Incorporating Vehicle Emission Models into the Highway Planning and Design Process: Application on Vertical Crest Curves

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ABSTRACT

INTRODUCTION
If design guidebooks/manuals were to provide any quantitative analysis of each design criterion/feature on safety, it could reduce the uncertainty associated with making engineering judgment for given design criteria/features. For example, the TxDOT Roadway Design Manual 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. (2006) intended to provide quantitative safety design guidelines and evaluation tools to be used by designers/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 for environmental analyses. 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; 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.

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.
METHODOLOGY

Speed Prediction Model
Fitzpatrick et al. (2000) provided a speed prediction model for predicting operating speeds 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). 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; these curve shapes described that acceleration rates were zero at the start and end of acceleration and supported the better fit to driving pattern of deceleration from cruise speed and acceleration to the cruise speed. According to Akcelik and Biggs (1987) and Akcelik and Besley (2001), this pattern of acceleration could be explained by the polynomial model.

Motor Vehicle Emission Simulator (MOVES)
MOVES categorized operating modes for predicting running exhaust emissions into 23 bins. The fuel consumption and emissions rates for each of the 23 operating mode bins were extracted from MOVES for two types of vehicles, a passenger car and heavy-duty diesel truck, in Jefferson County, Washington. 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.

DATA SIMULATION
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 (AASHTO), recommends the minimum K of 39 m/percent for the design speed of 90 km/h on the vertical curve design. 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. The author considered the cases of the below- and above-design using a K-value lower and greater than the minimum standards in the Green Book, respectively. Figure 1 illustrates the base conditions and assumptions for the speed profiles on vertical crest curve in a two-lane highway.
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). 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.

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. In fact, the impact levels for acceleration and deceleration and operating speed as related to the change in \( K \)-values for fuel consumption and emissions were not stronger than the level of impact due to grade changes. Figure 2 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.

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 CO2 on the curve designed with a 50-percent increased K (i.e., 58.5 m/percent) than the minimum standard (i.e., 39 m/percent). However, 10 percent more fuel and CO2 were consumed and produced on a 50-percent reduced K (i.e., 19.5 m/percent). Additionally, the vehicle produced 12 percent more NOx and PM2.5 on the curve of a 50-percent reduced K, and 15 percent less NOx and PM2.5 on a 50-percent increased K. Especially, for CO and HC emissions, the impacts of the K changes were

FIGURE 4 Fuel consumption and emissions by rate of vertical curvature.
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**
This study selected actual geometric data on U.S. Route 101 (US 101) in Jefferson County, Washington. Most segments of US 101 were defined as a two-lane rural principal arterial. At the selected horizontal curves, 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. Those speed profiles, in turn, were matched with the fuel consumption and emissions rates in terms of the 23 operating mode bins. In general, the EMF 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.

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**
A benefit-cost analysis was carried out using the selected actual data above. The analysis shows the reduced costs (i.e., benefits) from the fuel consumption and societal and health categories and the increased construction costs. When a vertical curve was designed with the above minimum standards, it caused additional earthwork because of the flattening curvature design. Increased construction costs for the earthwork were estimated with the amount of volumes and unit price (i.e., one cubic meter earthwork equals $9.4).

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. In some curves, 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**
On vertical curve design, greater K values allowed for longer vertical curvature length, and the longer length allowed for gradual flattening grade changing. As a result, the design vehicle respectively consumed and produced 10 percent less fuel and CO2 with greater K-values. 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 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.
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. 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.