Impact of Stops on Vehicle Fuel Consumption and Emissions

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ABSTRACT

Macroscopic emission models use average speed as a sole traffic-related explanatory variable. Research, however, has demonstrated that the use of average speed as a single traffic-related explanatory variable is insufficient in estimating vehicle emissions. The objective of this paper is to attempt to quantify, using simple examples, the impact of vehicle stops on fuel consumption and emissions of hydrocarbons, carbon monoxide, and oxides of nitrogen.

This study indicates that the vehicle fuel consumption rate is more sensitive to cruise speed levels than to vehicle stops. The aggressiveness of a vehicle stop, as represented by the vehicle's acceleration and deceleration level, does have a significant impact on vehicle emission rates. Specifically, HC and CO emission rates are highly sensitive to the level of acceleration when compared to cruise speeds in the range of 10 to 120 km/h. Alternatively, the impact of deceleration levels on all measures of effectiveness is relatively small. Noteworthy is the fact that at high speeds the introduction of vehicle stops involving extremely mild deceleration and acceleration levels can actually reduce vehicle emission rates.

INTRODUCTION

The primary sources of motor vehicle emissions are exhaust emissions from chemical compounds that leave the engine through the tail pipe system and crankcase, and evaporative emissions from the fueling system, which mainly volatile organic compounds (VOCs) (EPA, 1993). For gasoline vehicles, exhaust emissions are originally generated as a result of fuel combusting in the engine (called engine-out emissions), and are reduced by passing through the catalytic converter (called tail pipe or exhaust emissions). Currently, diesel-powered engines cannot use catalytic oxidizers due to plugging from particulate matter (PM).

Carbon monoxide (CO) and VOCs are products of incomplete combustion of motor fuels and, in the case of VOCs, of fuel vapors emitted from the engine and fuel system (EPA, 1993). Oxides of nitrogen (NO_x) emissions are the products of high-temperature chemical processes that occur during the combustion itself.

Limitations of Current State-of-Practice Macroscopic Models

Current estimates of vehicle emission rates are produced by macroscopic models, namely the MOBILE5a and EMFAC models. In these models, vehicle emissions are expressed as functions of average speed and are based on vehicle testing on a limited number of standard drive cycles. For example, the MOBILE5a model utilizes baseline emission rates that are derived from the Federal Test Procedure (FTP), which is the vehicle test procedure commonly used for light-duty vehicle testing and is composed of three different phases: a cold start phase, a stabilized phase, and a hot start phase. In the MOBILE5a model, the emissions from vehicles operating in all three phases are used to estimate baseline emissions. The baseline emission rates for a vehicle class are computed as the average of the three phases of the FTP cycle, which corresponds to an average speed of 31.6 km/h (19.6 mph). In the latest EMFAC model (EMFAC2000), the baseline emission rate is derived from the Unified Drive Cycle (LA92) with an average operating speed of 39.4 km/h (24.6 mph). Emission rates at other average speeds are multiplied by an appropriate Speed Correction Factor (SCF) that is specific

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for a vehicle class and operating speed. SCFs are derived from emissions data from tests over several driving cycles of different average speeds. The SCFs are estimated using the average cycle speed as an independent variable and the emission rates as a dependent variable. Therefore, speed-corrected emission rates used in macroscopic emission models are highly dependent on the average cycle speed. The literature demonstrates that the SCF decreases as a function of the average speed in the range of 0 to 90 km/h (55 mph) for HC and CO emissions, while NO_x emissions display a slight increase in emissions for speeds above 30 km/h (National Research Council, 2000).

Research in Germany has indicated that traffic calming can reduce idle times by 15 percent and gasoline use by 12 percent (Newman and Kenworthy 1992). The slower and calmer style of driving was found to reduce CO emission rates by up to 17 percent, VOC emission rates by up to 22 percent, and NO_x emission rates by up to 48 percent depending on the gear engaged and the driver's aggressiveness. These findings are attributed to the fact that while both instantaneous speed and acceleration significantly affect vehicle emission rates per unit of time, vehicle accelerations become a more dominant factor on HC and CO emissions, especially at high speeds (Rakha *et al.* 2000a). The high emissions that are produced while the vehicle is accelerating are attributed to an operating design that allows vehicles to operate with a richer fuel/air mixture in order to prevent engine knock and damage to the catalytic converter. In addition, the catalytic converter is overridden, thereby producing high levels of emissions (National Research Council 1995).

Furthermore, studies using the current state-of-practice macroscopic emission models (MOBILE5a and EMFAC) indicate a high level of uncertainty in estimating emission rates. For example, the 95 percent confidence interval for CO emission rates associated with an increase in average speed from 31 km/h (FTP city cycle average speed) to 63 km/h (close to fuel economy cycle average speed (77 km/h)) ranges from a 10 percent increase to a 75 percent decrease in CO emission rates (National Research Council 1995). Based on these findings, it has been concluded that "the current models do not reflect important explanatory variables that can significantly affect emission levels, such as the incidence of sharp accelerations at lower and moderate speeds" (National Research Council 1995). However, up to this date there has not been a systematic attempt to quantify the impacts of different explanatory variables on vehicle fuel consumption and emission rates.

The MOBILE6 Model

EPA's Office of Transportation and Air Quality (OTAQ) is currently developing a new version of the MOBILE model, which is referred to as MOBLE6. This version of the model is significantly different from MOBLE5a in many model components. Specifically, MOBILE6 is based on recent vehicle emission testing data collected by EPA, CARB, automobile manufacturers, as well as inspection and maintenance tests conducted in various states. In addition, the model also allows for the modeling of the impact of different petroleum refiners on vehicle emissions.

A major characteristic of the MOBILE6 model is the addition of so-called off-cycle emissions, which involve aggressive driving with the air conditioning operating. This aggressive driving behavior is not included in the FTP drive cycle, but is included in the Supplemental FTP cycle, which applies to MY2000 and newer vehicles. Given that drive cycles utilized in MOBILE6 include vehicle operations at high speeds and high accelerations, the model produces significantly higher pollutants in comparison with MOBILE5a. As was the case with MOBILE5a, MOBILE6 uses average speed to estimate vehicle emissions; however, the emission factors are categorized by roadway type (e.g., highways, arterials, locals). Emission factors can be adjusted, based on vehicle testing over a series of facility cycles, for different facility types and different average speeds. MOBILE6 estimates emission factors for the start portion and the running portion of the trip separately. The cold start emissions are calculated using the FTP bag1, which includes cold start emissions, and the FTP bag3, which includes hot start emissions.

In addition to the previously mentioned enhancements, other significant enhancements over MOBILE5a include: dramatic reductions in vehicle emissions as vehicles age and accumulate mileage; control of off-cycle emissions with the Supplemental FTP (SFTP) drive cycle; the inclusion of evaporative diurnal emission factors estimated from real-time diurnal test data previously unavailable; the revision of the effects of oxygenated fuels; the revision of effects of Inspection and Maintenance (I/M) programs on vehicle emissions; the addition of off-cycle NO_x emissions for heavy-duty diesel vehicles; the addition of in-use fuel sulfur content effects on all emissions; and the addition of the effects of national low-emission vehicles (NLEV) and Tier 3 standards (EPA 2001; National Research Council 2000).

The Comprehensive Modal Emissions Model

In order to overcome the shortcomings of macroscopic energy and emission models, a number of microscopic models have been developed. The Comprehensive Modal Emissions Model (CMEM), which is one of the newest power demand-based emission models, was developed by researchers at the University of California, Riverside. CMEM estimates Light-Duty Vehicle (LDV) emissions as a function of the vehicle's operating mode. The term "comprehensive" is utilized to reflect the ability of the model to predict emissions for a wide variety of LDVs in various operating states (e.g., properly functioning, deteriorated, malfunctioning). For the test data, both engine-out and tailpipe emissions of over 300 vehicles, including more than 30 high emitters, were measured second-by-second on three driving cycles; FTP, US06, and Modal Emission Cycle (MEC). The MEC was developed by determining the load that a vehicle enters fuel enrichment in order to test vehicles under high engine loads. CMEM predicts second-by-second tailpipe emissions and fuel consumption rates for a wide range of vehicle/technology categories (Barth *et al.* 2000). The model is based on a simple parameterized physical approach that decomposes the entire emission process into components corresponding to the physical phenomena associated with vehicle operation and emission production. The model consists of six modules that predict engine power, engine speed, air-to-fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction. Vehicle and operation variables (such as speed, acceleration, and road grade) and model calibrated parameters (such as cold start coefficients and an engine friction factor) are utilized as input data for the model (Barth *et al.* 2000).

The Virginia Tech Microscopic Energy and Emission Models

The Virginia Tech Microscopic energy and emission model (VT-Micro) was developed from experimentation with numerous polynomial combinations of speed and acceleration levels (Ahn *et al.* 1999; Rakha *et al.* 2000a). Specifically, linear, quadratic, cubic, and quartic 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. While a more detailed description of the derivation of the model is provided in a subsequent section, it is sufficient to note at this point that the model was utilized to conduct the research that is presented in this paper.

Paper Layout

The objective of this study was to quantify systematically the impact of vehicle stops and their associated levels of acceleration and deceleration on light-duty vehicle fuel consumption and emission rates per unit distance traveled under hot stabilized conditions. In addressing this objective, the study first quantified the impact of different levels of cruise speed on vehicle fuel consumption and emission rates in order to establish a base case for the subsequent analysis of vehicle stops. In quantifying the impact of vehicle stops on fuel consumption and emission rates, typical acceleration and deceleration rates were first established using second-by-second speed measurements that were collected using floating cars driven along a signalized arterial in Phoenix, AZ. These typical acceleration and deceleration levels were then utilized to construct simple single-stop drive cycles. The total fuel consumption and emissions for each driven cycle were computed based on instantaneous speed measurements using the VT-Micro fuel consumption and emission models and then summed up for the entire trip. The fuel consumption and emission rates per unit distance were then calculated by dividing the total trip fuel consumption and emissions by the trip distance.

ENERGY AND EMISSION MODELS USED IN STUDY

Prior to describing the specifics of the study, a concise description of the instantaneous VT-Micro energy and emission models is presented. As mentioned earlier, the models were developed using data that were collected at the ORNL on a chassis dynamometer (West *et al.* 1997). The data that were utilized to develop the fuel consumption and emission models presented in this paper were collected at the ORNL. Specifically, vehicles were tested both on-road and on a chassis dynamometer to characterize the entire operating range of each vehicle. Test vehicles were driven in the field in order to verify their engine parameters as functions of vehicle speed and acceleration while driving them through their entire operating envelope. Following road testing, vehicle fuel consumption and emission rates were measured in a laboratory on a chassis dynamometer within the vehicle's feasible speed and acceleration envelope as a function of the same engine parameters. Subsequently, data sets were generated that included vehicle energy consumption and emission rates as a function of the vehicle's instantaneous speed and acceleration levels. Several measurements were made in order to obtain an average fuel consumption and emission rate. The emission data gathered included hydrocarbon (HC), oxides of nitrogen (NO_x), and carbon monoxide (CO) emission rates.

The eight normal emitting vehicles included five 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. Specifically, the average engine size was 3.3 liters, the average number of cylinders was 5.8, and the average curb weight was 1497 kg (3300 lbs) (West *et al.* 1997). While it may be argued that eight vehicles may not be reflective of the entire U.S. vehicle fleet, a comprehensive validation effort using EPA's 16 drive cycles demonstrated that the VT-Micro model emission rates were consistent with field data and MOBILE5a. Specifically, the validation effort demonstrated that the emission estimates fell within the 95 percent confidence limits over all the 16 drive cycles (Ding and Rakha 2002; Ahn *et al.* 2002). Furthermore, the relative changes in emission rates between drive cycles were found to be consistent with third party field data. Consequently, it was concluded that both the absolute magnitude in vehicle emissions and the variation in vehicle emissions between drive cycles were valid.

The data collected at ORNL contained between 1,300 to 1,600 individual measurements for each vehicle and Measure of Effectiveness (MOE) combination depending on each vehicle's envelope of operation. Typically, vehicle acceleration values ranged from –1.5 to 3.7 m/s^2 at increments of 0.3 m/s^2 (-5 to 12 ft/s^2 at 1 ft/s^2 increments). Vehicle speeds varied from 0 to 33.5 m/s (0 to 121 km/h or 0 to 110 ft/s) at increments of 0.3 m/s.

It is essential to note that the ORNL data represents a unique vehicle performance envelope. For example, low weight-to-power ratio vehicles have better acceleration characteristics at high speeds than their high weight-to-power ratio counterparts. This inherent performance boundary is extremely important when these models are used in conjunction with microscopic traffic flow models as they represent a physical vehicle dynamics constraint in the car-following equations of motion. In order to represent the on-road vehicle fleet, a hypothetical composite vehicle was created. The composite vehicle was derived as an average of the eight test vehicles to reflect a typical average vehicle.

Utilizing the data for the composite vehicle fuel consumption and emission data, polynomial regression models were fit to the measured data in the form of Equation 1, with coefficients of determination ranging from 0.72 to 0.99 (Ahn *et al.* 1999; Rakha *et al.* 2000a). The models demonstrate that the composite vehicle fuel consumption rates vary fairly linearly when the vehicle is cruising or decelerating; however, the relationship is significantly non-linear for higher levels of acceleration (acceleration greater than or equal to 1.2 m/s^2). In terms of emissions, the HC and CO surfaces appear to be similar and non-linear in nature except for the fact that CO emission rates are much higher (up to 2500 mg/s in the case of CO versus 60 mg/s in the case of HC), as illustrated in Figure 1. Alternatively, the NO_x surface appears to be more non-linear in nature when compared to HC and CO surfaces when the vehicle is decelerating or cruising.

$$MOE_e = e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(K_{i,j}^{e} \times u^{i} \times a^{j})} \qquad [1]$$

MOE_e	Instantaneous fuel consumption or emission rate (ml/s or mg/s)
$K^e_{i,j}$	Model regression coefficient for MOE "e" at speed power "*i*" and acceleration power "*j*"
u	Instantaneous Speed (km/h)
a	Instantaneous acceleration (km/h/s)
i	Power to speed (i.e. s, s^2, s^3)
j	Power to acceleration (i.e. a, a^2, a^3)

IMPACT OF CRUISE SPEED ON VEHICLE FUEL CONSUMPTION AND EMISSION RATES

A first step in characterizing the impact of vehicle stops on vehicle fuel consumption and emissions was to characterize the impact of different levels of constant cruise speed on these MOEs. The objective of this base analysis was to provide a reference for future analyses. In conducting this analysis, a sequence of trips at constant cruise speeds ranging from 10 to 120 km/h was executed over a fixed 4.5-km section. Vehicle fuel consumption and emissions were estimated using the

VT-Micro model every second and were integrated over the entire trip to compute trip fuel consumption and emissions. The MOE rates per unit distance were then computed by dividing trip MOEs by the constant trip distance of 4.5 km.

As illustrated in Figure 1. Variations of Emissions as a Function of Vehicle's Speed and Acceleration (Ahn *et al.* 1999; Rakha *et al.* 2000)

, the fuel consumption rate per unit distance exhibited a convex function with respect to cruise speed. Specifically, the fuel consumption rate decreased from a highest rate, which appeared at the lowest speed in this study (i.e. 10 km/h), reaching its minimum at a speed of approximately 80 km/h and then increasing again with an increase in the cruise speed. This convex relation is by no means revolutionary and is fairly widely recognized. Specifically, the speed limit of 90 km/h (55 mph) was designed because it provided minimum fuel consumption per unit distance of travel. Consequently, this function demonstrated the validity of the VT-Micro model for steady-state constant speed traveling. The function also demonstrated that differences between highest and lowest rates were in the range of 300 percent.

Similarly, the HC emission rate followed a convex function; however, unlike the fuel consumption rate, it was higher for high cruise speeds. Specifically, the minimum HC emission rate was attained at a cruise speed of 55 km/h while the highest emission rate occured at a cruise speed of 120 km/h. The variation in HC emission rate constituted a difference in the range of 300 percent over the 10 to 120-km/h cruise speed range. The minimum CO emission rate was achieved at a cruise speed of 20 km/h while the maximum rate was reached at a cruise speed of 120 km/h, with a variation in the range of 600 percent. Similarly, NO_X emission rates as a function of cruise speed demonstrated a trend that was consistent with CO emissions with a variation in the range of 350 percent.

Consequently, the findings show that an increase in a facility speed limit from 90 km/h (55 mph) to a speed limit of 106 km/h (65 mph) could result in minor increases in vehicle fuel consumption rates with major increases in vehicle emission rates. Specifically, the increase in vehicle fuel consumption rates is in the range of less than 1 percent with an increase in HC emission rates in the range of 50 percent and an increase in CO and NO_x emission rates in the range of 100 percent.

CHARACTERIZING TYPICAL VEHICLE ACCELERATION AND DECELERATION BEHAVIORS ALONG URBANIZED ARTERIAL SECTIONS

In order to quantify the impact of vehicle stops on fuel consumption and emission rates, a number of simplistic single-stop drive cycles were constructed over the same 4.5-km section. To make sure these hypothetical drive cycles were consistent with typical driving behavior, vehicle acceleration and deceleration behavior were characterized from field observations and then applied to the development of the drive cycles.

The acceleration/deceleration characterization utilized data that were collected along a signalized arterial corridor in Phoenix, AZ using GPS-equipped vehicles (Rakha *et al.* 2000b; Rakha *et al.* 2001). These vehicles were driven by different drivers along the study corridor for three days (Tuesday through Thursday) before and after changes were made to traffic signal timings along a major corridor during the AM peak (7am-8am), the off-peak (11am-1pm), and the PM peak (4pm-6pm). A total of 301 trips were recorded over the 9.6-km study section using a GPS unit to measure each vehicle's location, its heading, and its speed every second. The acceleration was computed as the first derivative of the second-by-second speed measurements. Due to some isolated errors in the speed measurements, the acceleration estimates resulted in occasional unrealistic observations, which exceeded the maximum feasible acceleration that a vehicle can attain at a specific speed (Samuels 1976). Consequently, a robust form of acceleration smoothing was applied to the acceleration estimates, which in turn removed any unrealistic speed estimates (Rakha *et al.* 2001). The details of the data smoothing are beyond the scope of this paper.

The distribution of speed and acceleration estimates for the entire 301 trips is summarized in Figure 3. As shown, the accelerations that were experienced by the majority of observations (56 percent) were located in the 0 m/s^2 acceleration bin, which represents an acceleration ranging from -0.25 m/s^2 to +0.25 m/s^2. Furthermore, the table demonstrates that feasible accelerations in the range of 1.5 m/s^2 and minimum decelerations in the range of -2.5 m/s^2 were observed. Given that the maximum vehicle acceleration rate decreases as a function of the vehicle's speed (assuming a constant vehicle power), typical acceleration rates can be best reported as a percentage of the maximum rate at a given speed. The data indicated that acceleration levels ranged from 0 to 60 percent of the maximum feasible acceleration levels. The deceleration levels were found to range between 0 and -3 m/s^2 with the majority of observations in the range from 0 to -

0.5 m/s^2. The mean acceleration rate was estimated to be 19 percent of the maximum feasible acceleration rate and the mean deceleration rate was computed to be -0.52 m/s^2. Consequently, in constructing the single-stop drive cycles, an acceleration rate of 20 percent of the maximum feasible acceleration rate and a deceleration rate of -0.5 m/s^2 were utilized.

The authors recognize that further analysis is required to characterize typical acceleration behavior; however, such a study is beyond the scope of this paper. Instead, this paper conducts a sensitivity analysis of the impact of vehicle stops on vehicle fuel consumption and emission rates considering different deceleration and acceleration rates.

IMPACT OF FULL STOPS ON VEHICLE FUEL CONSUMPTION AND EMISSIONS

In quantifying the impact of vehicle stops on fuel consumption and emission rates, a single-stop was introduced into the sequence of constant speed trips. An acceleration rate of 20 percent of the maximum feasible acceleration ($0.2a_{max}$) and a deceleration rate of -0.5 m/s^2 were utilized in constructing the base vehicle stop. The stop involved traveling at a constant cruise speed, followed by decelerating to a complete stop, and then accelerating back to the initial cruise speed. The trips, which covered the same 4.5-km section, did not involve any idling. Finally, it should be noted that a sensitivity analysis of different deceleration and acceleration rates was conducted.

The impact of vehicle stops on fuel consumption was found to be minor, as illustrated in Figure 4. Specifically, the variation in vehicle fuel consumption as a function of constant cruising speed is significantly larger than that associated with a stop. Notice that the acceleration rate utilized in this analysis is 20 percent of the maximum feasible acceleration rate. Further analyses discussed later investigated the impact of more aggressive driving behaviors on vehicle fuel consumption and emissions. Noteworthy is the fact that the introduction of a stop reduces the trip average speed, as demonstrated by the shorter single-stop line in Figure 4.

Figure 4 also illustrates that, while maintaining an identical average speed (x-axis), the HC emission rates were impacted significantly by the introduction of a vehicle stop (100 percent increase for an average speed of 80 km/h). However, it should be noted that the impact of a vehicle stop on HC emission rates falls within the range of variation in HC emissions for different constant cruise speeds (ranging from 0.10 to 0.25 g/km) as discussed earlier. Similarly, CO and NO_x emission rates exhibit comparable trends.

In summary, the introduction of a typical vehicle stop can increase a vehicle's emission rate by up to 100 percent when compared to a constant speed trip with an identical average speed. Alternatively, a vehicle's fuel consumption rate is marginally impacted by a typical vehicle stop (less than 10 percent increase).

IMPACT OF LEVEL OF ACCELERATION ON VEHICLE FUEL CONSUMPTION AND EMISSIONS

To quantify further the impact of vehicle stops on fuel consumption and emission rates, the analysis presented in this section systematically quantified the impact of different levels of driver acceleration aggressiveness on various MOEs. Specifically, the impact of different levels of acceleration on vehicle fuel consumption and emission rates was quantified. Again, the emission rates were computed per unit distance of travel over a constant distance of 4.5 kilometers.

While it is well documented that vehicle emissions are highly dependent on a vehicle's level of acceleration, especially at high speeds, this impact has not been systematically quantified for vehicle stops. The objective of this section was to systematically quantify the impact of a vehicle stop involving different levels of acceleration on vehicle fuel consumption and emissions. Specifically, five different levels of acceleration ranging from 20 to 100 percent of the maximum feasible acceleration rate were applied to the previously described single-stop drive cycles. This resulted in a total of 30 single-stop drive cycles (combination of 6 cruise speed levels and 5 acceleration levels). Again, as was the case in the previous scenarios, the VT-Micro models were applied to each cycle to compute the vehicle's fuel consumption and emission rates per unit distance. It should be noted that a linear decay in the maximum acceleration rate as a function of the vehicle speed provided a reasonable approximation for vehicle behavior. The linear-decreasing acceleration model was presented by Samuels (1976) and Lee *et al.* (1977). Even though Akcelik and Biggs (1987) indicated that a polynomial model was more consistent with field data, a linear-decreasing model provides a reasonable approximation for purposes of this analysis.

For illustrative purposes, the impact of different levels of acceleration on vehicle fuel consumption and emissions was initially analyzed for a single cruise speed. Subsequently, the interaction of different acceleration rates and cruise speeds was analyzed.

Impact of Level of Acceleration on Vehicle Fuel Consumption and Emission Rates for a Sample Cruise Speed

The five acceleration levels described earlier were initially applied to a single-stop drive cycle that involved decelerating from a cruise speed of 80 km/h to a full stop at a constant deceleration of -0.5 m/s^2, followed by a subsequent acceleration to the 80 km/h cruise speed without idling. As illustrated in Figure 5, the impact of level of acceleration on the vehicle fuel consumption rate was found to be minor. Specifically, the figure illustrates a minor increase in fuel consumption as the level of acceleration increases (increase from 0.0941 l/km to 0.0985 l/km for an increase in the acceleration rate from 20 to 100 percent of the maximum feasible rate). Alternatively, the HC and CO emission rates are shown to be highly sensitive to the level of acceleration. Specifically, the HC emission rate increased from 0.1 g/km at an acceleration level of 20 percent the maximum feasible acceleration rate to 0.45 g/km at the maximum feasible acceleration rate (i.e. an increase of 450 percent). The high HC and CO emission rates associated with high levels of acceleration most probably result when the rich fuel to air ratio emissions, which are required in order to prevent engine knocking, bypass the catalytic converter.

The NO_x emission rates, on the other hand, demonstrated a different trend when compared to HC and CO emission rates. Specifically, the impact of the acceleration levels on NO_x emission rates was minor when compared to the impact of cruise speed. Furthermore, the trend indicated a slight increase in NO_x emission rates as the vehicle acceleration increased from 20 to 80 percent of the maximum feasible acceleration rate (increase from 0.24 g/km to 0.30 g/km), and indicated a subsequent decrease as the acceleration level exceeded a rate of 80 percent of the maximum feasible acceleration rate. This decrease in NO_x emissions is consistent with what has been reported in the literature, namely that NO_x emissions are highest at stoichiometric engine conditions, as opposed to high engine loads.

Combined Impact of Level of Acceleration and Cruise Speed on Vehicle Fuel Consumption and Emissions

Depending on the aggressiveness of a driver, the impact of vehicle stops on vehicle fuel consumption and emission rates may vary. The objective of this section was to compare the impact of the level of acceleration that is associated with a vehicle stop at lower speeds with that at higher speeds. In conducting this analysis, the five acceleration levels considered earlier were applied to the various full-stop scenarios that were described in the previous section. Notice that a constant deceleration rate of -0.5 m/s^2 was utilized in all scenarios for the purpose of this analysis.

The analysis demonstrated the non-linear behavior of vehicle fuel consumption rates. In general, as the level of acceleration increased, the vehicle fuel consumption rate increased. This finding showed that the additional fuel consumption associated with a stop more than offset the reduction in time spent in acceleration mode at higher levels of acceleration. The HC and CO emission rates demonstrated similar trends that involved an increase in vehicle emission rates as the level of acceleration increased. Furthermore, as illustrated in Figure 6, HC emission rates were more sensitive to acceleration levels than to average speeds within the speed range of 20 to 90 km/h. NO_x emissions displayed a highly non-linear nature with the emission rates, typically increasing at acceleration rates in the range of 0.2 to $0.8a_{max}$ and decreasing at acceleration rates in excess of $0.8a_{max}$.

When a vehicle stop is introduced to a trip and as a vehicle's cruise speed increases, the vehicle's fuel consumption and emission rates may increase or, in some instances, decrease depending on the aggressiveness of the driver, as demonstrated in Figure 7. In the case of HC emission rates, Figure 8 demonstrates a convex relationship between the emission rate and the approach cruise speed in a cruise mode, an acceleration mode, and a deceleration mode. It should be noted that fuel consumption and emission rates in these three modes (deceleration, acceleration, cruise modes) were normalized by distance using the total fuel consumption and emissions in each mode divided by the distance traveled in that mode. The CO and NO_x emission rates demonstrated similar trends as those presented for HC emissions. Consequently, the impact of a stop on vehicle fuel consumption and emission rates was determined by the combined effect of the acceleration level, cruise speed, and deceleration level. For example, an introduction of a vehicle stop that involved a deceleration rate of -0.5 m/s^2 and an acceleration rate of $0.2a_{max}$ for a cruising speed of 80 km/h, resulted in an increase in the HC emission rate when compared to the base constant cruise speed scenario. This is illustrated in Figure

9, which represents average rates per unit distance for each mode of travel. This increase was caused by the fact that the area under the constant speed scenario was less than the area under the single-stop scenario. Alternatively, for the same stop using a cruise speed of 120 km/h instead of 80 km/h, the HC emissions decreased compared to the base constant speed scenario (cruise speed of 120 km/h). The reduction in the HC emissions was caused by the lower emission rate associated with both the deceleration and acceleration modes, as illustrated in Figure 8.

Emission rates for HC, CO, and NO_x do decrease occasionally by introducing vehicle stops into relatively high constant speed trips (speed of 120 km/h). These reductions in emission rates can occur if the vehicle stop involves a mild acceleration when the acceleration emission rate is less than the cruising emission rate, as illustrated in Figure 4. Consequently, at high speeds the introduction of vehicle stops involving extremely mild acceleration levels can actually reduce vehicle emission rates.

IMPACT OF LEVEL OF DECELERATION OR VEHICLE FUEL CONSUMPTION AND EMISSIONS

The next step in quantifying the impact of vehicle stops on fuel consumption and emissions was to isolate the impact of vehicle deceleration levels on these MOEs. In conducting this analysis, six levels of constant deceleration rates were considered, ranging from -0.25 m/s^2 to -1.50 m/s^2 at increments of -0.25 m/s^2. The deceleration range considered is consistent with field observations presented earlier in this paper. It should be noted that a constant acceleration level of 20 percent of the maximum feasible acceleration rate was applied to each trip in this analysis. Fuel consumption and emission rates were computed per unit distance of travel by dividing total MOE estimates by the trip distance of 4.5 kilometers.

Initially, various deceleration rates were applied to a single cruise speed in order to quantify the impact of vehicle deceleration on various MOEs, Subsequently, different levels of cruise speeds were considered in order to capture the combined impact of deceleration and cruise speed on vehicle fuel consumption and emission rates.

Impact of Level of Deceleration on Vehicle Fuel Consumption and Emission Rates for a Sample Cruise Speed

Different levels of deceleration were applied to a single-stop drive cycle that involved decelerating from a cruise speed of 80 km/h to a full stop, followed by a subsequent acceleration to the 80 km/h cruise speed at $0.2a_{max}$. The variation in fuel consumption and emissions as a function of the deceleration level demonstrated that the vehicle fuel consumption and emissions were generally insensitive to the level of deceleration, as illustrated in Figure 10.

Combined Impact of Level of Deceleration and Cruise Speed on Vehicle Fuel Consumption and Emissions

In order to quantify the combined effect of vehicle deceleration and cruise speed on vehicle fuel consumption and emission rates, a total of 36 single-stop drive cycles involving 6 cruise speeds and 6 levels of deceleration were constructed.

The analysis indicated that the vehicle fuel consumption rate per unit distance was insensitive to the level of deceleration. Similarly, the impact of level of deceleration on HC emissions was found to be relatively small (within 40 percent) when compared with the impact of the level of acceleration or cruise speed (in excess of 100 percent). Specifically, the HC emission rate was less sensitive to the level of deceleration associated with lower cruise speeds than with higher cruise speeds. Similar finding were observed from the analysis of CO and NO_x emission rates. The analysis in this section also verified the pervious finding that at high speeds the introduction of vehicle stops involving extremely mild acceleration levels can actually reduce vehicle emission rates.

CONCLUSIONS OF STUDY

This study attempted to quantify the impact of vehicle stops on fuel consumption and emission rates using the VT-Micro models. The conclusions of this study are clearly dependent on the accuracy of the emission models utilized. Consequently, it is recommended that further research be conducted to validate the findings of this study using field data.

The study indicated that vehicle fuel consumption and emission rates increased considerably as a vehicle stop was introduced, especially at high cruising speeds. However, vehicle fuel consumption was more sensitive to constant cruise speed levels than it was to vehicle stops. Alternatively, the aggressiveness of a vehicle stop did have a significant impact on vehicle emission rates. Specifically, HC and CO emission rates were highly sensitive to the level of acceleration when compared to cruise speed in the range of 10 to 120 km/h. Alternatively, NO_x emissions typically increased at acceleration rates in the range of 0.2 to $0.8a_{max}$ and decreased at acceleration rates in excess of $0.8a_{max}$. The impact of the deceleration level on all MOEs was relatively small compared with the other factors considered in the study. Furthermore, the combined effect of the level of acceleration, the level of deceleration, and the cruise speed determined the direction that vehicle fuel consumption and emission rates could change. Contrary to traditional understanding, this study demonstrated that at high speeds the introduction of vehicle stops involving extremely mild acceleration levels could actually reduce vehicle emission rates per unit distance.

The study also demonstrated that an increase in a facility speed limit could have extremely negative environmental consequences. Specifically, an increase in the speed limit from 90 km/h (55 mph) to 106 km/h (65 mph) may result in a 60 percent increase in HC emissions, an 80 percent increase in CO emissions, and a 40 percent increase in NO_x emissions.

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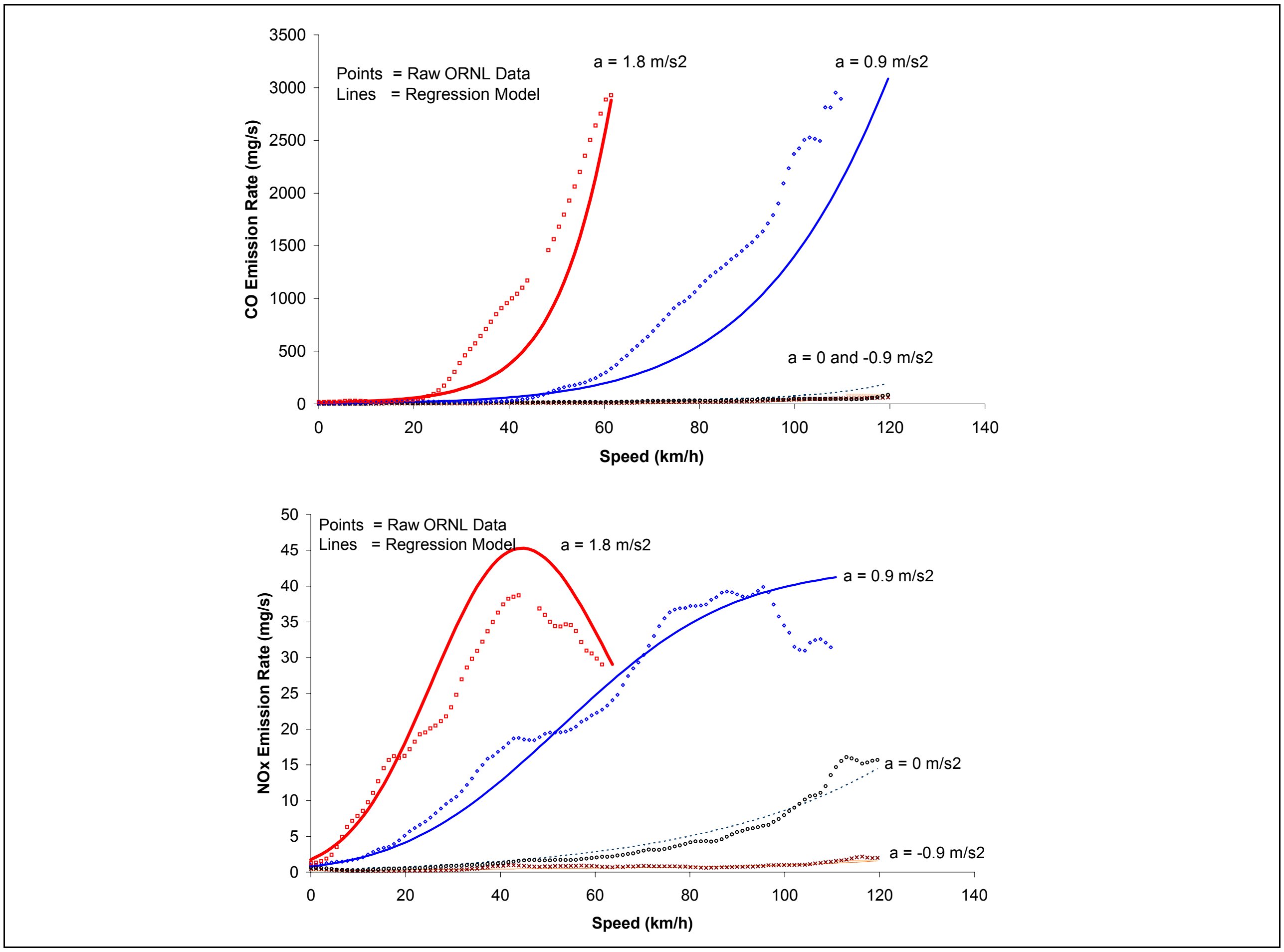

Figure 1. Variations of Emissions as a Function of Vehicle's Speed and Acceleration (Ahn *et al.* 1999; Rakha *et al.* 2000)

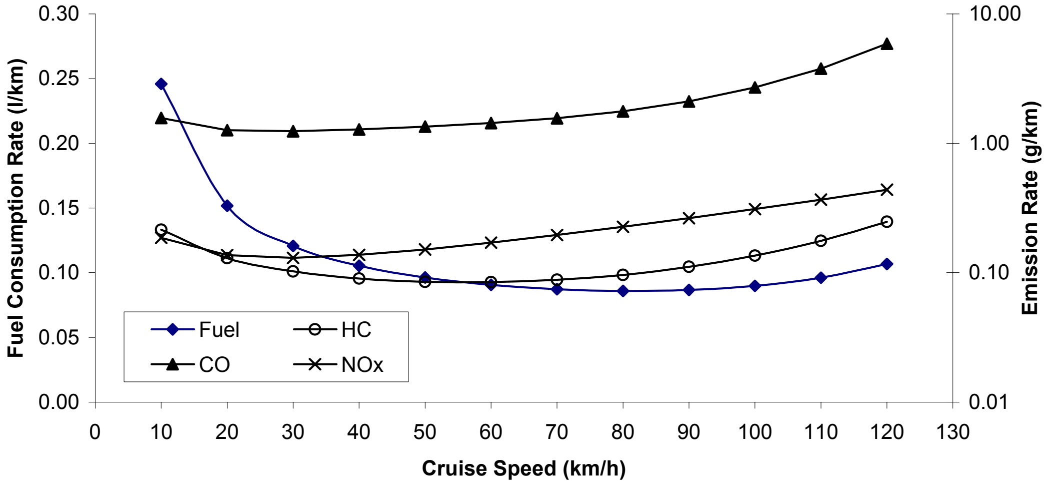

Figure 2. Variation in Vehicle Fuel Consumption and Emission Rates as a Function of Cruise Speed

		Speed (km/h)											**Total**
		10	20	30	40	50	60	70	80	90	100	110	
Acceleration (m/s^2)	-3.0												
	-2.5	0.03	0.11	0.16	0.19	0.15	0.11	0.04	0.00				0.80
	-2.0	0.05	0.14	0.22	0.24	0.20	0.12	0.04	0.01				1.02
	-1.5	0.19	0.44	0.51	0.52	0.49	0.34	0.12	0.02				2.65
	-1.0	0.74	0.55	0.52	0.55	0.73	0.81	0.47	0.09	0.00			4.49
	-0.5	1.93	0.52	0.44	0.62	1.24	2.94	4.17	1.16	0.05			13.07
	0.0	16.23	0.46	0.52	0.96	2.30	8.59	20.92	5.92	0.15	0.00		56.05
	0.5	1.53	0.21	0.37	0.88	1.81	3.54	3.39	0.64	0.01			12.40
	1.0	0.34	0.19	0.50	1.12	1.51	1.09	0.41					5.16
	1.5	1.23	1.40	1.13									3.77
	2.0												
Total		22.28	4.03	4.38	5.09	8.44	17.55	29.57	7.85	0.22	0.01		100.00

Figure 3. Speed/Acceleration Distribution for GPS Arterial Data

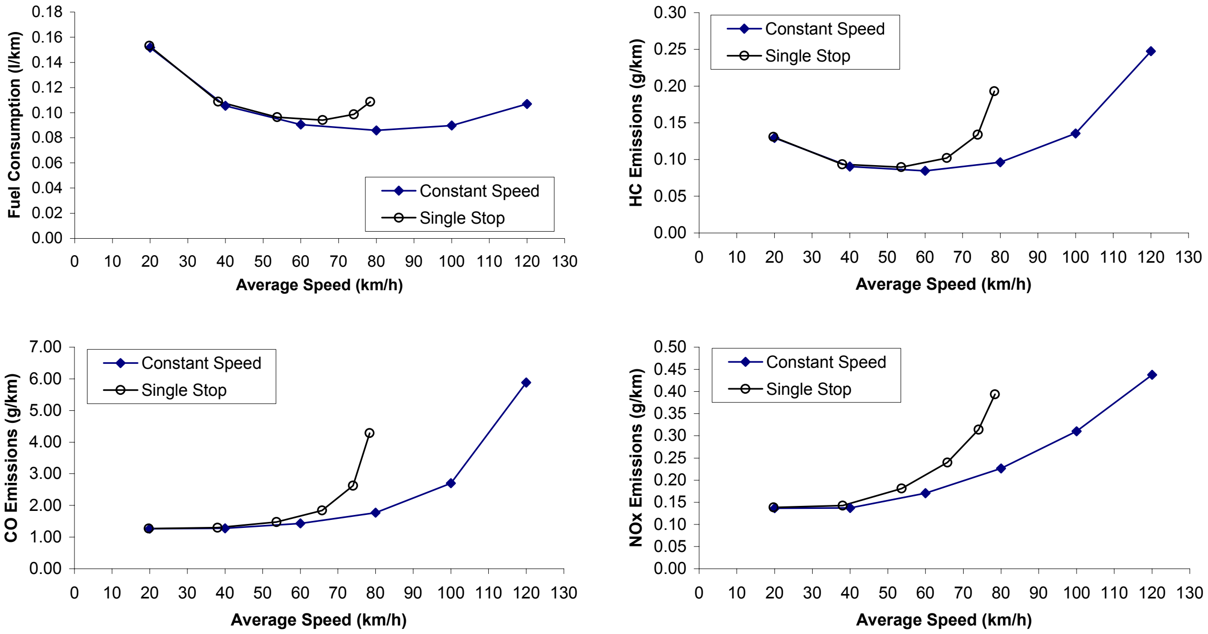

Figure 4. Impact of Single Vehicle Stop on Fuel Consumption and HC Emission Rate as a Function of Average Speed

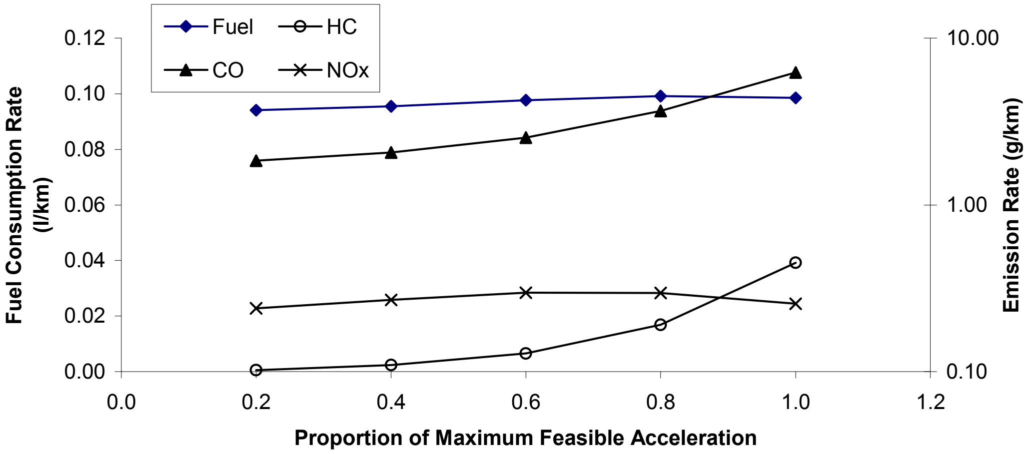

Figure 5. Variation in Fuel Consumption and Emission Rate as a Function of Acceleration Level (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Deceleration Rate = -0.5 m/s^2)

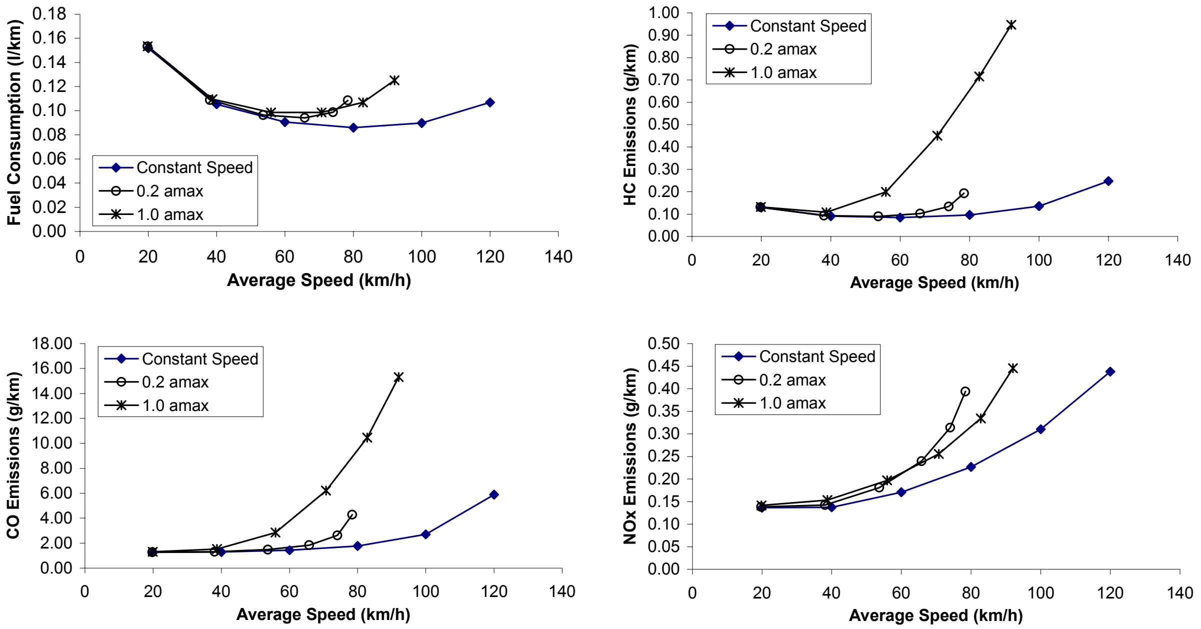

Figure 6. Impact of Level of Acceleration in HC Emission Rate as a Function of Average Speed (Distance = 4.5 km, Deceleration Rate for Single-Stop Cycles = -0.5 m/s²)

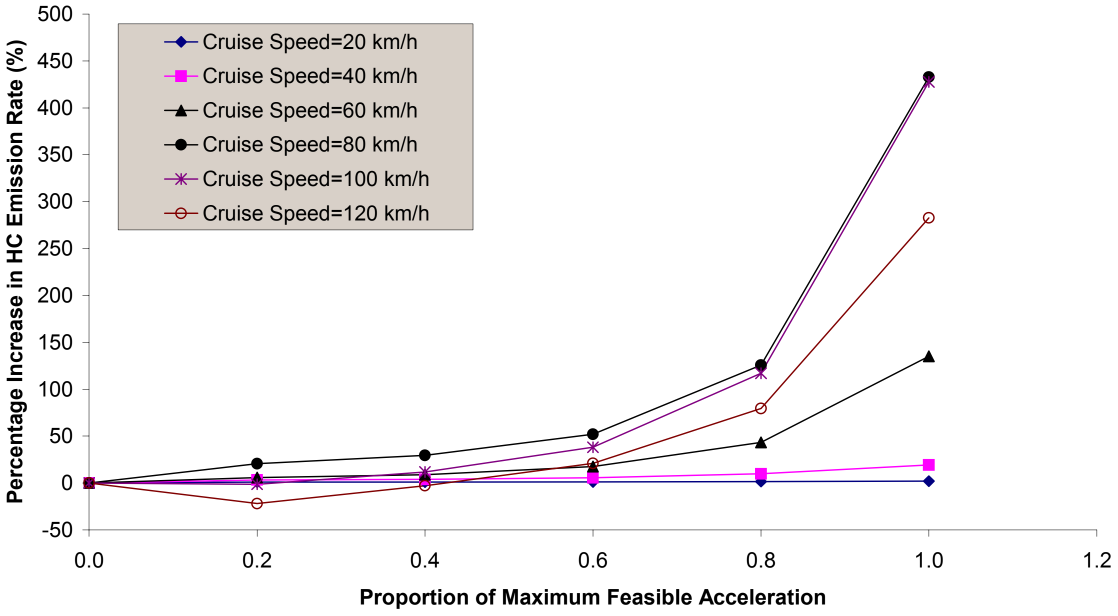

Figure 7. Percentage Increase in HC Emission Rate as a Function of Level of Acceleration (Distance = 4.5 km, Deceleration Rate = -0.5 m/s²)

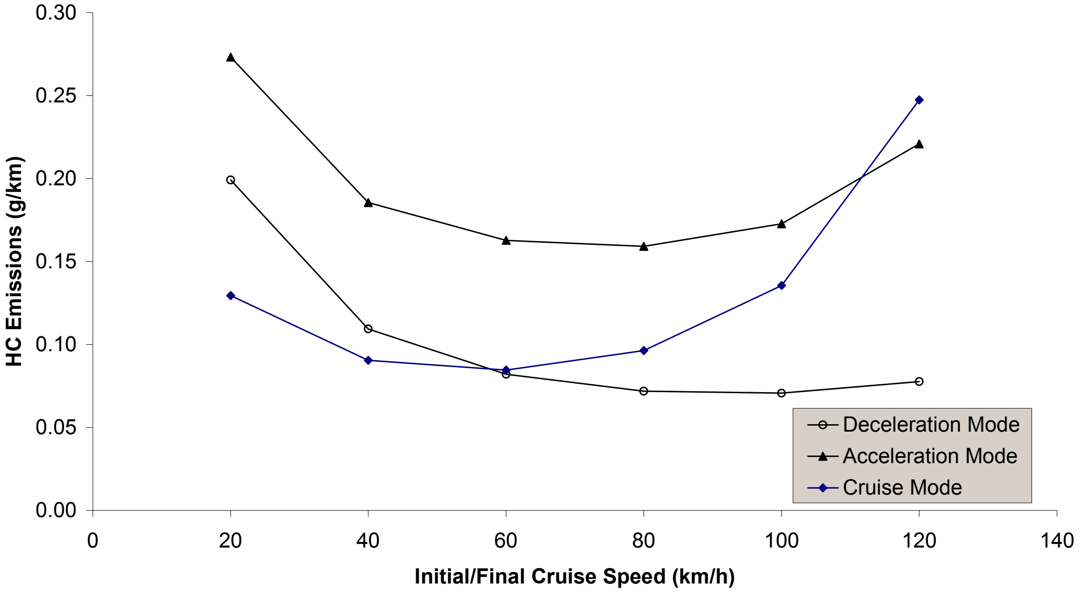

Figure 8. HC Emission Rate in Different Operation Modes (Distance = 4.5 km, Deceleration Rate = -0.5 m/s^2, Acceleration Rate = 0.2a$_{max}$)

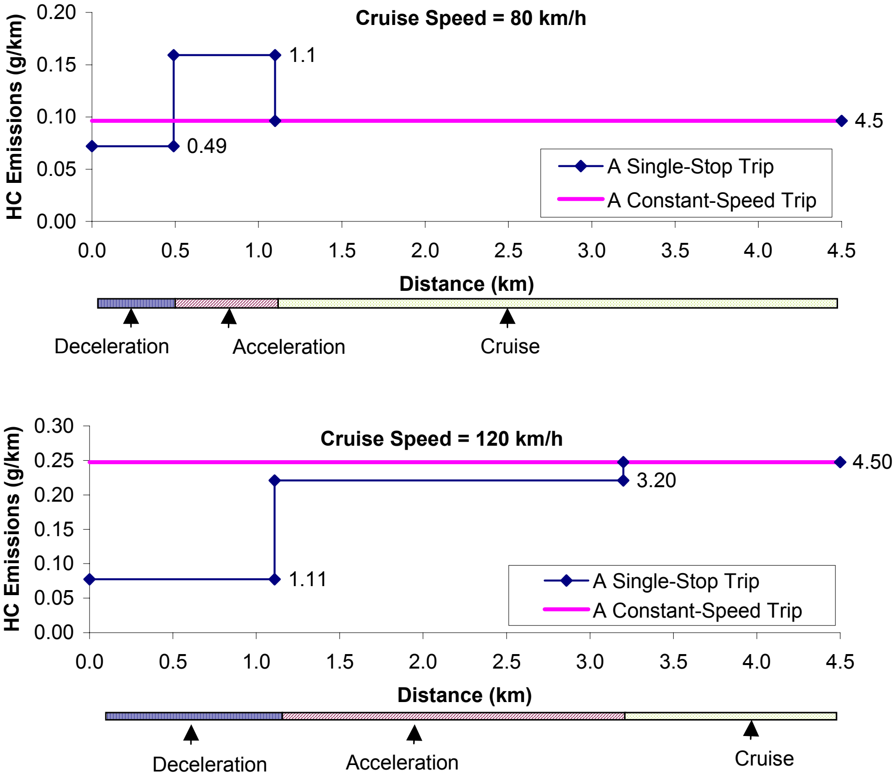

Figure 9. HC Emission Rate in Different Operation Modes (Distance = 4.5 km, Deceleration Rate = -0.5 m/s^2, Acceleration Rate = 0.2a$_{max}$)

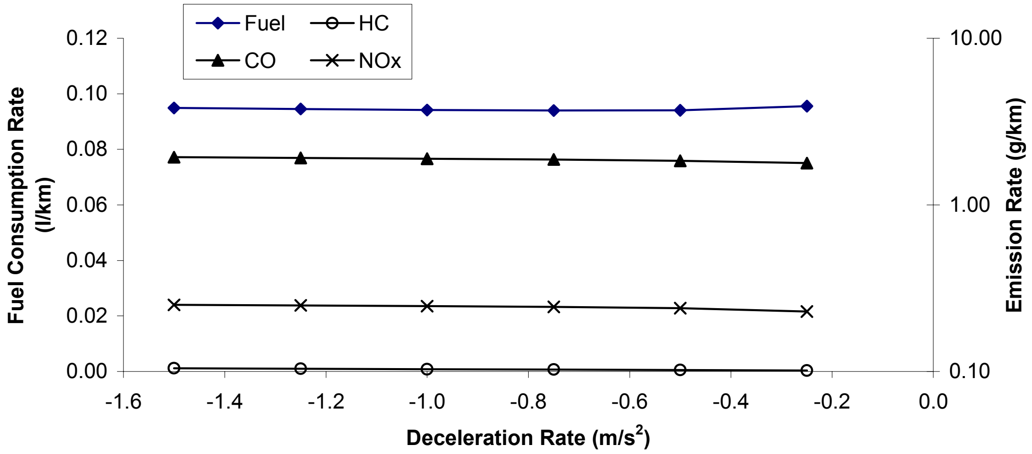

Figure 10. Variations in Fuel Consumption and Emission Rates as a Function of Deceleration Level (Cruise Speed = 80 km/h, Travel Distance = 4.5 km, Acceleration Rate = 0.2a_{max})