Environmentally-Conscious Highway Design for Vertical Grades

by

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ABSTRACT

This paper provides guidelines and tools for quantitative evaluations by means of fuel consumption and emissions for various vertical grade design conditions. Detailed vehicle operation conditions were represented by second-by-second speed profiles generated using the truck dynamic model and non-uniform acceleration/deceleration models. The rates of fuel consumption and emissions based on vehicle-specific power and speeds were extracted using recently developed motor vehicle emission simulator (MOVES). The generated speed profiles were matched with the extracted rates and aggregated during a trip on the grades. As a result, the design vehicle consumed more than five times the amount of fuel on a 3,000-m graded segment when the vehicle had a speed reduction of greater than 20 km/h, as opposed to the vehicle with a speed reduction of less than 10 km/h. For emissions—carbon dioxide, carbon monoxide, oxides of nitrogen, hydrocarbons, and particulate matter of 2.5 microns or less—there were up to five-fold increases on the segment. Thus, controlling a speed reduction of less than 20 km/h can minimize adverse environmental impacts from vehicle movements. In addition, this study shows that environmentally-conscious vertical grade design is feasible and economically beneficial throughout the life of the highway. The provided guidelines and tools can reduce uncertainty for designing environmentally-conscious highways and can be used as part of the highway design process.
INTRODUCTION
The intent of guidebooks or manuals used as part of the highway development process is to permit sufficient flexibility for designers and engineers by providing a range or minimum values for critical dimensions. Although documents, such as the Green Book (1), offer useful tools that can help selecting the most appropriate design features, they do not provide specific information about how the selected design features impact important external factors, such as those related to crash risk and environmental emissions. In these cases, very often designers need to rely on engineering judgment to make a final decision that balances direct and indirect costs, and societal benefits. In order to reduce the uncertainty associated with engineering judgment, AASHTO has recently published the Highway Safety Manual (2) among others. This Manual provides tools and methods that allow practitioners to make planning, design, and operations decisions based on safety. It is designed to facilitate explicit consideration of safety in the decision making process.

Unfortunately, no such tools exist that explicitly consider environmental issues for making highway design decisions. As discussed by Ko (3), even though there are several stages that incorporate environmental analysis in this process, these analyses are usually conducted for mobile emissions inventory prediction rather than for evaluating various geometric design criteria. Research on concepts linked to environmentally-conscious highway geometric design is still in its infancy, and highway design manuals/guidebooks do not provide any information regarding the quantitative environmental impacts of highway geometric design features. Therefore, including environmental factors in the highway design process is completely reliant on engineering judgment. Guidelines are therefore needed to reduce the uncertainty linked with engineering judgment.

The objectives of this paper are to 1) analyze the quantitative impacts of roadway grade design features on fuel consumption and emissions; 2) show what degree of fuel consumption and emissions can be changed by varying specific roadway grade design values with the conceptual evaluation tool known as modification factors; and 3) propose practical methods and processes of speed profiles and emissions rates for designers/engineers. The quantitatively environmental research included in this paper can reduce uncertainty in engineering for designing environmentally-conscious highways design. In addition, the research illustrates that environmentally-friendly highway design can be one strategy that can be used to increase the sustainability of transportation systems. This paper focuses only on vertical grade design; the environmental evaluation of other design features can be found in the other studies (3, 4).

BACKGROUND
Examining the impact of vehicle operation conditions on fuel consumption and emissions, Servin et al. (5) found that intelligent speed adaptation that regulates speed variation in driving significantly saves fuel and reduced carbon dioxide (CO₂) by approximately 37 percent and 35 percent, respectively. Existing research regarding the prediction of fuel consumption and emissions uses vehicle speed expressed as a second-by-second variable. Average speed is not adequate for evaluating the impacts of highway geometric design and traffic-signal control on emissions and fuel consumption due to the lack of accounting for vehicle driving dynamics, such as acceleration or deceleration (6, 7). Ahn et al. (8) and Qi et al. (7) developed microscopic emissions models that predict vehicle fuel consumption and emissions using instantaneous speed and acceleration/deceleration as explanatory variables. These models more accurately predict fuel consumption and emissions compared to measured data.
Roadway grade is one of the key variables affecting fuel consumption and emissions, as are vehicle speed and acceleration. According to Boriboonsomsin and Barth (9), a vehicle consumes 15 to 20 percent more fuel on an uphill segment at a 6-percent grade followed by downhill segment at a 6-percent grade than on flat section of equal length. The larger amount of fuel consumed going uphill is not fully compensated for by the smaller amount of fuel consumption going downhill. Boriboonsomsin and Barth (9) concluded that speed and acceleration have a large impact on vehicle fuel consumption and emissions. They found that roadway grade is one of the primary variables that determine the power requirements necessary for specific driving maneuvers. The aggregated emissions and fuel consumption based on the second-by-second speed profile, including acceleration and roadway grades, can be used to represent an inventory of emissions and fuel consumption related to highway geometric design features.

METHODOLOGY
This section describes the non-uniform acceleration models used to obtain second-by-second speed profiles along roadway grade design features. Fuel consumption and emissions rates from the mobile emissions model are then matched with the generated speed profiles, and calculated emissions per second are aggregated along traveled distance and time.

Non-Uniform Acceleration/Deceleration Models
Non-uniform acceleration/deceleration models can be categorized into vehicle kinematics models and vehicle dynamics models (10). The vehicle kinematics model predicts vehicle acceleration from simplified mathematical relationships with speed and distance; however, it does not account for vehicle type and mass, roadway grades, and other factors affecting vehicle accelerating capacity (10). The vehicle dynamic model, on the other hand, predicts vehicle acceleration from such factors.

The vehicle dynamics model is used for creating the second-by-second vehicle speed profile related to roadway vertical grades; the calculated second-by-second speeds and accelerations are used for estimating fuel consumption and emissions. Roadway vertical grade design features are based on a typical heavy truck weighing 120 kg/kW, because the effect of grades is more critical for a truck movement than for a passenger car (1). Generally, all passenger cars can negotiate grades as steep as 4 to 5 percent without any significant speed reduction (1). Truck performance (ma, where m is vehicle mass and a is vehicle acceleration) may be subjected to the following forces as shown in Eq. (1): tractive effort (F), aerodynamic resistance (Ra), rolling resistance (Rr), and grade resistance (Rg):

\[ ma = F - (R_a + R_r + R_g) \] (1)

The tractive effort generated by a truck’s engine acts to overcome external resistance and/or to accelerate the truck; 5 to 25 percent of tractive effort is typically lost due to the transmission system (11). The tractive effort can be expressed as Eq. (2):

\[ F = \frac{1000rp}{V} \] (2)

Where,

\[ r = \text{engine efficiency factor;} \]
\( P = \) engine generated power (kW); and, 
\( V = \) vehicle speed (m/s).

Aerodynamic resistance \( (R_a = \frac{1}{2} C_D A_f V^2) \) is a function of air density \( (\rho) \), the coefficient of drag \( (C_D) \), frontal area of the vehicle \( (A_f) \), and a square of vehicle speed \( (V) \). Rolling resistance \( (R_r = (C_r + C_R V) W, \text{ where } W = mg) \) is expressed with two coefficients \( (C_r \text{ and } C_R) \). When vehicles operate on paved roadway surfaces, \( C_r \text{ and } C_R \) are approximately 0.01 and 1/4,473, respectively \((11)\). Grade resistance \( (R_g = WG) \) is generated from the gravitational force caused by a graded roadway profile, and grades \( (G) \) are defined as the rate of vertical rise (ft or m) per 100 (ft or m) horizontal distance.

Vehicle accelerating force is required for the static mass as well as the rotating mass due to the inertia of rotating parts and the gear reduction ratio. When rotating masses are added to the static mass, the result is the effective mass \( (M_e) \) \((12)\). The ratio \( M/M_e \) differs in trucks according to the size of the engine and the number of gears. According to Bester \((13)\), the ratio \( M/M_e \) can be divided and calculated as

\[
\frac{M}{M_e} = \begin{cases} 
0.2 & \text{for } V \leq 1.8 \text{ m/s} \\
1.02 - 1.45/V & \text{for } V > 1.8 \text{ m/s} 
\end{cases} \tag{3}
\]

\[
\frac{M}{M_e} = \begin{cases} 
0.2 & \text{for } V \leq 1.8 \text{ m/s} \\
1.02 - 1.45/V & \text{for } V > 1.8 \text{ m/s} 
\end{cases} \tag{4}
\]

Considering the accelerating force \( (F_a = M_e a) \), the ratio \( M/M_e \), and resistance forces, the acceleration rate (Eq. 1) is rewritten as Eq. 5 \((12)\):

\[
a = \left(1.02 - \frac{1.45}{V}\right) \times \left\{\frac{101.97 \rho}{W V} - \left(\frac{\rho}{2 W} C_D A_f V^2 + g(C_r + C_R V + G)\right)\right\} \quad (V > 1.8 \text{ m/s}) \tag{5}
\]

Speed and distance by travel time can be determined using the integration \( (dt = \frac{dv}{a(t)} = \int_{V_0}^{V} \frac{dv}{a(t)} = \int_{V_0}^{V} \frac{vdv}{a(t)} = \int_{V_0}^{V} \frac{vdv}{\alpha - \beta V(t)} = \int_{V_0}^{V} \frac{vdv}{\alpha - \beta V(t)} = \int_{V_0}^{V} \frac{vdv}{\alpha - \beta V(t)} \) of Eq. (5). However, the numerical integration is intractable due to the cubic speed function in the denominator. Therefore, Lan and Menendez \((12)\) provide an alternative method for practical design with the non-linear and linear acceleration models to increase the accuracy of the estimation under the actual acceleration-speed functional relationship:

1. Under all possible ranges of trucks’ weight-to-power ratio, power, and grades, the relationship between acceleration and speed is linear above a truck speed of 65 km/h, i.e., \( a(t) = \alpha - \beta V(t) \).
2. At speeds lower than 65 km/h, acceleration is a reciprocal function of speed due to lower resistance forces, i.e., \( a(t) = c + \frac{d}{V(t)} \).

Based on the initial speed \( (V_i) \) and final speed \( (V_f) \), four possible cases can be considered whether these speeds are greater than \( V_0 \) (cut-off speed: 65 km/h); each case has its own equations for travel time and distance with \( V_i \) and \( V_f \).
• Case I: \( V_i \geq V_0 \) and \( V_f \geq V_0 \)

\[
t = -\frac{1}{\beta} \ln \left( \frac{\alpha - \beta V_f}{\alpha - \beta V_i} \right)
\]

\[
x = \frac{v_i - v_f}{\beta} - \frac{\alpha}{\beta^2} \ln \left( \frac{\alpha - \beta V_f}{\alpha - \beta V_i} \right)
\]

(6)

(7)

• Case II: \( V_i \leq V_0 \) and \( V_f \leq V_0 \)

\[
t = \frac{v_i - v_f}{c} - \frac{d}{c^2} \ln \left( \frac{cV_f + d}{cV_i + d} \right)
\]

\[
x = \frac{v_i^2 - v_f^2}{2c} - \frac{d}{c^2} (V_f - V_i) + \frac{d^2}{c^3} \ln \left( \frac{cV_f + d}{cV_i + d} \right)
\]

(8)

(9)

• Case III: \( V_i \geq V_0 \) and \( V_f \leq V_0 \)

\[
t = -\frac{1}{\beta} \ln \left( \frac{\alpha - \beta V_0}{\alpha - \beta V_i} \right) + \frac{v_i - v_f}{c} - \frac{d}{c^2} \ln \left( \frac{cV_f + d}{cV_0 + d} \right)
\]

\[
x = \frac{v_i - v_0}{\beta} - \frac{\alpha}{\beta^2} \ln \left( \frac{\alpha - \beta V_0}{\alpha - \beta V_i} \right) + \frac{v_i^2 - v_0^2}{2c} - \frac{d}{c^2} (V_f - V_0) + \frac{d^2}{c^3} \ln \left( \frac{cV_f + d}{cV_i + d} \right)
\]

(10)

(11)

• Case IV: \( V_i \leq V_0 \) and \( V_f \geq V_0 \)

\[
t = -\frac{1}{\beta} \ln \left( \frac{\alpha - \beta V_f}{\alpha - \beta V_0} \right) + \frac{v_i - v_0}{c} - \frac{d}{c^2} \ln \left( \frac{cV_0 + d}{cV_f + d} \right)
\]

\[
x = \frac{v_0^2 - v_i^2}{2c} - \frac{d}{c^2} (V_0 - V_i) + \frac{d^2}{c^3} \ln \left( \frac{cV_0 + d}{cV_f + d} \right) + \frac{v_0 - v_f}{\beta} - \frac{\alpha}{\beta^2} \ln \left( \frac{\alpha - \beta V_f}{\alpha - \beta V_0} \right)
\]

(12)

(13)

**Motor Vehicle Emission Simulator (MOVES)**

MOVES is the U.S. Environmental Protection Agency’s (EPA) state-of-the-art tool for estimating fuel consumption and emissions from vehicle operations. MOVES incorporates large amounts of in-use data from a variety of sources based on the analyses of emissions test results and generates fuel consumption and emissions rates based on 23 operating mode bins with instantaneous vehicle speeds and VSPs. The fuel consumption and emissions rates are based on the condition provided in Table 1. Fuel consumption and emissions are aggregated during travel time based on second-by-second operating mode bins from speed profiles and rates for each operating mode bin.

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

(14)

Where,

\( E_{type} \) = total emissions each for CO₂, NOₓ, CO, HC, and PM_{2.5} or total fuel consumption; and
\( e_{\text{type, bin, } t} \) = fuel consumption or emissions rate for type (i.e., passenger car and heavy-duty truck) and operating bin at time \( t \).

### TABLE 1 Basic Condition for MOVES Processing

<table>
<thead>
<tr>
<th>Variable</th>
<th>Specification</th>
</tr>
</thead>
</table>
| **Input** Vehicle Type | A Single Passenger Car
| | A Single Heavy Duty Truck
| Mass (ton) | Passenger Car 1.478
| | Heavy-Duty Truck 31.404
| Model Year | Passenger Car Age Distribution
| | Heavy-Duty Truck Age Distribution
| Fuel | Passenger Car Conventional Gasoline (Market Share: 28 percent)
| | Gasohol (E10) (Market Share: 72 percent)
| | Heavy-Duty Truck Conventional Diesel Fuel
| Roadway Type | Rural Unrestricted Access
| Grade | Level
| Area | Jefferson County, WA
| Year | 2010
| month | May
| Temperature (°F) | 60.8
| Relative Humidity (percent) | 63.9
| **Output** Fuel Consumption | Rate (gal/s) on each operating mode by each vehicle type
| Emissions | Rates (g/s) of \( \text{CO}_2, \text{NO}_x, \text{HC, CO, and PM}_{2.5} \) on each operating mode by each vehicle type

NOTE: \(^1\) vehicle age distribution (source: User Guide for MOVES2010a (14)).

### DATA SIMULATION

Second-by-second speed profiles related to vertical grade design on two-lane rural highways were generated under the same conditions provided in the Green Book (1) using Eqs. 6 through 13. Figure 1 shows the example of speed profiles of a 110 km/h initial speed for various grades (i.e., zero to nine percent).
FIGURE 1 Speed profiles of a 110 km/h initial speed.

(a) 1,500 m travel distance

(b) 3,000 m travel distance
There are three key factors—grades, initial speeds, and critical length of grades—in the design of roadway vertical grades. As shown in Figure 2(a), fuel consumption and emissions were aggregated from the trips reflecting various grades of zero to 9 percent (increased by one percent) and initial speeds of 10 to 110 km/h (increased by 10 km/h) while traveling 1,500 m and 3,000 m (the minimum grade should be 0.5 percent for drainage purposes in the highway design, but a zero-percent grade was considered to simplification). In terms of critical length of grades, the length was divided into two segments: vertical graded ($d_1$) and leveled ($d_2$). The length of vertical graded segment was dependent on speed reductions of 10 or 20 km/h. Based on the study by Lamm et al. (15), if the speed reduction was less than 10 km/h, the grade design was categorized as a good design. When the speed reduction was greater or equal to 10 km/h and less than 20 km/h, the grade design was considered as a fair design. The design was classified as a poor design if the reduction was greater than or equal to 20 km/h. The length of leveled segment was determined by subtracting the graded length from the total distance of 1,500 m and 3,000 m as in Figure 2(b).

**FIGURE 2** Description of simulations for initial speeds, grades, and critical length of grades.

**SIMULATION RESULTS**

This section describes the results of the simulation and the development of the environmental modification factors (EMFs). These EMFs represent the ratio between the changed geometric design feature and the base conditions. For example, an EMF equal to one means that there is no impact of the design change on fuel consumption or emissions. EMFs less than one indicate that the design change consumes less fuel or emissions relative to the base design condition, while EMFs greater than one show more fuel consumption or emissions.

**Initial Speeds**

Figure 3 provides the aggregated fuel consumption and emissions and EMFs by initial speeds from 10 to 110 km/h. Based on the trips on vertical grade segments lengthened to 1,500 m and 3,000 m, the amount of fuel consumed and emissions produced decreased with increasing initial speeds. When the trip lengthened to 1,500 m, the design truck with an initial speed of 10 km/h consumed about 0.35 gallons of diesel; however, the truck traveling 110 km/h consumed 0.2 gallons. EMF indicates that 10 km/h of initial speed consumed 71 percent more fuel than the truck travelling at 110 km/h (base condition). In addition, emissions of CO$_2$, NO$_x$, CO, HC, and PM$_{2.5}$ showed a similar trend with fuel consumption.
<table>
<thead>
<tr>
<th>Travel Distance (1,500 m)</th>
<th>Travel Distance (3,000 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td><strong>Fuel Consumption</strong></td>
<td><strong>Fuel Consumption</strong></td>
</tr>
<tr>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
<tr>
<td><strong>CO₂</strong></td>
<td><strong>CO₂</strong></td>
</tr>
<tr>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td><strong>NOₓ</strong></td>
<td><strong>NOₓ</strong></td>
</tr>
<tr>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

**FIGURE 3** Fuel consumption and emissions by initial speeds.
The truck at higher initial speeds emitted fewer emissions. For the comparison between 10 km/h and 110 km/h, the trip beginning with an initial speed of 10 km/h produced:
- 71 percent more CO₂;
- 69 percent more NOₓ;
- 63 percent more CO;
- 57 percent more HC; and
- 83 percent more PM₂,₅ than the trip with an initial speed of 110 km/h.
During the 3,000 m trip, the truck consumed 34 percent more fuel and produced up to 37 percent more emissions at an initial speed of 10 km/h than at a speed of 110 km/h. Based on the fuel consumption and emissions from the initial speed, the truck consumed less fuel and produced less pollution at higher speeds.

**Grades**

This section provides the aggregated fuel consumption and emissions by grades, from zero to 9 percent. These aggregated values are based on average fuel consumption and emissions from different initial speeds (10 to 110 km/h) within one grade category. EMFs describe how much fuel consumption and emissions increased or decreased as a function of the vertical grade, relative to the flat grade (base condition). Grades showed more distinctive results than those produced by the initial speeds (Figure 4).

FIGURE 4 Fuel consumption and emissions by grades.
<table>
<thead>
<tr>
<th>Travel Distance (1,500 m)</th>
<th>Travel Distance (3,000 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e) NOx</td>
<td>(f) NOx</td>
</tr>
<tr>
<td>(g) CO</td>
<td>(h) CO</td>
</tr>
<tr>
<td>(i) HC</td>
<td>(j) HC</td>
</tr>
<tr>
<td>(k) PM$_{2.5}$</td>
<td>(l) PM$_{2.5}$</td>
</tr>
</tbody>
</table>

**FIGURE 4 Continued.**
The truck consumed 0.20 gallons of diesel on a flat segment with a 3,000 m travel distance, but the fuel consumption linearly increased with highway grades. On a 9-percent grade, the truck consumed 0.93 gallons. According to the EMF, more than four times the amount of fuel was consumed on a 9-percent grade than on the flat grade during the 3,000 m trip. Similarly, this inclination trend also occurred for CO₂, NOₓ, and PM₂.₅ emissions. In the comparison between zero- and 9-percent grades, the truck produced more than four times more CO₂, NOₓ, and PM₂.₅ emissions. For the other emissions, a 9-percent grade resulted in three times more CO and HC emissions production than emissions produced on the flat grade. As expected, grades strongly affected fuel consumption and emissions. With other conditions fixed, except for highway grades, higher engine loads on steeper grades increased fuel consumption and emissions during the trip.

Critical Length of Grade

Based on speed reductions on second-by-second speed profiles, the researchers calculated the critical length of grades for initial speeds, design categorization, and grades (Table 2). As initial speed or grade decreased, the highway grade design was less restricted by the length of the grade segment, because the design vehicle had more available engine power to maintain the current speed on the lower grades/initial speeds. Below initial speeds of 30 km/h, the vehicle did not have any speed reduction greater than 10 km/h, relative to the initial speeds.

**TABLE 2 Critical Length of Grade by Speed, Grades, and Design Categories**

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Speed Reduction</th>
<th>Critical Length of Grade (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grade (%)</td>
<td>0</td>
</tr>
<tr>
<td>110</td>
<td>10 km/h</td>
<td>871</td>
</tr>
<tr>
<td></td>
<td>20 km/h</td>
<td>3,720</td>
</tr>
<tr>
<td>100</td>
<td>10 km/h</td>
<td>2,848</td>
</tr>
<tr>
<td></td>
<td>20 km/h</td>
<td>1,538</td>
</tr>
<tr>
<td>90</td>
<td>10 km/h</td>
<td>983</td>
</tr>
<tr>
<td></td>
<td>20 km/h</td>
<td>960</td>
</tr>
<tr>
<td>80</td>
<td>10 km/h</td>
<td>560</td>
</tr>
<tr>
<td></td>
<td>20 km/h</td>
<td>1,975</td>
</tr>
<tr>
<td>70</td>
<td>10 km/h</td>
<td>1,481</td>
</tr>
<tr>
<td></td>
<td>20 km/h</td>
<td>1,225</td>
</tr>
<tr>
<td>60</td>
<td>10 km/h</td>
<td>1,072</td>
</tr>
<tr>
<td></td>
<td>20 km/h</td>
<td>439</td>
</tr>
<tr>
<td>50</td>
<td>10 km/h</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 km/h</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>10 km/h</td>
<td></td>
</tr>
</tbody>
</table>

This paper focuses on the difference in fuel consumption and emissions in three design categories (i.e., good, fair, and poor design) based on the critical lengths documented in Table 2.
The difference is described with EMFs representing the ratio between fair design and poor design and the base condition (i.e., good design).

During a 3,000 m travel distance, the design truck consumed up to 61 percent more fuel on a fair highway than a good highway (Figure 5). The degree of fuel consumption and emissions more significantly increased on a poor highway. When the highway had a 9-percent grade, the design truck consumed five times more fuel on a poor-designed highway than on a well-designed highway. In terms of emissions, the results on fair or poor highways were similar to the fuel consumption results. In comparing fair and good designs, the emissions on a fair highway were 63 percent higher than on a good highway. Compared with the poor highway, emissions on the fair highway were five times higher for CO\textsubscript{2}, NO\textsubscript{x}, and PM\textsubscript{2.5} than the good highway, and three times higher for CO and HC.

![Image of graphs showing fuel consumption and emissions by critical length of grades.](image-url)

**FIGURE 5** Fuel consumption and emissions by critical length of grades.
FIGURE 5 Continued.

Ko, Lord, and Zietsman
Finally, the amount of fuel consumption and emissions were minimized when speed reductions greater than 10 km/h were prevented on the vertical grades. Note that speed reduction of more than 20 km/h on steep grades should be avoided because of significantly adverse impacts. Since EMFs for the fair design did not show any specific relationship with increasing grades, the adverse impacts for the fair highway seemed to be less affected by the steepness of the grade. EMFs for the poor design, however, linearly increased with grades except for 5-percent and 6-percent grades from the 3,000 m travel distance (Figure 5 (l)). The design vehicle consumed less fuel and produced less CO$_2$, NO$_x$, and PM$_{2.5}$ on a 6-percent grade relative to a 5-percent grade. On a 5-percent grade, the most frequently accounted operating bins were #24. On a 6-percent grade, however, the most frequently accounted operating mode bin was #14. When the operating mode bins changed from #24 to #14, the rates for fuel consumption, CO$_2$, NO$_x$, and PM$_{2.5}$ decreased by 13 percent, 13 percent, 14 percent, and 19 percent, respectively. The results on the accumulated fuel consumption and emissions are dependent on the rates for each second and total travel time. The reduced fuel consumption and emissions from the operating mode bin changes offset the amount of increased emissions due to the longer travel time.

APPLICATION ON HIGHWAY GEOMETRIC FIELD DATA
This section presents the application of environmental evaluation with highway geometric field data. In addition, this section includes a benefit-cost analysis for the environmental outputs.

Characteristics of Selected Segments
Actual geometric data on U.S. Route 101 (US 101) in Jefferson County, Washington were used for an environmental evaluation. The available geometric data were retrieved from the Washington Department of Transportation (WSDOT) and the Highway Safety Information System. The researchers selected some highway segments built with longer graded lengths than the critical values in relation to the speed reductions of 10 and 20 km/h on the grades. These speed reductions, in turn, were categorized as fair and poor designs. Table 3 lists three segments as a fair design and one segment as a poor design identified on US 101.

Table 3 summarizes the fuel consumption and emissions of EMFs from design improvement of fair/poor designs to the good design. The environmental evaluation on the grades was conducted assuming that speed limits on each segment were in the 85$^{th}$ percentile of initial speeds and that the design truck used maximum engine-generated power. It was estimated that about 7 to 40 percent more fuel was consumed for the selected segments, relative to the hypothetical condition that these segments were built under the concept of good design. As the speed reduction was greater and a length of vertical grade segment was longer, more fuel was consumed as expected. In addition, the EMFs for CO$_2$, and NO$_x$ were similar to those for fuel consumption. If the selected segments were designed under the good design, the emissions would reduce by up to 40 percent. In the case of CO, HC, and PM$_{2.5}$, emissions were 60 percent lower.
### TABLE 3 Application of Highway Geometric Field Data on Environmental Evaluation

<table>
<thead>
<tr>
<th>Case</th>
<th>Speed Limit (km/h)</th>
<th>Grade (%)</th>
<th>Design Category</th>
<th>Actual Length of Grade (m)</th>
<th>Critical Length of Grade(^1) (m)</th>
<th>EMF</th>
<th>FC</th>
<th>CO₂</th>
<th>NOₓ</th>
<th>CO</th>
<th>HC</th>
<th>PM₂.₅</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>Fair</td>
<td>306</td>
<td>147(^1)</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
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<tr>
<td>2</td>
<td>88</td>
<td>6</td>
<td>Poor</td>
<td>483</td>
<td>139(^1) (282(^2))</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
<td>1.2</td>
<td>1.1</td>
<td>1.5</td>
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<tr>
<td>3</td>
<td>72</td>
<td>4</td>
<td>Fair</td>
<td>563</td>
<td>336(^1)</td>
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<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
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<tr>
<td>4</td>
<td>88</td>
<td>2</td>
<td>Fair</td>
<td>2,559</td>
<td>1,147(^1)</td>
<td>1.4</td>
<td>1.4</td>
<td>1.3</td>
<td>1.2</td>
<td>1.0</td>
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#### Estimated Costs and Annual Benefits (In 2010 Dollars)

<table>
<thead>
<tr>
<th>Case</th>
<th>Cost Additional Construction Cost</th>
<th>Fuel Cost Saving(^3) PC(^4)</th>
<th>Emissions Cost Saving(^3) PC(^4)</th>
<th>Travel Time Cost Saving(^3) PC(^4)</th>
<th>Truck(^5)</th>
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<tbody>
<tr>
<td>1</td>
<td>129,638</td>
<td>11,077</td>
<td>357</td>
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<td>2</td>
<td>654,147</td>
<td>2,683</td>
<td>489</td>
<td>292</td>
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<tr>
<td>3</td>
<td>184,692</td>
<td>10,609</td>
<td>648</td>
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<tr>
<td>4</td>
<td>2,883,419</td>
<td>17,050</td>
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#### Estimated Future Benefits and Costs (In 2010 Dollars)

<table>
<thead>
<tr>
<th>Case</th>
<th>Benefit-Cost Ratios</th>
<th>5%(^6)</th>
<th>10%(^3)</th>
<th>15%(^7)</th>
<th>20%(^8)</th>
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<tbody>
<tr>
<td></td>
<td>10-20-30 Yr Yr Yr</td>
<td>1.09</td>
<td>1.92</td>
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<td></td>
<td>10-20-30 Yr Yr Yr</td>
<td>2.00</td>
<td>2.89</td>
<td>1.19</td>
<td>2.09</td>
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<td>10-20-30 Yr Yr Yr</td>
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<td>2.15</td>
<td>1.64</td>
<td>1.40</td>
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<td></td>
<td>10-20-30 Yr Yr Yr</td>
<td>2.18</td>
<td>3.14</td>
<td>3.14</td>
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<tr>
<td></td>
<td>10-20-30 Yr Yr Yr</td>
<td>3.18</td>
<td>3.14</td>
<td>3.14</td>
<td>3.14</td>
</tr>
</tbody>
</table>

**NOTE:** 1 critical length for good design; \(^2\) critical length for fair design; \(^3\) 10 percent truck and 90 percent passenger car volumes; \(^4\) passenger car; \(^5\) a typical heavy duty diesel truck of 120 kg/kW; \(^6\) 5 percent truck volume and 95 percent passenger car volume of total traffic volume; \(^7\) 15 percent truck and 85 percent passenger car volumes; \(^8\) 20 percent truck and 80 percent passenger car volumes.
Benefit/Cost Analysis

The analyses for benefits and costs were applied for the segments listed in Table 3. To perform an environmental evaluation for the design passenger car, the researchers used the same process that was applied for the design truck.

A grade adjustment can affect highway construction costs throughout the change of a lane-length or roadway earthworks. For the selected graded segments (Table 3), the grade design improvement from fair/poor designs to a good design (i.e., graded to non-graded adjustment on the section beyond the critical length of vertical grade segment) increased the construction cost for additional earthwork. However, this grade adjustment did not make any change greater than one meter in the lane-length at the selected segments. The earthwork volumes were determined using the average area method under the assumptions that the width of a two-lane highway was 9 m and cut side slopes were 2:1. Additional construction costs for the earthwork were estimated with the amount of volumes and the unit price (i.e., the price of one cubic meter earthwork was $9.4 (16)). The costs were about $130,000 to $3 million, depending on the amount of earthwork needed (Table 3).

Lower vehicle engine loads on the leveled segments resulted in fuel savings. Annual fuel costs during trips were estimated with fuel consumption per a single passenger car/heavy duty diesel truck, annual traffic volume, and the unit price of gasoline/diesel. Since WSDOT does not provide traffic volumes for each type of vehicle, researchers considered various traffic conditions that showed traffic volumes for the passenger car and the truck accounted for 95 percent and 5 percent, 90 percent and 10 percent, 85 percent and 15 percent, and 80 percent and 20 percent of annual average daily traffic (AADT), respectively. In 2010, AADTs in the selected cases were 4,600, 1,300, 2,600, and 2,000 vehicles, respectively (17). According to the U.S. Energy Information Administration (18), in 2010, the average unit prices of gasoline and diesel in Washington were $2.89 and $2.99, respectively. The fuel costs from the good design condition were subtracted from those of the fair/poor design condition for both the passenger car and heavy-duty diesel truck. Under the assumption of a 10-percent truck proportion, the estimated savings in the fuel cost are provided in Table 3.

Emissions from vehicle movements affect public health and welfare. For example, children residing close to main roads are at a higher risk of respiratory symptoms (19). Economic benefits from the emissions reductions were monetized with the unit values of reduced CO$_2$, NO$_x$, and PM$_{2.5}$ estimated at $21, $4,000, and $168,000 per metric ton, respectively, in 2007 dollars (20). Each amount of difference in the three emissions resulting from the design improvement for a single vehicle was multiplied by the annual traffic volume and the unit values of the emissions per metric ton.

On the roadway vertical grades controlling a speed reduction less than 10 km/h, vehicle travel times were reduced. In terms of the design truck, there were reductions by up to 11 seconds in travel time on the segments with the good design criteria; however, the design improvement did not result in travel time savings for the passenger car (130 kW power and 1,478 kg mass), because the car could travel without any speed reduction. Related to the reduced travel time, the amount of cost savings was estimated under the assumption that the value of the truck travel time per hour was $22.91 (21).

Benefit/Cost Analysis Results

The benefit-cost analysis was conducted under the assumption of highway operations during 10-year, 20-year, and 30-year design periods since being built or improved in 2010. In addition, benefits and costs were adjusted to 2010 dollars with a 3-percent discount rate for societal and
health costs and a 7-percent discount rate for fuel and travel time costs (22). For a 10-percent truck proportion and a 20-year design period, the benefits surpassed the costs in half of the cases (Table 3). As described in Case 1, the cost savings from the design improvement was two times greater than the construction cost of the additional earthwork for a 20-year design period. However, for half of the selected cases, the design improvements were not beneficial for a 30-year design period due to a significant amount of additional construction costs. In terms of truck proportions, the cost/benefit ratios increased with higher truck proportions.

**DISCUSSION AND CONCLUSIONS**

This paper has presented guidelines and tools on environmental impacts for quantifying fuel consumption and emissions for the design of vertical grades. These guidelines and tools play an important role in reducing the uncertainty in engineering judgment for environmentally-friendly highway grade design. The research shows that adverse environmental impacts from vehicle movements on vertical grades can be controlled and reduced throughout environmentally-conscious highway design.

When traveling at an initial speed lower than a crawl speed, the truck could accelerate up to the crawl speed due to available tractive force. However, the truck decelerated to the crawl speed due to grade resistance forces when starting with an initial speed higher than the crawl speed. The positive impact of high speeds on VSPs was neutralized by the negative impact of deceleration on VSPs. In addition, shorter travel times resulting from higher initial speeds assisted in saving fuel and reducing emissions during the trip. At least 26 percent of the fuel costs and emissions could be saved by starting the trip with an initial speed of 110 km/h relative to 10 km/h on the vertical grades lengthened to 1,500 m and 3,000 m. Faster initial speeds in the grade design would help in reducing fuel consumption and emissions (which the highway designer cannot control).

For the grade variable, the impact was more distinctive. Steeper grades caused more speed reductions and increased travel times on the vertical grade segments. Fuel consumption and emissions increased by a factor of up to four on a 9-percent graded segment compared to a leveled segment. Steeper grades caused more fuel to be consumed and emissions produced due to high vehicle engine loads and longer travel times. The Green Book specifies that most passenger cars can travel on graded highways as steep as 4 to 5 percent without a significant speed reduction (1). However, it is clear that steep grades have adverse environmental impacts on the vehicle movement.

For the critical length, the concept of design categories of good, fair, and poor were used. When the fair design criteria was applied for the vertical grade design, the fuel consumption and emissions increased because of extended travel time resulting from the speed reduction; the design vehicle consumed fuel and produced emissions up to 70 percent more in the fair design than with the good design. The poor design criteria had even more adverse results. The fuel consumption and emissions with the poor design increased by a factor of up to five relative to the good design criteria. This was due to significantly longer travel times. Good grade design preventing significant speed reduction not only improved highway safety but also reduced the degree of adverse environmental impacts.

The data collected in Washington State showed that the design truck consumed up to 35 percent more fuel and produced up to 61 percent more emissions on the actual grades, relative to the hypothetical condition that these segments were built under the concept of controlling speed reduction of less than 10 km/h. The benefit/cost analysis showed that the economic benefits
exceeded the costs for half of the segments for a 20-year design period. The design improvement could lead to reductions in direct, indirect, and societal costs related to vehicle fuel, societal and public health, and travel time; the monetary savings surpassed the construction costs resulting from additional earthwork. However, the design improvements on the other half of the segments were not beneficial for the design period because of the additional construction costs caused by the unbalanced cut and fill volumes. In addition, it should be pointed out that the results are dependent on the assumptions related to the selection of the design vehicle characteristics, fuel type, weather conditions, traffic 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 grade were not considered in the benefit-cost analysis. As future research, a systematic tool predicting fuel consumption and emissions based on various design and traffic conditions will be beneficial; highway designers and engineers can predict the environmental impact based on the selected conditions and compare that impact with other conditions without any complex calculation and repetitive processing used in this study. In addition, validation of the findings at this research with real-world drive-cycles and measurements is an important topic for future research.

REFERENCES


