Environmental Conscious Highway Design for Vertical Crest Curves

by

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The primary objective of this paper was to provide guidelines and tools for quantifying the environmental impacts, by means of fuel consumption and emissions, of various highway geometric design conditions related to vertical crest curves. Second-by-second speed profiles were generated with the speed prediction and polynomial models, and fuel consumption and emissions rates based on vehicle-specific power and speeds were extracted using the recently developed motor vehicle emission simulator (MOVES). The generated speed profiles were matched with the extracted rates and aggregated during a trip on the curves. A benefit-cost analysis was also carried out using existing data from the State of Washington. The results demonstrated that the design vehicle respectively consumed and produced 10 percent less fuel and carbon dioxide on the vertical crest curve designed with 1.5 times greater than the minimum rate of vertical curvature value documented in the Green Book; for other emissions – carbon monoxide, oxides of nitrogen, hydrocarbons, and particulate matter of 2.5 microns or less – there were also reductions by up to 31 percent on the curve. The results also showed that the environmental economic benefits from flattening the curve design exceeded addition construction costs for a 30-year design period. In conclusion, vertical curve design providing a flatten curvature can be environmentally and economically beneficial throughout the life of the highway. Finally, this paper shows the efficacy of environmentally-friendly design for sustainable transportation.
INTRODUCTION

Surface transportation is a major contributor to energy consumption and air pollution and accounts for about one-third of greenhouse gas (GHG) emissions emitted in the U.S., according to the U.S. House of Representatives Committee on Science and Technology (1). Multiple strategies (e.g., public transportation, smart growth, alternative transportation mode, high-occupancy toll (HOT)/high-occupancy vehicle (HOV) lanes) should be considered to address these challenges. Increasing capacity by constructing new highways, widening existing highways, or improving highway design features are also key strategies. Considering the significant impact, environmentally sustainable highways will be a main objective in developing new highways or improving existing ones.

During the highway design process, the reference most often used by designers and engineers for design features and criteria is the Green Book, also known as A Policy on Geometric Design of Highways and Streets, published by the American Association of State Highway and Transportation Officials (2). It is a series of guidelines on geometric design, providing a range or a minimum for desirable design standards (3). When the applied design criteria do not meet the standards, a design exception is usually required. The range or minimum guidelines and design exception provide designers and engineers with flexibility regarding geometric situations in the highway design process. For instance, the Texas Department of Transportation (TxDOT) Roadway Design Manual (4) recommends that use of higher rather than the minimum design standards results in a safer environment, better compensating for drivers’ errors.

In addition to providing a recommended range or minimum values for critical dimensions, if design guidebooks/manuals were to provide any quantitative analysis of each design criteria/features on safety, it could reduce the uncertainty associated with making engineering judgment for given design criteria/features. For example, some guidebooks/manuals (e.g., Highway Safety Manual (5)) have recently provided quantitative analysis between design criteria and specific features, such as safety. The TxDOT Roadway Design Manual (4) specified a vertical alignment design in which the length of the ascending grade should consider a heavy truck operation without an undesirable speed reduction, typically 15 km/h, below the average running speed of traffic. This manual does not provide any quantitative information on the impacts of roadway grades on safety. However, Bonneson et al. (6) intended to provide quantitative safety design guidelines and evaluation tools to be used by designers and engineers. They reported that 16 percent more crashes occurred on an eight-percent grade relative to a flat or leveled section of freeway. If a vertical alignment design has a flatter grade than the allowable maximum standard, it could significantly increase the construction costs, but at the same time, it will reduce the crash risk and societal costs throughout the life of the highway. There is a similar issue in the environmental analysis. As long as highway design manuals/guidebooks do not provide any information regarding the quantitative environmental impacts of highway geometric design features on fuel consumption and emissions, the matter of environmental issues related to the selected design features is completely dependent upon engineering judgment.

The objectives of this study were to: 1) analyze the impacts of vertical crest curve design features on fuel consumption and emissions using the recently developed vehicle emissions model and speed profiles generated by the speed prediction and polynomial models; 2) show that the degree of fuel consumption and emissions could be changed by varying specific highway geometric design values with the conceptual evaluation tool such as modification factors; 3) propose practical methods and processes of speed profiles and emissions rates for...
designers/engineers to apply for other geometric design conditions/features; and 4) evaluate the environmental impacts of actual vertical curve data using the proposed methods and processes.

This paper focuses only on the quantitatively environmental analyses on vertical crest curves under the selected design and traffic conditions; the environmental evaluation of other conditions (e.g., various truck proportions), other features (e.g., horizontal curves), and the detailed procedures for quantifying environmental impacts as part of the highway design process can be found in the original dissertation (7). The results provided in this study are beneficial for highway designers and engineers by providing the guidelines and evaluation tools on the environmental impacts related to the selection of highway geometric design conditions/features; therefore, it can reduce the uncertainty in engineering judgment for environmentally-conscious highway design. Second, this study shows the importance of the environmental effect of highway design, and supports the statement that environmentally-friendly highway design can be one strategy for sustainable transportation. The next section describes the background on the factors affecting fuel consumption and emissions.

BACKGROUND

The U.S. Environmental Protection Agency’s motor vehicle emissions simulator (MOVES) model is based on vehicle-specific power (VSP), because VSP quantifies vehicle emissions and fuel consumption related to various vehicle characteristics and operating conditions (8, 9). VSP (kW/ton) is defined as the instantaneous power per unit mass of vehicle as shown in Eq. (1).

\[
VSP = \frac{A_v V + B V^2 + C V^3 + M (a + g \sin \theta)}{M}
\]  

(1)

where,

\begin{align*}
V & = \text{vehicle speed (m/s)}; \\
a & = \text{vehicle acceleration (m/s}^2); \\
A_r & = \text{rolling resistance coefficient (kW/m/s)}; \\
B & = \text{speed correction to rolling resistance coefficient (kW/(m/s)}^2); \\
C & = \text{air drag resistance coefficient (kW/(m/s)}^3); \\
M & = \text{vehicle mass (ton)}; \\
g & = \text{gravitational constant (9.81 m/s}^2); \text{ and,} \\
\Theta & = \text{roadway grade (degree)}. 
\end{align*}

Vehicle speed was a key variable in measuring a vehicle’s operating conditions and predicting fuel consumption and emissions (10). Barth and Boriboonsomsin (10) concluded that carbon dioxide (CO\(_2\)) emission rates were highly dependent on speed; traveling at a steady-state speed (around 72-to-80 km/h) resulted in lower emissions and fuel consumption compared with speeds exceeding 105 km/h or below 72 km/h. Vehicle speed was expressed as a second-by-second variable, because average speed was not adequate for evaluation of the impacts of highway geometric design and traffic-signal control on emissions and fuel consumption. This was due to the lack of accounting for vehicle driving dynamics, such as acceleration or deceleration (8, 11, and 12). Servin et al. (11) analyzed how much fuel consumption and emissions could be reduced by intelligent speed adaptation (ISA) that regulates speed variation in driving, and found that the ISA significantly saved fuel and reduced CO\(_2\) by approximately 37 percent and 35 percent, respectively. Strategies regulating vehicle speeds, such as the ISA, were closely linked with acceleration because regulating speed variation could be achieved by
reducing the frequencies of acceleration. Ahn et al. (13) and Qi et al. (12) developed the microscopic emissions models that predict vehicle fuel consumption and emissions using instantaneous speed and acceleration/deceleration as explanatory variables. These models more accurately predicted fuel consumption and emissions as compared to the measured data.

Several studies concluded that roadway grade was one of the key variables affecting fuel consumption and emissions, as were vehicle speed and acceleration. Boriboonsomsin and Barth (14) and Park and Rakha (15) analyzed the impacts of roadway grades on fuel consumption and emissions. According to Boriboonsomsin and Barth (14), a vehicle consumed 15-to-20 percent more fuel on an uphill route at a six-percent grade followed by downhill route at a six-percent grade than on flat route. The larger amount of fuel consumed going uphill was not fully compensated for by the smaller amount of fuel consumption going downhill. They concluded that speed and acceleration had a large impact on vehicle fuel consumption and tailpipe emissions, and found that roadway grade was one of the primary variables that determine the power requirements necessary for specific driving maneuvers.

**METHODOLOGY**

This section describes the speed prediction and polynomial models used to collect second-by-second speed profiles along vertical crest curves. Emissions rates from MOVES are then matched with the generated speed profiles and calculated emissions per second are aggregated along traveled distance and time.

**Speed Prediction Model**

Fitzpatrick et al. (16) provided a speed prediction model (Eq. (2)) for predicting operating speeds of passenger vehicles at the middle of vertical crest curves on two-lane rural highways, in which the predicted operating speed was dependent on the rate of vertical curvature ($K$).

$$V_{85} = 105.08 - \frac{149.69}{K} \quad (K \leq 39) \quad (2)$$

For trucks, they did not provide a model because of the limited amount of measured data. According to the Green Book (2), the truck operation of the larger and heavier units than passenger vehicles needed longer braking distances; however, higher height of truck driver’s eye allowed seeing farther beyond vertical sight obstructions. The longer braking distance and higher height in truck operations balanced with the shorter braking distance and lower height in passenger vehicles. In addition, the Green Book did not provide separate design criteria for truck and passenger vehicles on vertical curves. Thus, the authors of this paper assumed that trucks had same speed profiles as passenger vehicles for the benefit-cost analysis.

The predicted operating speeds based on the model were classified as spot speeds at the middle of vertical crest curves. However, vehicles did not move at constant speeds on vertical curves. To consider speed variation on the curves, this study expressed vehicle speed as a second-by-second variable along a traveled distance/time, and the instantaneous speeds were calculated from acceleration/deceleration rates based on the polynomial model.

**Polynomial Model**

In real-life driving, the curve representing the relationship between acceleration and time typically had a bell-shape and S shape for speed and time curve (17, 18); these curve shapes described that acceleration rates were zero at the start and end of acceleration and supported the
bENER F| TO DRIVING PATTERN OF DECELERATION FROM CRUISE SPEED AND ACCELERATION TO THE CRUISE SPEED. ACcORDING TO AKCELIK AND BIGGS (17) AND AKCELIK AND BEsLEY (19), THIS PATTERN OF ACCELERATION COULD BE EXPLAINED BY THE POLYNOMIAL MODEL EXPRESSED AS EQ. (3):

\[ a(t) = r a_m \theta (1 - \theta^m)^2 \quad (m > -0.5) \]  

where, 

\[ a_m = \text{maximum acceleration}; \]

\[ \theta = \text{the ratio of time since the start of acceleration to total acceleration time (t_a), } t/t_a; \]

and,

\[ m, r = \text{parameters.} \]

The values for m, r, and a_m were determined with the following equations:

\[ \frac{V_a - V_i}{V_f - V_i} = \frac{2m^2 + 15m + 19}{3[(m+3)(2m+3)]} \]  

(4)

\[ r = \left[ \frac{(1+2m)^2 + \frac{1}{m}}{4m^2} \right] \]  

(5)

\[ a_m = \frac{V_f - V_i}{(2m+2)(m+2)} \]  

(6)

In Eq. (4), \( V_a \), \( V_f \), and \( V_i \) represented average speed, final speed, and initial speed during acceleration, respectively. Using Eqs. (3) to (6), an acceleration rate at time t could be calculated, and speed and distance at time t could be determined with the following equations (19).

\[ dV = a(t)dt = r a_m \theta (1 - \theta^m)^2 dt = r a_m \left( \frac{t}{t_a} \right)^m \left[ 1 - \left( \frac{t}{t_a} \right)^m \right]^2 dt \]  

(7)

\[ V(t) = \int_0^t \left( \frac{t}{t_a} \right)^m \left[ 1 - \left( \frac{t}{t_a} \right)^m \right]^2 dt \]  

(8)

\[ dx = V(t)dt = \left\{ \int_0^t \left[ r a_m \left( \frac{t}{t_a} \right)^m \left[ 1 - \left( \frac{t}{t_a} \right)^m \right]^2 dt \right] \right\} dt \]  

(9)

\[ x(t) = \int_0^t \left\{ \int_0^t \left[ r a_m \left( \frac{t}{t_a} \right)^m \left[ 1 - \left( \frac{t}{t_a} \right)^m \right]^2 dt \right] \right\} dt \]  

(10)

Integrating Eqs. (8) and (10), the equations for speed and distance at time t could be determined:

\[ V(t) = V_i + 3.6 r a_m t_a \theta^2 \left[ 0.5 - \frac{2\theta^m}{(m+2)} + \frac{\theta^{2m}}{(2m+2)} \right] \]  

(11)
These equations were based on the known acceleration time \( t_a \). When the acceleration time and distance were unknown, the regression equation (Eq. (13)), provided by Akcelik and Biggs (17), for acceleration time could be used.

\[
t_a = \frac{V_f - V_i}{2.08 + 0.127(V_f - V_i)^{1/2} - 0.0182V_i}
\]  

**Motor Vehicle Emission Simulator (MOVES)**

Based on instantaneous vehicle speeds and VSPs, MOVES categorized operating modes for predicting running exhaust emissions into 23 bins. Since MOVES did not directly report the emissions rates for each bin, this study used a project-level analysis, a single model year, and a single operating mode distribution (i.e., one for the target bin and zero for the remainder). The repetitive processing by changing the target bin generated the fuel consumption and emissions rates for each of the 23 operating mode bins. The extracted fuel consumption and emissions rates were based on two types of vehicles, a passenger car and heavy-duty diesel truck, in Jefferson County, Washington (Table 1).

Fuel consumption and emissions were aggregated during travel times based on the second-by-second operating mode bins from the speed profiles and the rates for each operating mode bin. This process could be expressed as following:

\[
E_{type} = \sum_{t=1}^{n} e_{type,bin}
\]  

where,

\( E_{type} = \) total emission for each of CO\(_2\), oxides of nitrogen (NO\(_x\)), carbon monoxide (CO), hydrocarbons (HC), particulate matter of 2.5 microns or less (PM\(_{2.5}\)), or total fuel consumption; and,

\( e_{type,bin} = \) fuel consumption or emission rate for operating bin at time \( t \).
### TABLE 1 Basic Condition for MOVES Processing

<table>
<thead>
<tr>
<th>Variable</th>
<th>Specification</th>
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<tr>
<td><strong>Input</strong></td>
<td></td>
</tr>
<tr>
<td>Vehicle</td>
<td>Type</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>A Single Heavy Duty Truck</td>
</tr>
<tr>
<td></td>
<td>Mass (ton)</td>
</tr>
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<td></td>
<td>Passenger Car</td>
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<td></td>
<td>Heavy-Duty Truck</td>
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<tr>
<td></td>
<td>Year</td>
</tr>
<tr>
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<td>Month</td>
</tr>
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<td></td>
<td>Temperature (°F)</td>
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<tr>
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<td>Relative Humidity (percent)</td>
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<tr>
<td><strong>Output</strong></td>
<td>Fuel Consumption</td>
</tr>
<tr>
<td></td>
<td>Emissions</td>
</tr>
</tbody>
</table>

### DATA SIMULATION

The second-by-second speed profiles with various Ks were based on the trip by a passenger car that is the design vehicle on the vertical curve design. The Green Book recommended the minimum K of 39 m/percent for the design speed of 90 km/h (2). Although the vertical crest curve should be designed with a greater K-value than the minimum standard documented in the Green Book, a highway section might be designed with values lower than the minimum standards. Additional explanations on this issue would be presented with actual highway geometric data in the later section. The authors considered the cases of the below- and above-design using a K-value lower and greater than the minimum standards in the Green Book (2), respectively. Figure 1 illustrates the base conditions and assumptions for the speed profiles on vertical crest curve in a two-lane highway.
(a) Overall vertical crest curve profile

(b) Grade changes on the curve

**FIGURE 1 Description of simulation scenarios on vertical crest curves.**

The base condition in the simulation was illustrated with PC and PT in Figure 1 (a). In addition, fuel consumption and emissions were aggregated during the trip from 250 m before PC and 250 m after PT because the length of 250 m was sufficient for covering the possible the above-design conditions simulated in this study. When the vertical curve was designed with lower K than the base condition (i.e., the below-design), the curve was connected with two tangent segments at points of PCu and PTu. For the below-design scenario, speed profiles were respectively generated for 50 percent, 40 percent, 30 percent, 20 percent, and 10 percent reductions rather than the minimum standard K-value (39 m/percent), and fuel consumption and emissions would be aggregated during the trip from PC-250 to PT+250. For the above-design scenario, the curve was profiled with two connecting points of PCo and PTo (Figure 1 (a)), and speed profiles were respectively generated for 50 percent, 40 percent, 30 percent, 20 percent, and 10 percent increases rather than the minimum standard. The aggregation of fuel consumed and emissions would be performed during the trip from PC-250 to PT+250. Basically, the predicted operating speed on the curve should be lower or equal to the 85th percentile tangent speed (100 km/h). A grade change on the curve with a vehicle traveling (Figure 1 (b)). Using the elevation at the travel distance (i.e., xt: travel distance at time t) from the point of PC, grade changes on the curve can be calculated using Eq. (15):
\[ G_t(\text{percent}) = \left( \frac{E_t - E_{t-1}}{x_t - x_{t-1}} \right) \times 100 = G_0 + \frac{100A(x_t - x_{t-1})}{60.96L} \]  

(15)

where \( G_0 \) was 9 percent and \( A \) was the algebraic difference of the approach and departure tangent grades \((G_2 - G_1)\). Additionally, \( E_i \) was the elevation at the distance of \( x_i \) from the point of PC.

**Procedures for Second-by-Second Speed Profiles**

The speed profiles related with various K-values were developed with the following procedure.

1. Predict the operating speed at vertical crest curve and calculate the length of vertical curvature \( L = KA = K|G_2 - G_1| \). For example:

\[
V_{85} = 105.08 - \frac{149.69}{20} \approx 97 \text{ km/h}
\]

\[ L = KA = 20 \times |-9 - 9| = 351 \text{ m} \]

2. Determine the deceleration time (Eq. (13)) with the predicted operating speed \( V_f \) at the middle of curve and approaching tangent speed \( V_i \).

\[
t_a = \frac{V_f - V_i}{2.08 + 0.127(V_f - V_i)^{1/2} - 0.0182V_i} \approx 6 \text{ seconds}
\]

Based on the calculations above, the vehicle would decelerate from 100 km/h \( (V_i) \) to 97 km/h \( (V_f) \) in six seconds.

3. Calculate the speeds and travel distance every second using the following equations. For example, acceleration rate, speed, and distance at three second after beginning a deceleration on the curve:

\[
a(3) = r a_m \theta (1 - \theta^m) = -0.2185 \text{ m/s}^2
\]

\[
V(3) = V_i + 3.6r a_m t_a \theta^2 \left[ 0.5 - \frac{\theta^m}{(m+2)} + \frac{\theta^{2m}}{(2m+2)} \right] = 98.7 \text{ km/h}
\]

\[
x(3) = \frac{V_i t}{3.6} + r a_m t_a \theta^3 \left[ \frac{1}{6} - \frac{\theta^m}{(m+2)(m+3)} + \frac{\theta^{2m}}{(2m+2)(2m+3)} \right] = 81.8 \text{ m}
\]

where \( m = 3.2122, a_m = -0.2203 \), and \( r = 2.4929 \) would be calculated from Eqs. (4) to (6).

4. Grade per second would be calculated using Eq. (15). Figure 2 (a) describes the changes of grades on the curves.
From the procedures above, this study could have generated the second-by-second speed and acceleration profiles on vertical curves (Figure 2 (b) and (c)). However, there were speed reductions on only 50- and 40-percent reduced K scenarios; thus, acceleration/deceleration could be calculated from the speed changing for only two scenarios.
Fuel Consumption and Emissions Rates from MOVES

This section provides the rates of fuel consumption and emissions on the 23 operating mode bins from the MOVES processing. Figure 3 shows the fuel consumption and emissions rates for each of the 23 operating mode bins from the passenger car (Car) and heavy-duty diesel truck (HDDT). The fuel consumption and emissions rates increased linearly or exponentially with their VSPs within certain range. Higher engine load that can be represented by higher VSP directly resulted in the higher rates through the combustion process.

FIGURE 3 Fuel consumption and emissions rates for each operating mode bin.
SIMULATION RESULTS

This section documents the results on the aggregated fuel consumption and emissions from the combination of the rates (gal/s and g/s) with the second-by-second speed profiles and shows the comparison analysis between the aggregated results by environmental modification factors (EMFs). These EMFs represent the ratio between the changed geometric design conditions and the base conditions. For example, an EMF equal to 1.0 means that there is no impact on the design change on fuel consumption or emissions. EMFs less than 1.0 indicate that the design change would consume less fuel or produce lower emissions relative to the base design condition, while EMFs greater than 1.0 would show more fuel consumption or emissions production.
Application of MOVES for Vertical Curve Design

In the design of vertical crest curves, there was one key variable affecting the analysis; K affected not only operating speeds on the curves, but also the grades linked to the curve. The amount of grade change per second depended on K; as K increased, there were more gradual flattening changes between two tangent grades (Figure 2(a)). In fact, the impact levels of acceleration/deceleration and operating speeds related to the change of the K-values on fuel consumption and emissions was not stronger than the degree of the impact due to grade changes.

Figure 4 presents the amount of fuel consumption and emissions related to various K-values on the curves during a trip by the single-design vehicle. The comparisons were made between increased/decreased K-values and the minimum standard as the base condition.

FIGURE 4 Fuel consumption and emissions by rate of vertical curvature.
As K increased, the fuel consumption decreased while traveling on the curves. The design vehicle respectively consumed and produced about 10 percent less fuel and CO$_2$ on the curve designed with a 50-percent increased K (i.e., 59 m/percent) than the minimum standard (i.e., 39 m/percent). However, 10 percent more fuel and CO$_2$ were consumed and produced on a 50-percent reduced K (i.e., 20 m/percent). Additionally, the vehicle produced 12 percent more NO$_x$ and PM$_{2.5}$ on the curve of a 50-percent reduced K, and 15 percent less NO$_x$ and PM$_{2.5}$ on a 50-percent increased K. Especially, for CO and HC emissions, the impacts of the K changes were greater than on other emissions. The vehicle produced CO and HC by 25 percent and 14 percent more for a 50-percent reduced K and 31 percent and 20 percent less for a 50-percent increased K, respectively.

**APPLICATION ON HIGHWAY GEOMETRIC FIELD DATA**

The previous section quantified the changes in fuel consumption and emissions related to various highway geometric design conditions on the vertical crest curves. To reflect actual design conditions, this section presents an evaluation of fuel consumption and emissions using highway geometric field data collected. In addition, this section provides environmental outputs between actual design conditions and alternatives in terms of benefits and costs, which could be incorporated into the design process.

**Highway Geometric Field Data**

This study selected actual geometric data on U.S. Route 101 (US 101) in Jefferson County, Washington. Most segments of US101 were defined as a two-lane rural principal arterial. The available geometric data were retrieved from the Washington Department of Transportation websites (WSDOT) and the Highway Safety Information System.

Among 970 vertical crest curves identified on US 101, about 15 percent (i.e., 143 curves) were built with less than half of the minimum standard K-values in the Green Book ($^2$). In addition, 502 vertical crest curves, accounting for about 52 percent of total curves, were built with greater than 1.5 times the minimum standards. To apply an environmental evaluation on vertical crest curves, this study identified eight curves with the following features:

- greater than 1.5 times of the minimum standard K-value;
- greater than 48 km/h design speed;
- greater or equal to 152 m length of vertical curve (L); and
- greater than 10 percent of algebraic difference of approach and departure tangent grades ($G_2 - G_1$).

Table 2 shows the characteristics of selected curves.
TABLE 2 Characteristics of Analyzed Vertical Crest Curves on US 101

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Speed (km/h)</th>
<th>G₁ (%)</th>
<th>G₂ (%)</th>
<th>Actual L (m)</th>
<th>Actual K (m/%)</th>
<th>Minimum L (m)</th>
<th>Minimum K (m/%)</th>
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<tbody>
<tr>
<td>1</td>
<td>64</td>
<td>6.49</td>
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<td>366</td>
<td>28</td>
<td>176</td>
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<tr>
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<td>20</td>
<td>97</td>
<td>9</td>
<td>Above-design</td>
</tr>
</tbody>
</table>

NOTE: G₁= approach tangent grade; G₂=departure tangent grade.

Based on Table 2, the speed profiles were generated for both the actual geometric conditions (i.e., the above-minimum standards) and alternative design conditions with the minimum standards in the Green Book (2). Those speed profiles, in turn, were matched with the fuel consumption and emissions rates in terms of the 23 operating mode bins. Table 3 provides the EMFs comparing the actual conditions with the alternative conditions. In general, the ratios were less than one, meaning that the above-designed curves saved fuel to be consumed and reduced emissions produced (as expected). About four-to-10 percent of fuel consumption and up to 16 percent of emissions were reduced in the selected actual vertical curves, relative to the curves that were designed with the minimum standard K-values.

TABLE 3 EMFs of Fuel Consumption and Emissions for Selected Vertical Curves

<table>
<thead>
<tr>
<th>Case</th>
<th>Fuel Consumption</th>
<th>CO₂</th>
<th>NOₓ</th>
<th>CO</th>
<th>HC</th>
<th>PM₂.₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.93</td>
<td>0.93</td>
<td>0.90</td>
<td>0.92</td>
<td>0.92</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>0.95</td>
<td>0.95</td>
<td>0.92</td>
<td>0.94</td>
<td>0.94</td>
<td>0.97</td>
</tr>
<tr>
<td>3</td>
<td>0.93</td>
<td>0.93</td>
<td>0.91</td>
<td>0.93</td>
<td>0.93</td>
<td>0.94</td>
</tr>
<tr>
<td>4</td>
<td>0.95</td>
<td>0.95</td>
<td>0.93</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>5</td>
<td>0.90</td>
<td>0.88</td>
<td>0.88</td>
<td>0.84</td>
<td>0.87</td>
<td>0.87</td>
</tr>
<tr>
<td>6</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>7</td>
<td>0.93</td>
<td>0.93</td>
<td>0.90</td>
<td>0.92</td>
<td>0.92</td>
<td>0.93</td>
</tr>
<tr>
<td>8</td>
<td>0.94</td>
<td>0.94</td>
<td>0.91</td>
<td>0.93</td>
<td>0.94</td>
<td>0.97</td>
</tr>
</tbody>
</table>

The primary reason for fuel savings and emissions reductions for the above-designed curves could be explained by the length of vertical curve. Higher K-values created longer length of the vertical curves and provided more gradual flattening changes on the curvature. This gradual flattening, in turn, could reduce vehicle engine loads on the curves. The reduced demand on the engine power led to less fuel usage and less pollution.
Benefit-Cost Analysis

For the vertical curves used in the previous section, the authors conducted a benefit-cost analysis between the curves designed with the actual K-values and the minimum standards. For reference, the environmental evaluation process, same as the passenger car, was applied for the trucks, and both vehicles did not have speed reduction on the curves with greater than or equal to the minimum standard K-values. When a vertical curve was designed with the above minimum standards, it caused additional earthwork because of the flattening curvature design. The earthwork volumes were determined using the average area method under the assumptions that the width of a two-lane highway was nine meter and the cut side slopes were 2:1. Additional construction costs for the earthwork were estimated with the amount of volumes and unit price (i.e., one cubic meter earthwork equals $9.4 (20)).

For the selected cases (Table 2), the additional construction costs increased by up to $248,842 (Table 4). In terms of fuel costs, the flatten curvature design reduced vehicle engine loads and consequently reduced fuel consumptions during the trips. Annual fuel costs during the trips were estimated with 1) fuel consumption per a single passenger car/HDDT; 2) annual traffic volume; and 3) the unit price of gasoline/diesel. Since the WSDOT did not provide traffic volume for each type of vehicles, this study assumed that traffic volumes for the passenger car and the HDDT accounted for 90 percent and 10 percent of annual average daily traffic (AADT) sourced from the WSDOT, respectively. The fuel consumption for the above-designed curve was subtracted from the one related to the minimum standard, and then the difference was monetized by the unit price of fuel.

According to the U.S. Energy Information Administration (21), the average unit price of gasoline and diesel were $2.89 and $2.99 in Washington in 2010, respectively. Similar to the fuel cost savings, less emission was produced on the above-designed vertical curves. Emissions reductions from the above-designed curves were beneficial for societal and public health issues; the economic benefits from the emissions reductions were monetized with the unit values of reduced CO₂, NOₓ, and PM₂.₅, estimated as $21, $4,000, and $168,000 per metric ton, respectively, in 2007 U.S. dollars (22). The amount of reduced CO₂, NOₓ, and PM₂.₅, were monetized with the unit values for each emission.

### TABLE 4 Estimation on Benefits and Costs on Above-Designed Vertical Curves
(In 2010 Dollars)

<table>
<thead>
<tr>
<th>Case</th>
<th>Cost¹ ²</th>
<th>AADT¹ ³</th>
<th>Fuel Cost Saving¹</th>
<th>Social &amp; Health Cost Saving¹</th>
<th>Benefit-Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design Period</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-Year</td>
<td>20-Year</td>
<td>30-Year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>247,525</td>
<td>2,800</td>
<td>6,416</td>
<td>463</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>48,169</td>
<td>2,000</td>
<td>3,063</td>
<td>219</td>
<td>0.76</td>
</tr>
<tr>
<td>3</td>
<td>43,085</td>
<td>8,200</td>
<td>14,978</td>
<td>1,074</td>
<td>4.24</td>
</tr>
<tr>
<td>4</td>
<td>145,690</td>
<td>4,200</td>
<td>5,403</td>
<td>387</td>
<td>0.44</td>
</tr>
<tr>
<td>5</td>
<td>132,775</td>
<td>1,900</td>
<td>5,563</td>
<td>398</td>
<td>0.50</td>
</tr>
<tr>
<td>6</td>
<td>37,336</td>
<td>3,000</td>
<td>3,589</td>
<td>258</td>
<td>1.11</td>
</tr>
<tr>
<td>7</td>
<td>248,842</td>
<td>2,800</td>
<td>6,554</td>
<td>473</td>
<td>0.33</td>
</tr>
<tr>
<td>8</td>
<td>66,088</td>
<td>9,900</td>
<td>15,967</td>
<td>1,146</td>
<td>2.65</td>
</tr>
</tbody>
</table>

Note: ¹ estimated for the year 2010; ² additional construction cost; ³ Source: WSDOT (23).
Finally, Table 4 shows the reduced costs (i.e., benefits) from the fuel consumption and societal and health categories and the increased construction costs. Additionally, the expected benefits and costs during 10-year, 20-year, and 30-year design periods were adjusted to 2010 dollars with a three-percent discount rate for the social and health costs and a seven-percent discount rate for the fuel costs (24). In Case 3, the benefits due to the flattening curve design exceeded the cost for a 10-year design period; the benefits were greater than four times of the cost. Furthermore, about 19 times more benefits relative to the cost were expected for a 30-year design period. In 30 years after a highway construction or improvement project, benefits were greater than the costs for all cases.

DISCUSSION AND CONCLUSIONS

There were two key factors that affected fuel consumption and emissions during the trips on vertical crest curves – speed and grade variation resulting from the rate of vertical curvature. According to the speed prediction model, the operating speed in the middle of the vertical crest curve was reduced by the K-value. However, this research did not find an important reduction in speed in the middle of the curve under the scenarios evaluated. Less than 3 km/h speed reduction was found on the curves designed with only the 50-percent and 40-percent reduced K-values. Alternately, deceleration and acceleration did not have a great impact on environmental analyses because there was little difference between approaching tangent speeds and operating speeds on the curves. Rather than the K-value influencing the speed reduction, the grade adjustment by the K-value actually affected environmental analyses.

Greater K values allowed for longer vertical curvature length, and the longer length allowed for gradual flattening grade changing (Figure 2 (a)). As a result, the design vehicle respectively consumed and produced 10 percent less fuel and CO₂. For other emissions analyzed, there were also reductions by up to 31 percent. Lower grade changes resulted in reduced fuel consumption and emissions production from the trip on the vertical crest curve. In addition, from the application of environmental analysis on the selected actual vertical curves, this study showed that the actual vertical curve designed with greater K-values (the above-design) reduced fuel consumption and emissions by up to 16 percent, and the monetized benefits exceeded the additional construction costs for a 30-year design period for all selected cases. Although this paper did not provide the results with various truck proportions, the benefits increased with higher truck proportions (7).

In conclusion, a vertical curve should be designed so that the rate of vertical curvature is greater than or at least equal to the minimum standards in design handbooks. A design allowing the curve to be flatter reduces vehicle engine loads and results in less fuel consumption and lower emissions production on the curve.

From the quantified results of fuel consumption and emissions related to various conditions on the vertical crest curves, this paper provides the guidelines and tools to quantify environmental impacts that highway designers and engineers can use as part of the highway design process; an application on other geometric components will be covered elsewhere. For the vertical curve design, the guidelines and tools proposed in this paper can reduce the uncertainty associated with the engineering judgment for environmentally-friendly highway design. Finally, this paper shows that adverse environmental impacts from vehicle movements on the curve can be controlled and reduced throughout environmentally conscious highway design.

However, the results provided in this paper are dependent on the assumptions on the design vehicle characteristics, fuel type, weather condition, and/or truck proportion of total
traffic volume. The results should not be taken at face-value and should not be used for decision-making purposes. In addition, additional fuel consumption and emissions due to the construction for the flattening curvatures were not considered in the benefit-cost analysis. As future research, a systematic tool predicting fuel consumption and emissions merely by inputting selected design conditions into the system will be beneficial; highway designers and engineers can predict the environmental impact based on the selected design conditions and compare that impact with other design conditions without any complex calculation and repetitive processing used in this study.

REFERENCES


