical passenger car (sedan). The speed limit will also be considered based on the recommendation of Green book (AASHTO 2011) to investigate the dynamic behavior (side friction, lateral acceleration, etc.) of the passenger cars.

- Then, the hazardous segments will be modeled in various condition of road surfaces (μ = 0.9, 0.6, and 0.3 as the representative for the clear, rainy, and snowy surface, respectively), and the wind condition (at least for three different speed and four directions). The wind speeds and directions will be considered in the study after reviewing the background of the wind condition during last three years at the locations based on the available data from the related organizations. This part also includes different types of heavy vehicles (single-unit truck, tractor-trailer, and the axle double) with different weights (60,000-75,000 Ib) for the heavy vehicles. The effect of braking will also be added considering different cases of braking regarding time (short brakes as 2 sec or the long brakes about 5 sec), and the pressure (hard braking = 15 MPa, moderate = 10 MPa, and light braking = 5 MPa) of braking. This section will be tested considering four different speed limits. The reason for adding different speed limits is to increase the accuracy of the analysis part for finding the appropriate speed limit (the statistical analysis would be more precise by considering more data). For example, the speed limits of 30, 35, 40, and 45 mph will be applied in the modeling assuming the speed limit of 45 in the first part of the methodology.

Then, after the end of simulation modeling, the results (friction factors, lateral acceleration of CG, drag forces, braking forces, etc.) of these two phases will be compared. For this purpose, the margin of safety in terms of skidding (considering the side friction factors) and roll-over (considering the lateral accelerations) will be estimated for all the simulation scenarios considered in the study. The difference between available side friction ($\mu = 0.9$) and side friction demand is called the margin of safety in terms of skidding threat. If the side friction demand goes higher than the available side friction (i.e., the margin of safety becomes negative), the vehicle will slide (Bonneson, 2000). Static Stability Factor (SSF) is also the criteria to find the margin of safety regarding the possibility of roll-over crashes in this study. Equation 3 shows the formula for calculating the SSF. If the lateral acceleration (centrifugal acceleration) exceeds the SSF value, a roll-over occurs.

SSF = (Track Width) / 2*(Height of the Center of the Gravity) Equation. 3

Therefore, new models (equations) will be proposed for the speed limit using two-way ANOVA (to find the effect of the variables) and the regression (to find the relationship between variables). Table 2 and 3 show a summary of the variables involved in this simulation procedure:

Table 2. Variable involved in the first part of the simulation

Speed	Weather	Vehicle	Braking Condition
45	Clear (μ = 0.9) with no wind	Sedan	No Braking

Table 3. Variable involved in the second part of the simulation

<table>
<tr><th rowspan="2">Speed</th><th colspan="2">Weather Condition</th><th colspan="2">Vehicle</th><th colspan="2">Braking Condition</th></tr>
<tr><th>Wind</th><th>Surface</th><th>Type</th><th>Weight</th><th>Period</th><th>Pressure</th></tr>
<tr><td>45</td><td rowspan="4">Speed and the direction will be considered after reviewing the available wind data</td><td>Clear (μ = 0.9)</td><td>Single-Unit Truck</td><td>60,000 Ib</td><td>Short (2 sec)</td><td>Hard</td></tr>
<tr><td>40</td><td>Rainy (μ = 0.6)</td><td>Tractor Semitrailer</td><td>65,000 Ib</td><td>Long (5 sec)</td><td>Moderate</td></tr>
<tr><td>35</td><td>Snowy (μ = 0.3)</td><td>Axle Double</td><td>70,000 Ib</td><td></td><td>Light</td></tr>
<tr><td>30</td><td></td><td></td><td>75,000 Ib</td><td></td><td></td></tr>
</table>

The exclusive effect of each these variables (denied by point-mass model) on safety will be studied as a secondary goal in this study. This aim will be reached after a two-phase analysis:

- The first phase investigate the effect that each variable could create on the dynamic vehicle behavior based on the simulation outcomes
- The second phase will focus on a comparison of the crash statistics of hazardous locations. In fact, data regarding the geometric features, weather condition, and the type of the vehicle for all the sites will be collected and compared to their crash statistics.

The two-way ANOVA will be utilized as the tool for investigating the exclusive effect of the variables in this part of the study as well.

Expected Outcomes

Results in this study will cover a comprehensive analysis of the safety of the vehicle on hazardous sites in comparison to a safe (ideal) situation. Therefore, the most appropriate speed limit which provides a condition similar to the ideal situation will be proposed for each site. Also, the analytical models (equations) extracted in this study will be practical to be used for the other roads (which have not been studied in this research) and new values of speed limit can be assigned to roads based on geometric features (radius of the horizontal curve, superelevation rate, and longitudinal grade), vehicles characteristics (type, weight, and the braking forces), and the weather condition (side friction factor, wind speed, and wind direction).

Relevance to Strategic Goals

The main contribution of the current study is to increase the safety considering different effective variables regarding assigning an appropriate speed limit in the hazardous mountainous areas. As it was discussed in the methodology, all different aspects of the study focus on this goal.

Educational Benefits

Since the project includes a large number of simulation tests, at least two students should get involved in the project. For this reason, three training sessions (each one as long as 90 minutes) are predicted to introduce the project and teach the simulation packages to students. These training sessions provide an opportunity for students to get familiar with the usage of the popular vehicle simulation models (CarSim and TruckSim) and they will be able to use the packages for their future studies as well.

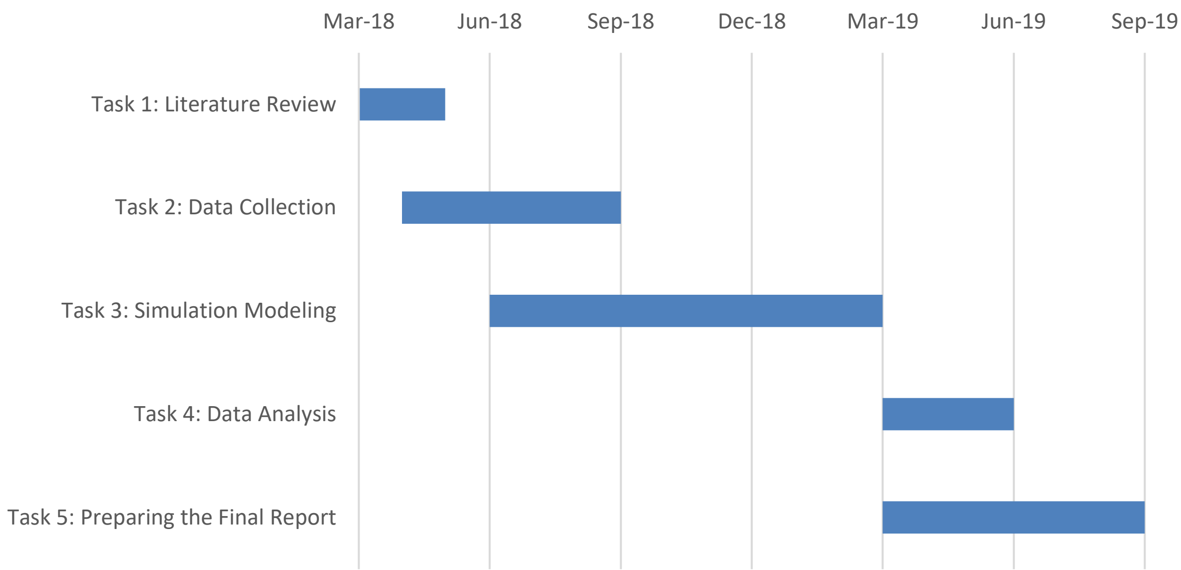
Technology Transfer

The study team will target the high-level journals of transportation engineering for publishing the results. Hopefully, the results will be considered in the next editions of the guidelines such as Green book as well.

Work Plan

1. Literature Review
2. Data Collection
3. Simulation Modeling
4. Data Analysis
5. Preparing the Final Report

The project will be completed in an 18-month span. The longest task belongs to the simulation modeling which requires nine months (half the whole project).



Project Cost

Total Project Costs:	$162,424
MPC Funds Requested:	$ 81,000
Matching Funds:	$ 81,424
Source of Matching Funds:	Wyoming Department of Transportation

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