# ENERGY AND ENVIRONMENTAL IMPACTS OF ROADWAY GRADES

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## ABSTRACT

Although roadway grades are known to affect vehicle fuel consumption and emission rates, there do not appear to be any systematic evaluations of these impacts in the literature. Consequently, this paper addresses this void by offering a systematic analysis of the impact of roadway grades on vehicle fuel consumption and emission rates using the INTEGRATION microscopic traffic simulation software. The energy and emission impacts are quantified for various cruising speeds, under stop and go conditions, and for various traffic signal control scenarios. The study demonstrates that the impact of roadway grade is significant with increases in vehicle fuel consumption and emission rates in excess of 9% for a 1% increase in roadway grade. Consequently, a reduction in roadway grades in the range of 1% can offer savings that are equivalent to various forms of advanced traffic management systems.

**Keywords**: mobile source emissions, vehicle fuel consumption, and roadway grades.

## INTRODUCTION

Although vehicle fuel economy has improved over the years, the contribution of mobile-source fuel consumption and emissions are still significant. Consequently, an accurate assessment of fuel consumption and emissions is essential for air-quality improvement programs. Factors affecting vehicle fuel consumption and emissions can be categorized into four categories, which are travel-related factors, driver-related factors, highway network characteristics, vehicle characteristics, and weather conditions. Roadway grades are one of the highway-related factors affecting fuel consumption and emission rates.

Although it is a well accepted fact that vehicles consume more energy and emit higher emissions as they travel along roadway upgrades, limited literature have attempted to study the effect of roadway grades on vehicle fuel consumption and emission rates. Pierson et al. conducted a field study aimed at quantifying the environmental impacts of driving modes using a large in-use vehicle fleet through remote sensor measurements [1]. The emission factors for a 3.76% uphill and downhill grade were measured in the Fort McHenry area. The study demonstrated that uphill grade emissions were higher than downhill emissions by a factor of 1.52, 1.86, and 2.19 for non-methane hydrocarbons (NMHC,) CO, and $NO_x$ emissions, respectively.

The objective of this paper is to quantify the impact of roadway grades on vehicle fuel consumption and mobile source emission rates. The paper investigates these impacts considering hot stabilized vehicle emissions of light duty gasoline vehicles and high emitter vehicles.

In terms of paper organization, initially an overview of the INTEGRATION modeling framework is presented, because the study employs the INTEGRATION software for the analysis. It should be emphasized, however, that the focus of the paper is on the results of the analysis as opposed to the modeling framework. The framework is only presented in order to provide confidence in the results and conclusions that are derived from this research effort. The following section presents the network construction and scenario development exercises. Subsequently, the simulation results are presented and described. Finally, the conclusions of the study and recommendations for further research are presented.

## INTEGRATION MODELING FRAMEWORK

The INTEGRATION software [2-6] was employed for this study because of several reasons. First of all, the software combines car-following, vehicle dynamics, lane-changing, energy, and emission models. Thus, mobile source emissions can be directly estimated from instantaneous speed and acceleration levels. Second, the traffic and emission modeling modules have been tested and validated extensively. For example, the software, which was developed over the past two decades, has not only been validated against standard traffic flow theory [7, 8], but has also been utilized for the evaluation of real-life applications [9, 10]. Furthermore, the INTEGRATION software offers unique capability through the explicit modeling of vehicle dynamics by computing the tractive and resistance forces on the vehicle each deci-second [11-13]. It should be noted that the procedures described in this paper are general and could be applied to other commercially available software if they combine the modeling of various resistance and tractive forces acting on a vehicle with accurate model vehicle fuel consumption and emission models.

The INTEGRATION software uses car-following models to capture the longitudinal interaction of a vehicle and its preceding vehicle in the same lane. The process of car-following is modeled as an equation of motion for steady-state conditions (also referred to as stationary conditions in some literature) plus a number of constraints that govern the behavior of vehicles while moving from one steady-state to another (decelerating and/or accelerating). The first constraint governs the vehicle acceleration behavior, which is typically a function of the vehicle dynamics [12, 13]. The second and final constraint ensures that vehicles maintain a safe position relative to the lead vehicle in order to ensure asymptotic stability within the traffic stream. A more detailed description of the longitudinal modeling of vehicle motion is provided by [14]. Alternatively, lane-changing behavior describes the lateral behavior of vehicles along a roadway segment. Lane changing behavior affects the vehicle car-following behavior especially at high intensity lane changing locations such as merge, diverge, and weaving sections.

The software also models vehicle fuel consumption and emission rates using the VT-Micro framework [15]. The VT-Micro model was developed from experimentation with numerous polynomial combinations of speed and acceleration levels. Specifically, linear, quadratic, cubic, and quadratic terms of speed and acceleration were tested using chassis dynamometer data collected at the Oak Ridge National Laboratory (ORNL). The final regression model included a combination of linear, quadratic, and cubic speed and acceleration terms because it provided the least number of terms with a relatively good fit to the original data ($R^2$ in excess of 0.92 for all Measures of Effectiveness (MOE)). The ORNL data consisted of nine normal emitting vehicles including six light-duty automobiles and three light duty trucks. These vehicles were selected in order to produce an average vehicle that was consistent with average vehicle sales in terms of engine displacement, vehicle curb weight, and vehicle type. The data collected at ORNL contained between 1,300 to 1,600 individual measurements for each vehicle and MOE combination depending on the envelope of operation of the vehicle, which has a significant advantage against emission data collected from few driving cycles since it is impossible to cover the entire vehicle operational regime with only a few driving cycles. Typically, vehicle acceleration values ranged from –1.5 to 3.7m/s$^2$ at increments of 0.3m/s$^2$ (-5 to 12ft/s$^2$ at 1 ft/s$^2$ increments). Vehicle speeds varied from 0 to 33.5m/s (0 to 121km/h or 0 to 110ft/s) at increments of 0.3m/s [16-18]. In addition to, the VT-Micro model was expanded by including data from 60 light duty vehicles and trucks. Statistical clustering techniques were applied to group vehicles into homogenous categories using Classification and Regression Tree algorithms. The 60 vehicles were classified into 5 LDV and 2 LDT categories. In addition, high-emitter vehicle emission models were constructed using second-by-second emission data. The HEV model was found to estimate vehicle emissions with a margin of error of 10% when compared to in-laboratory bag measurements [18, 19].

The INTEGRATION software computes the effective tractive force as the minimum of two forces; namely: the maximum engine tractive force ($F_e$) and the maximum frictional force that can be sustained between the vehicle wheels and the roadway surface ($F_{max}$) [11-13, 15]. The aerodynamic resistance ($R_a$), rolling resistance ($R_{rl}$), and the grade resistance ($R_g$) are also computed each deci-second. Subsequently, the maximum vehicle acceleration is then computed as

$$a = \frac{\min\left(F_e, F_{\max}\right) - \left(R_a + R_{rl} + R_g\right)}{m}, \qquad [1]$$

where $a$ is the vehicle acceleration (m/s$^2$) and $m$ is the vehicle mass (kg).

In estimating vehicle emissions, given that the power required to overcome the aerodynamic and rolling resistance forces were accounted for in the development of the fuel consumption and emission models, the effective vehicle acceleration is adjusted to account for the additional acceleration required to overcome the component of the vehicle weight opposing the vehicle motion as

$$a_e = a + 9.8067G, \qquad [2]$$

where $a_e$ is the effective acceleration (m/s$^2$), 9.8067 is the acceleration of gravity (m/s$^2$), and $G$ is the roadway grade. The effective acceleration accounts for the actual engine load required to negotiate a grade in addition to moving the vehicle. The speed and acceleration levels are then input into the VT-Micro model to estimate instantaneous vehicle fuel consumption and emission rates.

## SCENARIO DEVELOPMENT

In developing the test scenarios, three sets of variables are considered. The first variable set is comprised of network characteristics, which include link lengths, number of lanes, lane saturation flow rates, roadway grades, and control type (stop sign or signal control). The second set of variables includes operational characteristics such as signal timing parameters (cycle lengths, phase splits, and offsets). The third set of parameters includes traffic demand loadings, traffic composition, and vehicle characteristics.

In quantifying the impact of roadway grade on vehicle fuel consumption and emission rates, three scenario sets are analyzed. For each of these three scenario sets the roadway grade is varied from 0 to 6% considering a normal light duty vehicle (the Oak Ridge National Lab composite vehicle) and a high emitter vehicle (Type 4).

### Constant Speed Scenario

In the constant speed scenario vehicle fuel consumption (L/km) and emission rates (g/km) are compiled for different grades and cruising speeds. The cruising speeds are varied from 5 to 100 km/h at increments of 5 km/h while roadway grades are varied from -6 to +6% at increments of 1%. In addition, the analysis considers varying the length of the grade while maintaining a constant distance weighted average grade. This scenario evaluates the impact of climbing identical elevation differences considering different grade levels for the same travel distance.

The objective of the constant speed scenario is to quantify the impact of roadway grades on vehicle fuel consumption and emission rates at different cruising speeds.

### Stop Sign Control Scenario

The objective of this scenario is to quantify the impact of roadway grades on vehicle fuel consumption and emission rates for a stop sign controlled roadway. This scenario involves vehicle deceleration and acceleration considering different acceleration levels. The scenario is executed on a 2-km single lane roadway in which a single vehicle is simulated to travel a free-flow speed of 64 km/h where a stop sign is located after 1 km. The vehicle acceleration levels are varied from 40 to 100% the maximum rate at increments of 20% in order to analyze the impact of driver aggressiveness on fuel consumption and emission rates.

### Signal Control Scenario

The scenario quantifies the variation in MOEs as a function of traffic signal offsets and roadway uphill and downhill grades. The network used in this analysis is composed of three signalized intersections along a 2 km long roadway segment. Signalized intersections are located after 500 m, 1000 m, and 1500 m. The cycle length at each of the three intersections is set at 60 s with offsets varying from 0 to 50 s as the increment of 10 s. Each of three signals is controlled by two-phase timings with a 70:30 phase split (east/west versus north/south). Roadway grades are varied from 0 to 6% at increments of 1% with an uphill grade in the eastbound direction and a downhill grade in the westbound direction. The free-flow speed of the network is 64 km/h (40 mi/h) with a lane saturation flow rate of 1600 veh/h. A traffic demand of 800 veh/h is loaded in the eastbound and westbound directions, respectively. Alternatively, the northbound and southbound demands are set at 320 veh/h.

## RESULTS

The results for each of the three scenarios are presented in the following sections. We start with the uniform speed scenario followed by the stop-sign scenario and conclude with the traffic signal scenario.

## Uniform Speed Scenario

This section describes the results for the constant speed scenarios for both normal and high emitting vehicles. These runs were executed by simulating the motion of a vehicle along a 1-km section at a constant speed. Vehicle fuel consumption and emission rates were computed for the entire trip to compute a distance based fuel consumption and emission rate.

### *Normal Light Duty Vehicle*

The results demonstrate, as would be expected, an increase in the vehicle fuel consumption and emission rate with an increase in the roadway grade, as illustrated in Figure 1. The results also demonstrate a bowl-shaped relationship with respect to the cruise speed with the minimum fuel consumption rate occurring at a speed of 75 km/h. Given that a vehicle traveling at lower speeds spends more time traveling the 1-km roadway section, despite the lower time-based fuel consumption and emission rate, the total fuel and emissions consumed is significantly higher at lower speed levels. As a vehicle speed increases the time-dependent rate also increases, however at a rate that less than the travel time increase rate. Consequently, the distance-based fuel consumption and emission rate decreases until the rate of increase in the time-dependent rate exceeds the rate of decrease in time spent in the system. A more detailed description of these behaviors and the reasoning for these behaviors can be found elsewhere in the literature [20].

The variation in $CO_2$ emission rates as a function of cruise speed and roadway grade appears to be similar to that of fuel consumption. Specifically, the $CO_2$ emission rates demonstrate a bowl shaped functional form with respect to cruise speed with the highest rates occurring at low speeds. However, the minimum $CO_2$ emission rate, unlike the fuel consumption rate, varies as a function of the roadway grade. Specifically, the minimum $CO_2$ rate occurs at a cruise speed of 75 km/h for a 0 to 6% grade, as demonstrated in Table 1.

Alternatively, the functional form of the HC and CO emission profiles differs from the $CO_2$ and fuel consumption profiles. The HC and CO profiles are similar, however at low speed ranges the profiles differ. The HC and CO emission rates demonstrate a bowl shaped functional form with extremely high rates at high cruise speeds. In case of the CO emissions the increase in emissions at low speeds is minimal, this is not the case for HC emissions.

Finally, the variation in the $NO_x$ emission rate as a function of the cruise speed exhibits a slightly different behavior when compared to other measures of effectiveness (MOEs). Specifically, the functional form has an optimum speed that fairly low (30 km/h) that decreases with an increase in cruise speeds.

The MOE behavior as a function of vehicle cruise speed and roadway grade levels varies for different MOEs. For example, fuel consumption and $CO_2$ emission rates are more sensitive to variations in cruise speed levels than to variations in roadway grades. Alternatively, HC, CO, $NO_x$ emissions are more sensitive to roadway grades. Furthermore, $NO_x$ and $CO_2$ emissions are more sensitive to roadway grades in the 35 to 65 km/h and the 65 to 95 km/h cruise speed range, respectively, as illustrated in Figure 2. Alternatively, HC and CO emissions are more sensitive to roadway grades at high cruise speeds (100 km/h).

The higher HC, CO, and $NO_x$ emissions for 6% versus 0% grade at a speed of 100 km/h is a result of the higher engine load (combination of speed and acceleration) under these conditions. It should be noted that the scale for these emissions are much smaller and thus the figure exaggerates the impact of grades when compared to $CO_2$ and fuel consumption rates.

The final analysis investigates differences in vehicle fuel consumption and emission rates associated with alternative grade design scenarios considering identical overall grades. The results demonstrate that steep and short grades result in higher fuel consumption and emission rates when compared to long and mild grades for identical grade climbs considering equal segment lengths, as illustrated in Figure 3. Consequently, from a design perspective a mild long grade is more efficient than a short steep grade.

### High Emitting Vehicle

The fuel consumption and emissions for the HEV also increase as roadway grades increase. Comparing the results of the Normal LDV with those of the HEV, the shapes of fuel consumption, $CO_2$, and $NO_x$ emission behavior as a function of cruise speed and grade levels are similar. However, the absolute values of the HEV fuel consumption and $CO_2$ emission rates are less than those of the Normal LDV. This is because the Normal LDV utilized has a larger engine than the HEV. In case of the NOx emissions, the mass emissions for the HEV are significantly higher than those for the Normal LDV. Furthermore, the speed ranges at which the $NO_x$ emission rates are high shift to low speed ranges relative to those for the Normal LDV. On the other hand, the shapes of HC and CO emission profiles for the HEV are different from those for the Normal LDV. Specifically, the Normal LDV produces higher emissions at high speed ranges, while the HEV produces higher emissions at low speed ranges.

The percentage change in MOEs relative to the 0% grade scenario for each of the roadway grades considering an HEV is calculated. The percentage changes in MOEs of the HEV are relatively smaller than those of the Normal LDV. This is because the mass of emissions at zero grade, denominator, is much higher than that of the Normal LDV. That is, the changes in MOEs for the HEV are higher in terms of absolute values but smaller in terms of relative values than those of the Normal LDV.

Looking into the MOE profiles as a function of speed and roadway grade levels, the impacts of the HEV are different from those for Normal LDV. That is, Fuel consumption, HC, CO, and $CO_2$ emissions are more sensitive to the variation in speed levels. However, $NO_x$ emissions are more sensitive to roadway grades.

## Stop Sign Control Scenario

The main objective of the stop sign scenario is to quantify the impact of roadway grade during stop-and-go maneuvers. This scenario is different from the uniform speed scenario in that this scenario involves vehicle deceleration and acceleration. Within this scenario an analysis of the impacts of roadway grades and acceleration levels on vehicle fuel consumption and emission rates is conducted.

As discussed earlier in the methodology section, four different acceleration levels are considered in this scenario. The acceleration levels are varied from 40% to 100% the maximum rate at increments of 20%. Figure 4 illustrates the acceleration, speed, and emission profiles for two acceleration level runs. The upper-left figure illustrates the VT-Micro model validity boundary superimposed on the speed/acceleration profile of a simulated vehicle for different acceleration levels. As can be seen, two observations exceed the VT-Micro boundary when the vehicle accelerates at its maximum capacity (100% acceleration level). Otherwise all data are within the valid range of the VT-Micro model. The figure also illustrates the temporal variation in vehicle fuel consumption and emission rates as a vehicle decelerates and accelerates along different roadway grade sections. The figure demonstrates that the vehicle fuel consumption rate decreases as the vehicle decelerates and increases significantly while the vehicle accelerates. The figure also demonstrates that vehicle fuel consumption emission rates are significantly dissimilar for different grades.

### Normal Light Duty Vehicle

Before scrutinizing the results of the stop sign scenario, it is meaningful to compare the results of two scenarios, the uniform speed and stop sign scenarios, without any consideration of roadway grade impacts. The differences in fuel consumption and emission rates for the two scenarios considering a 0% grade are calculated. As the result of the comparison, the fuel consumption, HC, CO, $NO_x$, and $CO_2$ emission rates of the stop sign scenario are 23%, 143%, 274%, 78%, and 20% higher than those of the uniform speed scenario, respectively, considering the Normal LDV, and 13%, 18%, 20%, 4%, and 11% higher, respectively, considering the HEV. As can be seen, all MOEs of the stop-sign scenario were higher than those of the uniform speed scenario, as would be expected given that the vehicle has to stop. The additional HC and CO emissions for the Normal LDV that result from the introduction of a stop are significant. The results demonstrate that stop-and-go behavior has significant impacts on HC and CO emissions in comparison to other emissions for both normal and HEV.

Analyzing the roadway grade impact results for the stop sign scenario, the MOEs are more sensitive to roadway grades than vehicle acceleration levels. Changes in MOEs' as a function of acceleration levels, relative to the base 40% maximum acceleration level, vary from – 9% to 228%. Alternatively, the MOEs vary from 1% to 364% as a function of roadway grades, relative to the 0% grade base case.

The percentage change in MOEs as a function of the vehicle's acceleration level demonstrates a significant increase in HC and CO emissions in comparison to other MOEs. Considering the roadway grade effects, the percentage changes are more drastic at lower grade levels. The percentage change in MOEs relative to the 40% maximum acceleration level at 0% and 6% grade is calculated. Consequently, the HC and CO emission changes vary from 26% to 127% and from 32% to 228%, respectively. On the other hand, the $NO_x$ and $CO_2$ emissions slightly decrease as the vehicle's acceleration level increases. The $NO_x$ and $CO_2$ emission changes vary from -9% to 1% and from -3% to -1%, respectively. Finally, the fuel consumption rate is impacted slightly by the vehicle's acceleration level.

Comparing the results in terms of roadway grade impacts, the results demonstrate an increase in MOEs as roadway grades increase, as was the case for the uniform speed scenario. The percentage changes in the MOEs are not as significant as in the case with the uniform speed scenario. That is, the fuel consumption, HC, CO, $NO_x$, and $CO_2$ emissions have a maximum change of 111%, 207%, 338%, 364%, and 108%, respectively. Noteworthy is the fact that the roadway grade impacts on HC and CO emissions are relatively small, when a vehicle is operated at higher acceleration levels.

### *High Emitting Vehicle*

Comparing the HEV results to the Normal LDV results one observes that the MOEs decrease as the vehicle's acceleration level increases. The percentage changes in MOEs relative to the 40% acceleration level along a 0% and 6% grade are calculated. As the result of the comparison, the MOEs vary from -13% to 0%.

On the other hand, the MOEs and percentage change in MOEs as a function of roadway grade and acceleration levels are calculated. As the result of the comparison, the relative changes are not higher than those of the Normal LDV. The fuel consumption, HC, CO, $NO_x$, and $CO_2$ emissions have maximum changes of 98%, 70%, 104%, 94%, and 98%, respectively. However, the absolute values for the MOEs are much higher than those of the Normal LDV, except for the fuel consumption and $CO_2$ emission rates. The ratio of the HEV to Normal LDV MOEs is calculated for each of a 0%~6% roadway grade. Consequently, the fuel consumption, HC, CO, $NO_x$, and $CO_2$ vary 80%~76%, 697%~558%, 308%~262%, 896%~387%, and 101%~103%, respectively. The results demonstrate that unlike the Normal LDV, the HC and CO emissions are relatively insensitive to vehicle deceleration levels.

## Signal Control Scenario

Prior to discussing the signal control scenario results, a description of the Performance Index (PI) concept is presented given that it is utilized as an objective function in computing the optimum traffic signal offsets. The PI is computed as

*Performance Index = Number of Stops × 10 + Total Delay.*

First, the optimal offsets are computed to maximize the PI. Subsequently, the environmental impacts are computed for the identified signal timings. It should be noted that the east bound direction travels uphill while the west bound direction travels downhill.

The percentage changes in MOEs as a function of the roadway grade are calculated. The fuel consumption, HC, CO, NOx, $CO_2$ vary 13%~109%, 8%~121%, 12%~168%, 32%~424%, and 13%~109%, respectively, considering the east bound, and -37%~-9%, -30%~-6%, -50%~-9%, -59%~-20%, and -37%~-10%, respectively, considering the west bound. The results demonstrate an increase in MOE estimates as the roadway grade increases demonstrating that the additional MOE estimates in the east bound direction (uphill) outweigh the savings in MOEs in the west bound direction (downhill).

### *Normal Light Duty Vehicle*

Based on the simulation results, the optimal and worst offsets for the east bound (uphill) based on the PI are 40 and 0 seconds at 0% grade, respectively. The uniform speed scenario and the signal scenario at 0% grade are compared, when the network is being controlled at optimum and worst offset. As the result of the comparison, the MOEs at the offset of 0 and 40 seconds are higher 20% ~ 59% and 41%~65% than those of the uniform speed scenario, respectively.

Of interest is whether the optimal offset varies as a function of the MOE under consideration for different roadway grades. The optimal offset for the east bound direction (uphill) based on the PI is 40 s. The optimal offset for the east bound direction using other MOEs is also 40 s. Alternatively, when considering the aggregated MOEs for the east and west bound directions, the optimal offset based on the PI is 40 s at 0, 1, 2, and 3% grade and 30 s at 4, 5, and 6% grade. The optimal offset based on fuel consumption and emissions is always 40 s regardless of the roadway grade. Also the worst offset is almost 0 s regardless of the MOE that is considered in optimizing the signal offsets. This result shows that the fuel consumption and vehicle exhaust emissions are generally low, when the network is controlled at the optimal signal offset yielded based on the PI. In summary, the PI is a good objective function in selecting traffic signal timings that enhance the environment.

Figure 5 illustrates the variation of MOEs as a function of roadway grades and signal offsets for the Normal LDV. The figures demonstrate that the roadway grade is critical in estimating fuel consumption and emission rates. More specifically NOx emissions are extremely sensitive to roadway grades.

### *High Emitting Vehicle*

The variation in fuel consumption and emission rates for the HEV as a function of the roadway grade is very similar to the Normal LDV results. Similarly, the MOEs rates are close to optimal at the optimal signal offsets that are yielded by minimizing the PI. However, the differences in absolute values for the HEV are much higher than those of the Normal LDV. The ratio of the HEV to Normal LDV fuel consumption, HC, CO, $NO_x$, and $CO_2$ vary 84%~78%, 1522%~1201%, 944%~720%, 1118%~508%, and 99%~ 100%, respectively. As can be seen, the fuel consumption and $CO_2$ emissions are slightly lower than those of the Normal LDV. Alternatively, the HC, CO, and $NO_x$ emissions for the HEV are much higher than those of the Normal LDV.

## OVERALL ANALYSIS OF SCENARIOS

In this section we summarize the results of the analysis. The fuel consumption and vehicle exhaust emissions increase as roadway grade levels increase. The percentage changes in MOEs are significant, even for a 1% increase in roadway grade levels, regardless of the vehicle type (normal versus high emitter), as demonstrated in Table 2 and Figure 6 (a). For instance, the increases in MOEs for the Normal LDV range from 8% to 36% at a 1% grade relative to 0% grade under the signal control conditions. Comparing Normal LDVs with HEVs, grade impacts on HEVs are greater in terms of absolute values but lesser in terms of relative values compared to Normal LDVs.

For Normal LDVs, HC, CO, and $NO_x$ emissions are more sensitive to roadway grades in comparison to fuel consumption and $CO_2$ emission rates. In terms of relative changes, HC, CO, and $NO_x$ emissions are significantly impacted by roadway grades for cruise modes of travel. Fuel consumption, HC, CO, $NO_x$, and $CO_2$ emissions increase by 140%, 197%, 361%, 656%, and 138%, respectively, as illustrated in Figure 6. Alternatively, the absolute HC, CO, and $NO_x$ emissions for the stop sign control scenario are higher than those for the other scenarios, as illustrated in Figure 7. The reason for the higher emissions is a result of the larger number of stops that are involved in the stop scenario compared to the other scenarios.

The MOEs for HEVs are not as sensitive as those for Normal LDVs to vehicle acceleration levels. However, the relative values for HC, CO, and $NO_x$ emissions are also significant for cruising conditions. The fuel consumption, HC, CO, $NO_x$, and $CO_2$ emissions increase by 113%, 84%, 126%, 105%, and 112%, respectively for a 6% grade relative to a 0% grade, as illustrated in Figure 6. The absolute HC, CO, and $NO_x$ emissions from the signal control scenario with the worst offset are higher than those from other scenarios. This is because HEVs are more sensitive to the increase in travel time. The fuel consumption, HC, CO, and $CO_2$ emissions are 33%, 57%, 53%, 29% greater than those for cruising conditions.

Figure 8 shows the comparison between the benefits associated with a reduction of roadway grades and the benefits of signal optimization. As can be seen in Figure 8 (a), the benefits yielded from signal optimization are equivalent to those from reducing roadway grades from 0% to the range of negative 1% to negative 2%. Furthermore, the benefits associated with a reduction in the roadway grade from 2% to 1% or 0% is also equivalent to the benefits obtained from signal optimization, as illustrated in Figure 8 (b). Finally, the results indicate that the environmental benefits associated with a reduction in roadway grade for Normal LDVs is greater than that for HEVs.

## CONCLUSIONS

The study quantified the impact of roadway grades on vehicle fuel consumption and emission rates using the INTEGRATION software. Three types of traffic control scenarios were considered including cruising at a constant speed, traveling along a stop sign controlled arterial, and traveling through a network of traffic signals. The study clearly demonstrates that the impact of roadway grades on vehicle fuel consumption and exhaust emission rates should not be ignored while evaluating transportation investments. Specifically, from the uniform speed scenario to signal control scenario, the impacts of roadway grades on fuel consumption and emission rates increases significantly even for a 1% increase in roadway grades. For example, the fuel consumption, HC, CO, $NO_x$, and $CO_2$ emissions for a Normal LDV increases by 148%, 1,020%, 2,051%, 682%, and 139%, respectively, for cruising conditions as a result of a 6% increase in roadway grade. When considering the stop sign control scenario, the MOEs for the Normal LDV increase by 111%, 207%, 338%, 364%, and 108%, respectively. In the case of the traffic signal control scenario, the MOEs for the Normal LDVs increase by 109%, 121%, 168%, 424%, and 109%, respectively. Alternatively, the changes in MOEs for the HEVs are higher in terms of absolute values but smaller in terms of relative values than those for the Normal LDV.

The study also demonstrated that by minimizing the commonly known performance index function (a weighted combination of vehicle stops and delay) in computing the optimum offset; the environmental impacts associated with the signal timings are also minimized.

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## *List of Tables*

## List of Figures

**Table 1: Max/Min Fuel Consumption and Emission Rates (Normal LDV)**

| Grade | | Fuel Consumption | | HC | | CO | | NOx | | $CO_2$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Speed (km/h) | Rate (l/km) | Speed (km/h) | Rate (g/km) | Speed (km/h) | Rate (g/km) | Speed (km/h) | Rate (g/km) | Speed (km/h) | Rate (g/km) |
| Max | 0% | 5 | 0.354 | 5 | 0.347 | 5 | 1.876 | 100 | 0.283 | 5 | 822.71 |
| | 1% | 5 | 0.389 | 5 | 0.363 | 5 | 2.046 | 100 | 0.407 | 5 | 905.17 |
| | 2% | 5 | 0.427 | 5 | 0.378 | 100 | 2.783 | 100 | 0.560 | 5 | 992.98 |
| | 3% | 5 | 0.467 | 5 | 0.395 | 100 | 4.764 | 100 | 0.719 | 5 | 1086.13 |
| | 4% | 5 | 0.509 | 5 | 0.415 | 100 | 8.645 | 100 | 0.869 | 5 | 1184.83 |
| | 5% | 5 | 0.554 | 100 | 0.532 | 100 | 15.977 | 100 | 0.996 | 5 | 1288.84 |
| | 6% | 5 | 0.601 | 100 | 0.872 | 100 | 28.881 | 95 | 1.102 | 5 | 1398.16 |
| Min | 0% | 75 | 0.078 | 75 | 0.070 | 80 | 1.128 | 30 | 0.087 | 75 | 180.85 |
| | 1% | 75 | 0.092 | 75 | 0.071 | 75 | 1.221 | 30 | 0.123 | 75 | 212.26 |
| | 2% | 75 | 0.108 | 65 | 0.080 | 30 | 1.359 | 25 | 0.169 | 75 | 250.99 |
| | 3% | 75 | 0.127 | 60 | 0.093 | 20 | 1.435 | 20 | 0.223 | 75 | 292.99 |
| | 4% | 75 | 0.147 | 50 | 0.112 | 20 | 1.533 | 20 | 0.287 | 75 | 337.97 |
| | 5% | 60 | 0.168 | 45 | 0.133 | 20 | 1.660 | 15 | 0.360 | 75 | 384.94 |
| | 6% | 60 | 0.190 | 35 | 0.156 | 20 | 1.818 | 15 | 0.439 | 75 | 432.75 |

**Table 2: Comparison of scenarios at 0%, 1%, and 6% grade (FFS = 64km/h, Max. Acc. Level = 60%)**

| | | Uniform Speed Scenario | | Stop Sign Scenario | | Signal Scenario | |
|---|---|---|---|---|---|---|---|
| | | Normal | High Emitter | Normal | High Emitter | Normal | High Emitter |
| 0% | Fuel (L/km) | 0.0801 | 0.0709 | 0.0982 | 0.0802 | 0.0968 | 0.0824 |
| | HC (g/km) | 0.0720 | 1.1581 | 0.1749 | 1.3674 | 0.1030 | 1.5501 |
| | CO (g/km) | 1.1625 | 13.0496 | 4.3436 | 15.6208 | 1.8534 | 17.0251 |
| | $NO_x$ (g/km) | 0.1247 | 1.8709 | 0.2218 | 1.9440 | 0.1514 | 1.7963 |
| | $CO_2$ (g/km) | 185.2292 | 141.7317 | 222.2241 | 157.7008 | 223.0919 | 160.9206 |
| 1% | Fuel (L/km) | 0.0943 | 0.0818 | 0.1109 | 0.0909 | 0.1103 | 0.0928 |
| | HC (g/km) | 0.0728 | 1.2856 | 0.1939 | 1.4874 | 0.1111 | 1.6693 |
| | CO (g/km) | 1.2327 | 14.6258 | 5.0308 | 17.0627 | 2.0726 | 18.4108 |
| | $NO_x$ (g/km) | 0.1980 | 2.1332 | 0.2851 | 2.1803 | 0.2058 | 1.9552 |
| | $CO_2$ (g/km) | 218.3178 | 165.7147 | 250.7782 | 181.2075 | 254.2866 | 183.0239 |
| 6% | Fuel (L/km) | 0.1924 | 0.1511 | 0.2039 | 0.1552 | 0.2027 | 0.1596 |
| | HC (g/km) | 0.2141 | 2.1307 | 0.4241 | 2.2850 | 0.2276 | 2.4746 |
| | CO (g/km) | 5.3574 | 29.4986 | 11.8173 | 30.0671 | 4.9459 | 30.3239 |
| | $NO_x$ (g/km) | 0.9432 | 3.8262 | 0.9400 | 3.6576 | 0.7928 | 3.1558 |
| | $CO_2$ (g/km) | 440.7586 | 299.8061 | 456.8297 | 306.4108 | 465.4452 | 317.6261 |

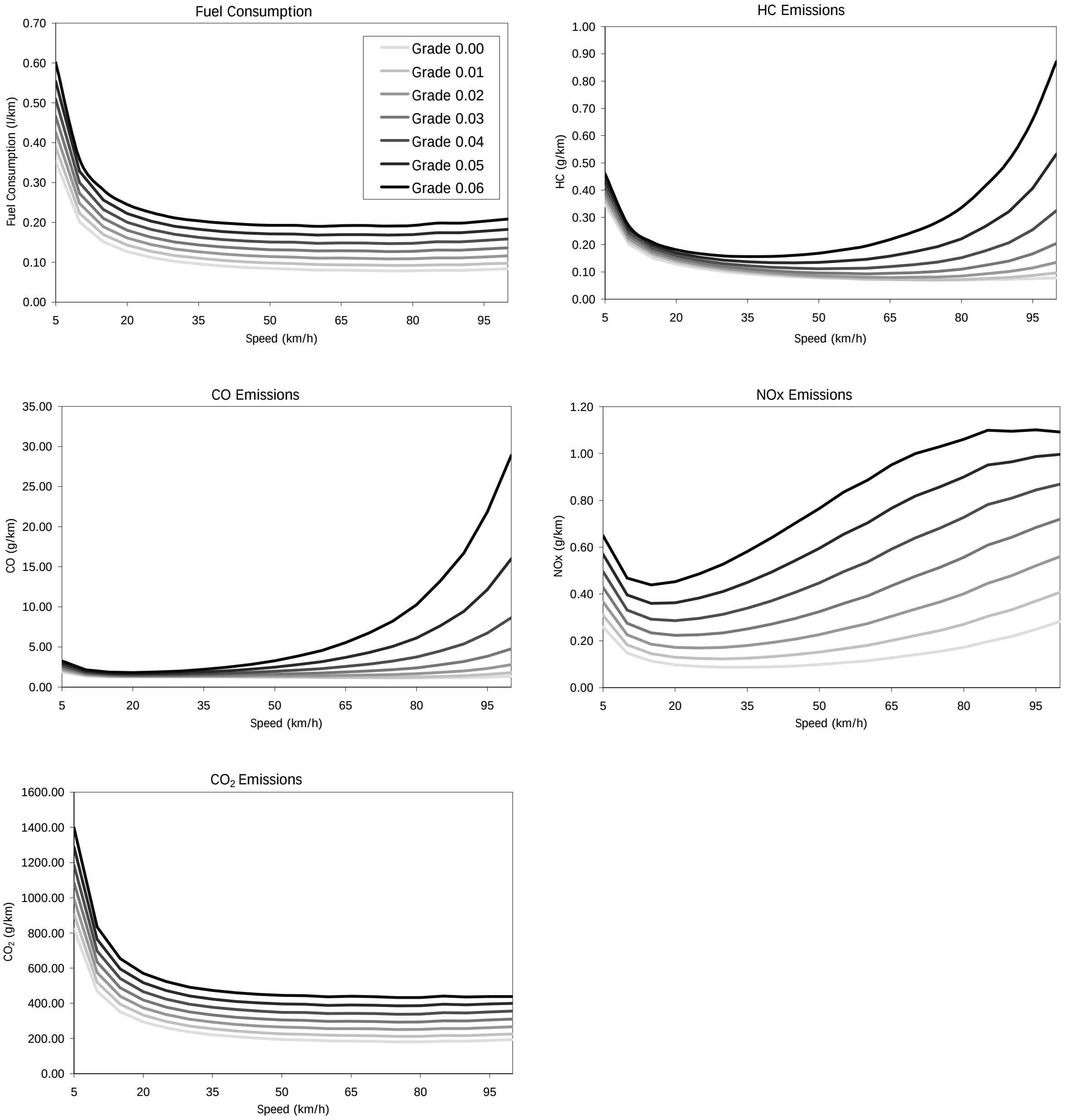

Figure 1: MOE profiles for Normal LDV

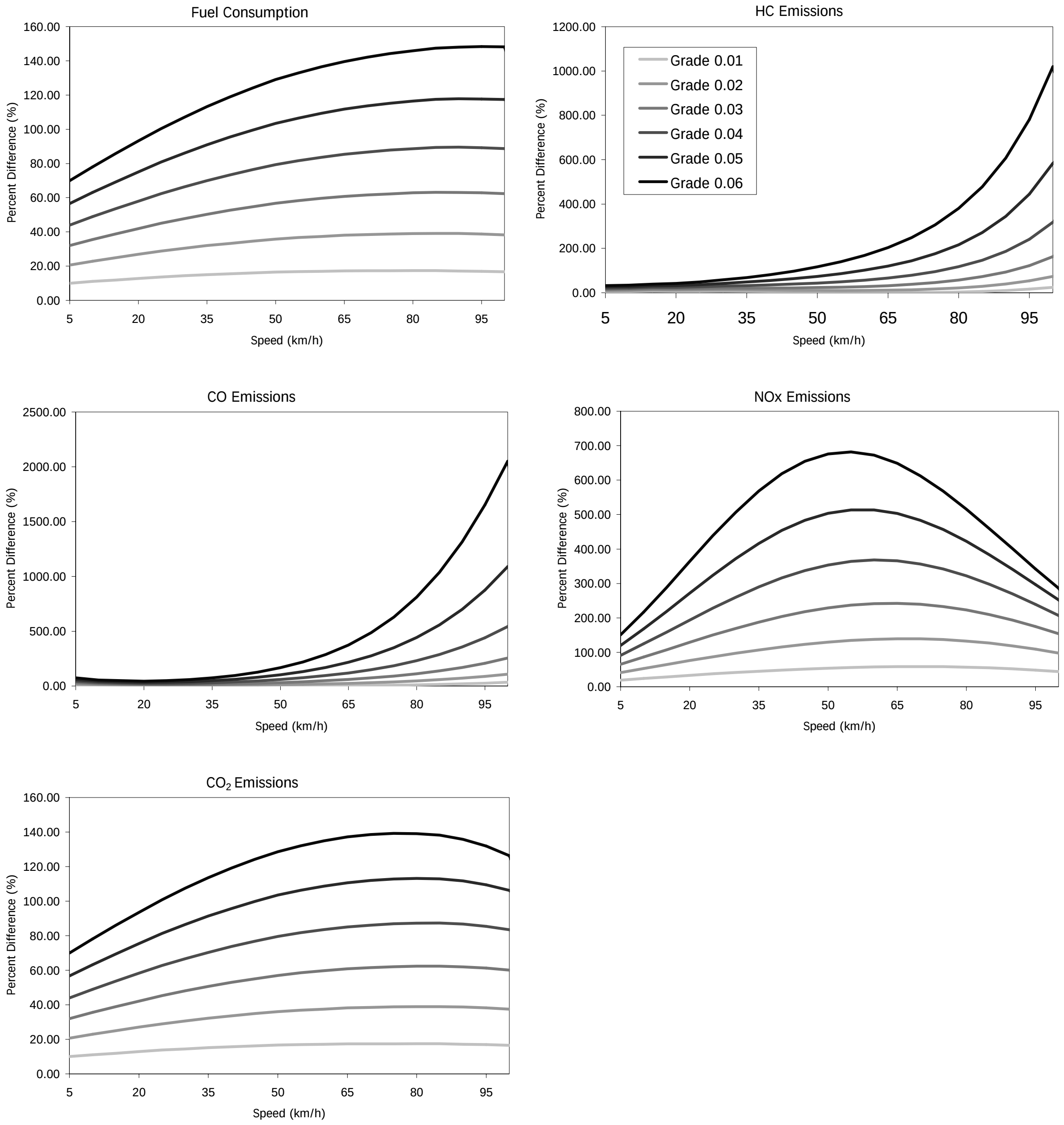

**Figure 2: Percent change in MOEs relative to 0% grade for Normal LDV**

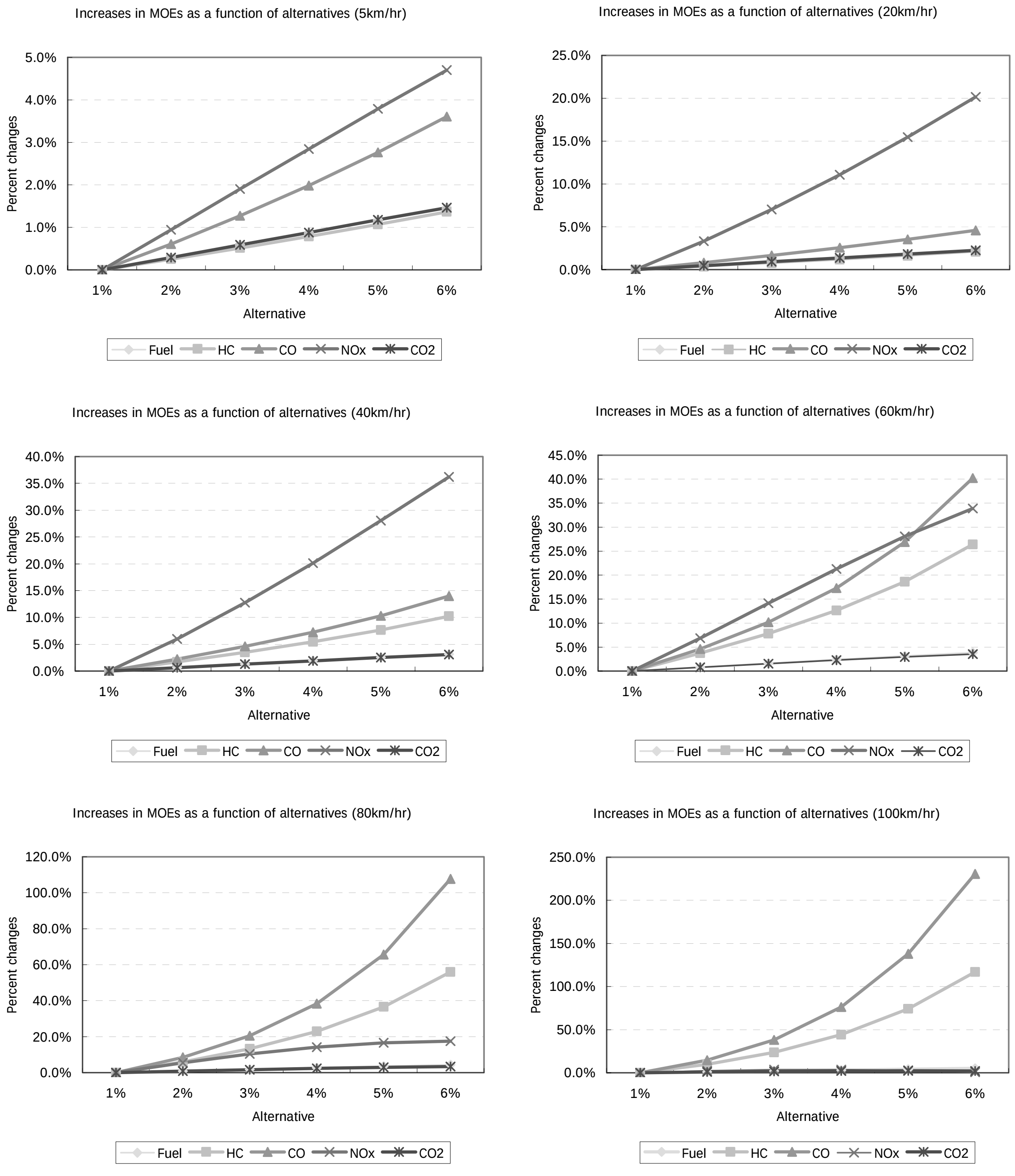

**Figure 3: Increases in MOEs as a function of Geometric Alternatives**

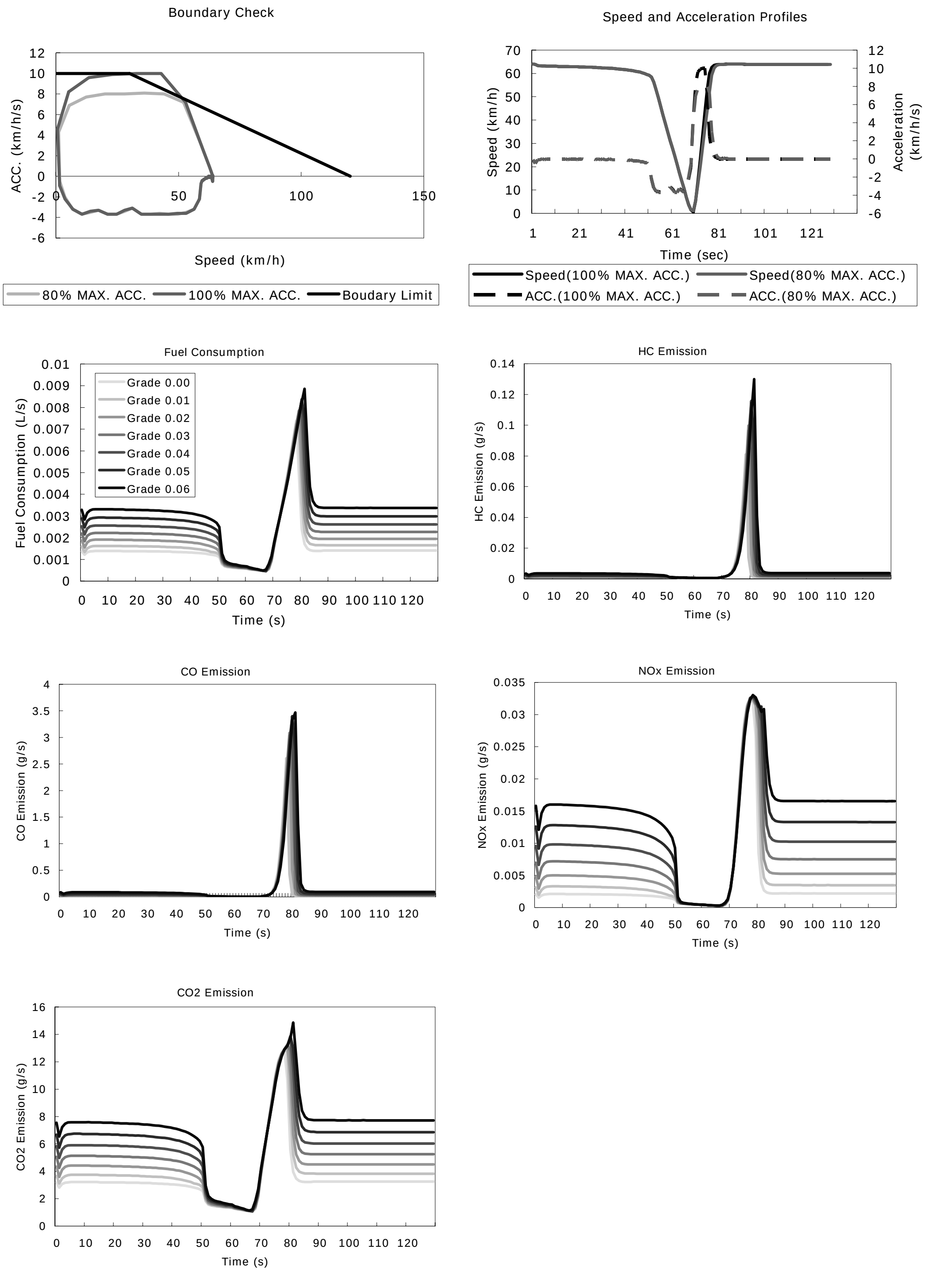

Figure 4: Speed, acceleration, and MOE profiles as a function of time

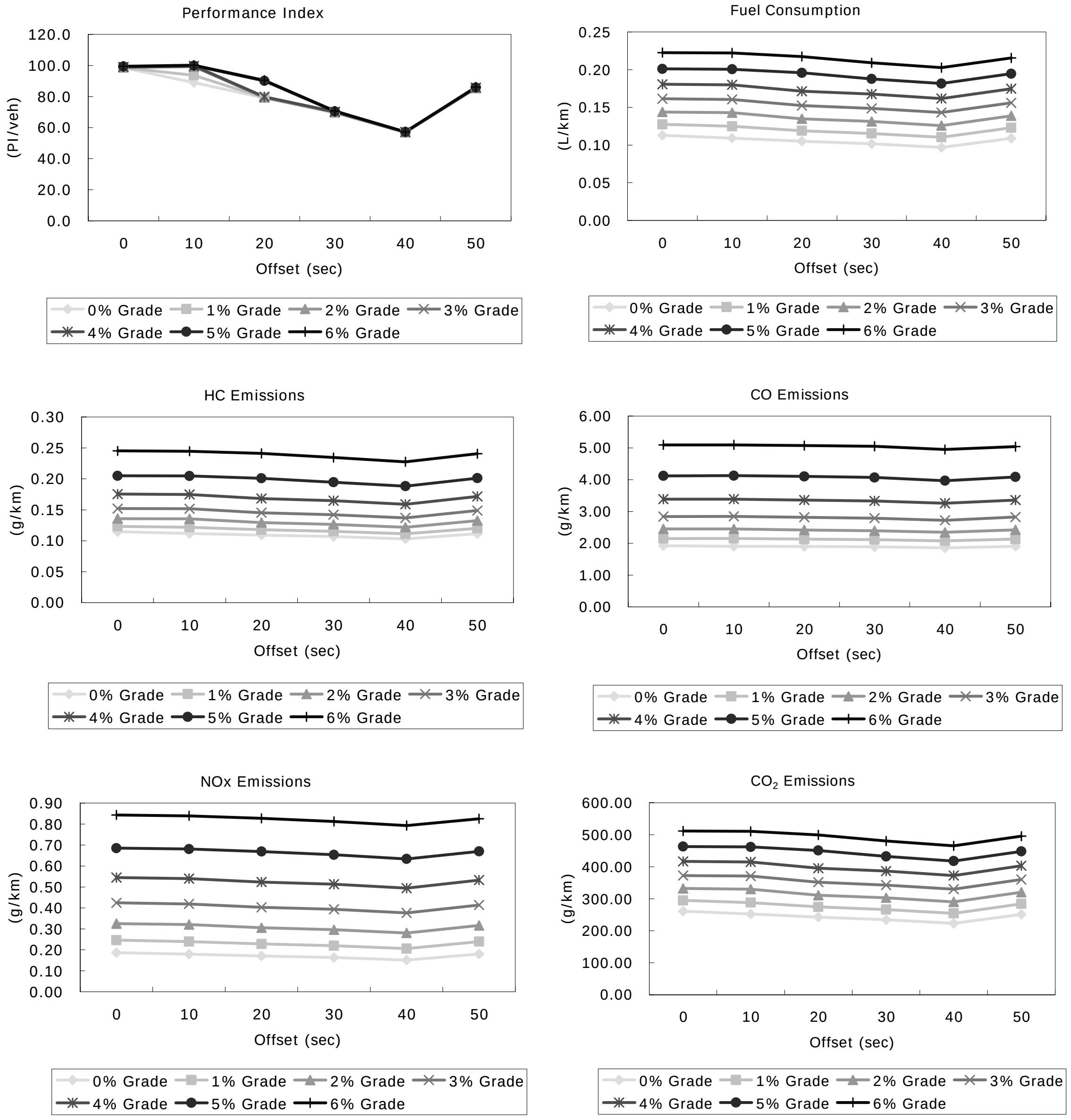

Figure 5: PI and MOEs as a function of signal offsets for Normal LDV

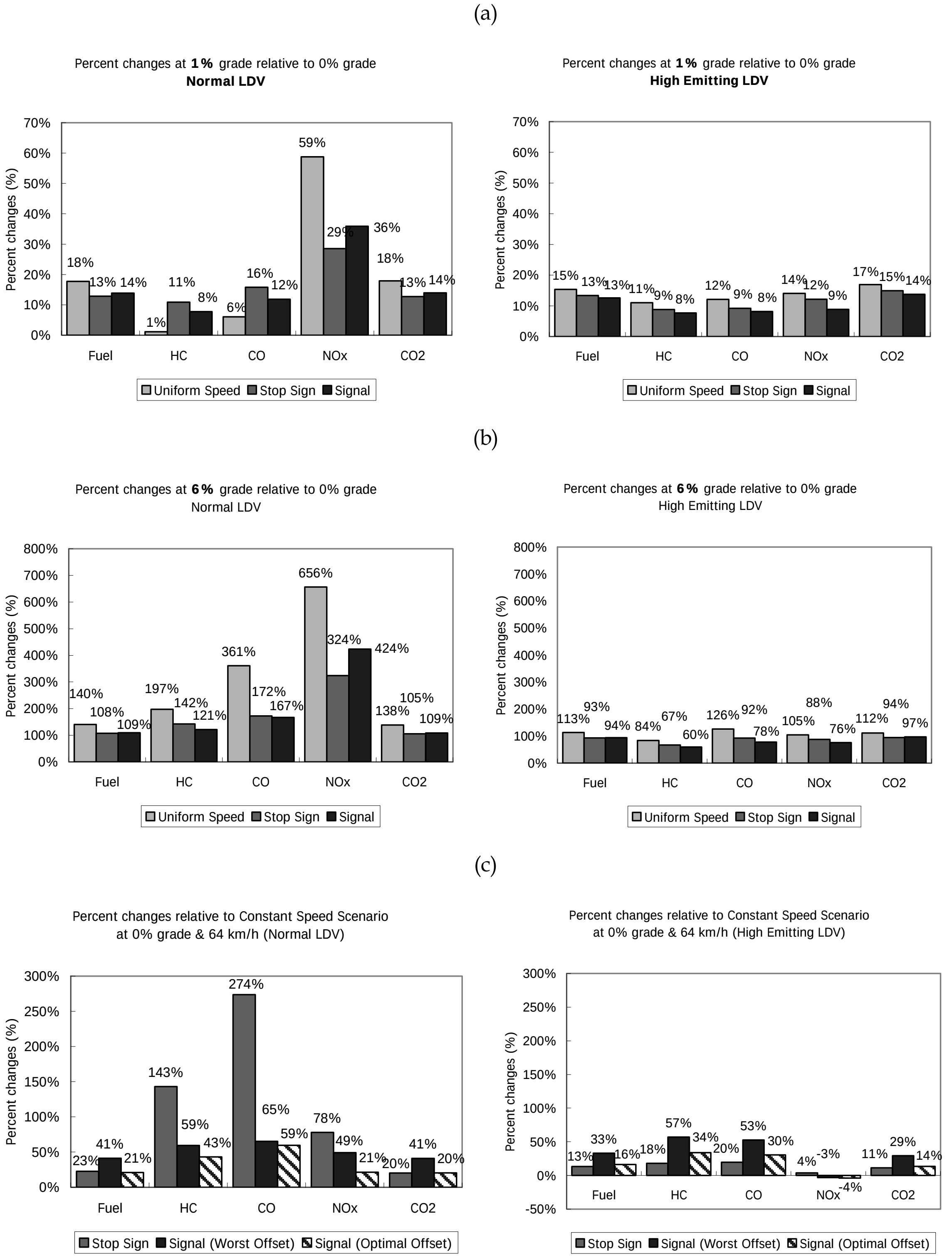

**Figure 6: Comparison of MOE Scenarios (Percent Changes)**

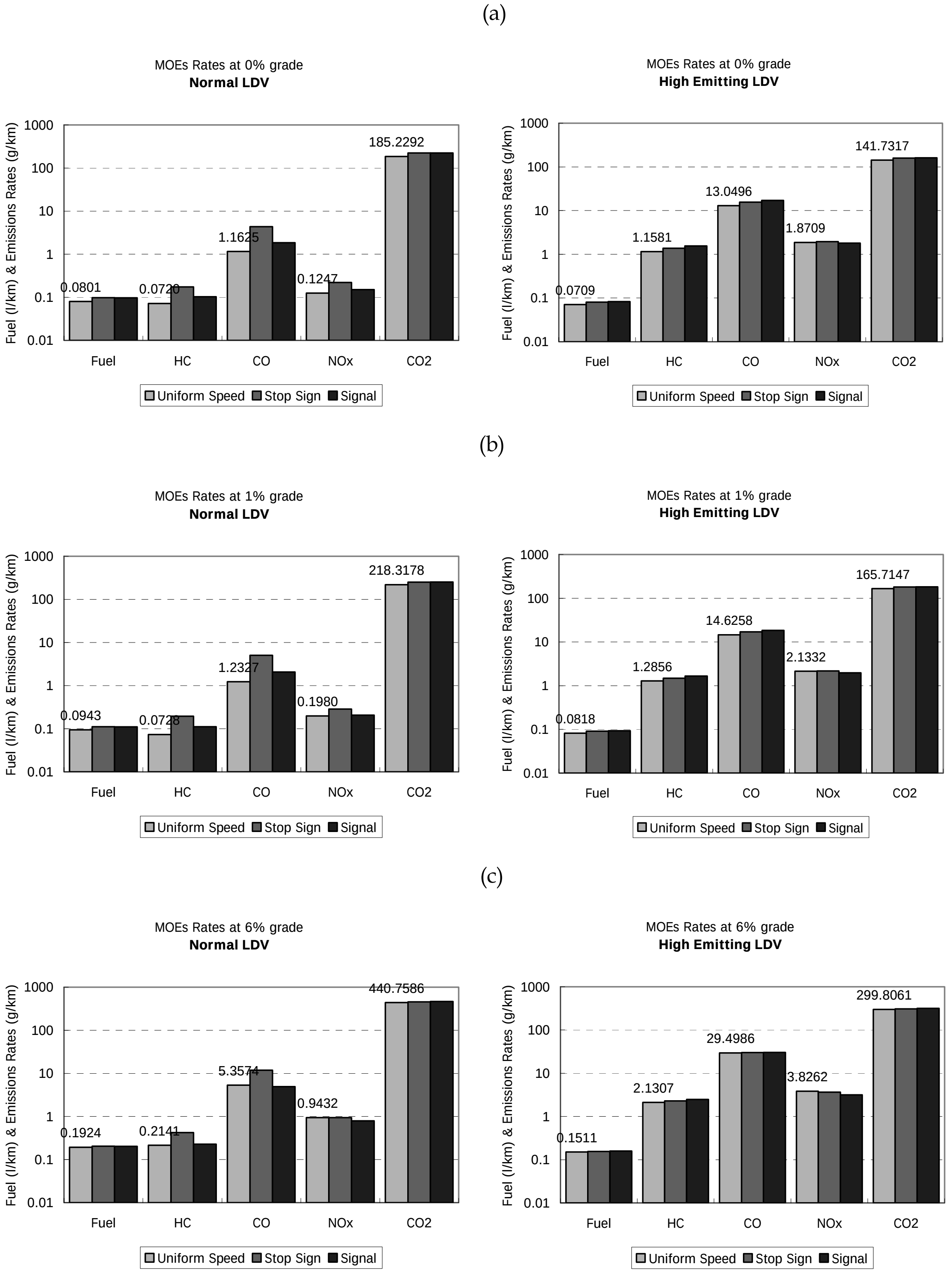

**Figure 7: Comparison of Scenario Mass MOEs**

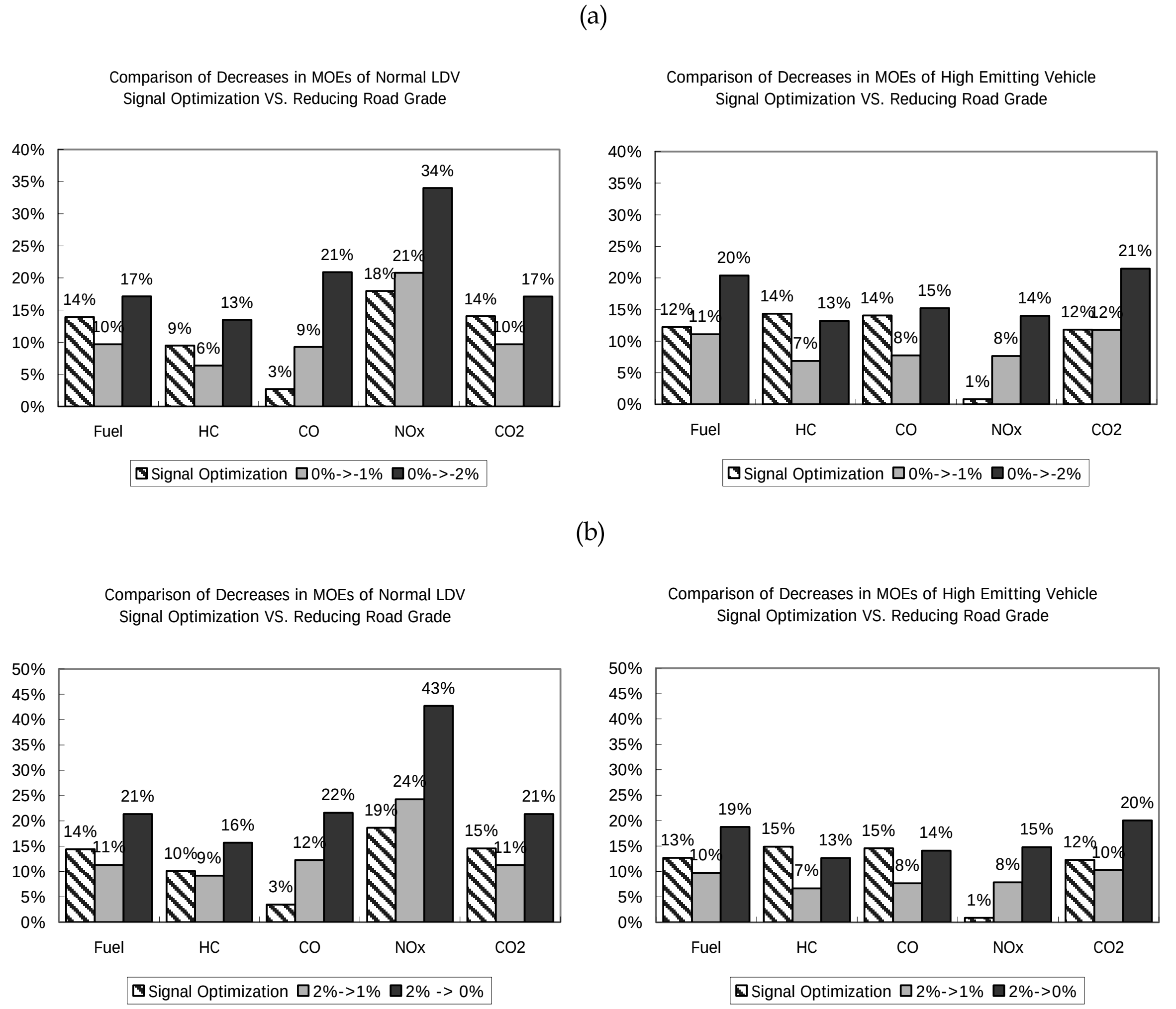

**Figure 8: Comparison of Benefits Associated with a Reduction of Roadway Grades and Signal Optimization**