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This research investigated the relationships between traffic operating characteristics and environmental factors such as fuel consumption, hydrocarbon emissions, carbon monoxide emissions, and nitrogen oxide emissions. A methodology was developed to analyze existing before and after data from traffic improvement projects that have been implemented. The change in fuel consumption was quantified and guidelines were developed to help predict energy benefits from implementing future freeway bottleneck improvements. The total reduction in fuel usage ranged from 0.0% to 5.2% for the examples studied, with an average of 2.2%.

However, the attempt to quantify the air quality benefits was less successful and further research, now underway on a national level, will be required. Current methodology is based on an average speed, and this fails to account for the stop and go nature of driving within congestion upstream of a bottleneck. Under such conditions it has been demonstrated that greater emissions occur, but this has not yet been reliably quantified.

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Energy and Air Quality Benefits of Freeway Bottleneck Improvements

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SWUTC/96/60039-1

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The Southwest Region University Transportation Center

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Abstract

Freeway bottlenecks cause deterioration in freeway operation. These overcapacity sections of freeway are responsible for increased fuel consumption, increased emissions, and increased delay to motorists. The Texas Department of Transportation has funded and implemented many freeway bottleneck improvement projects around the state to reduce these problems. These projects provide significant benefits in terms of increasing speeds and reducing delays; however, little information exists on quantifying energy and air quality benefits from implementation of bottleneck removal projects.

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However, the attempt to quantify the air quality benefits was less successful and further research, now underway on a national level, will be required. Current methodology is based on an average speed, and this fails to account for the stop and go nature of driving within congestion upstream of a bottleneck. Under such conditions it has been demonstrated that greater emissions occur, but more research is needed to reliably quantify the changes.

Executive Summary

Freeway bottlenecks cause deterioration in freeway operation. These overcapacity sections of freeway are responsible for increased fuel consumption, increased emissions, and increased delay to motorists. The Texas Department of Transportation has funded and implemented many freeway bottleneck improvement projects around the state to reduce these problems. These projects provide significant benefits in terms of increasing speeds and reducing delays; however, little information exists on quantifying energy and air quality benefits from implementation of bottleneck removal projects.

The existing methodology using average speeds and emission rates generated by the EPA's MOBILE5a model is not suitable for the level of analysis necessary to compare the before and after conditions of freeway bottleneck improvements. In the meantime, until future models are available, detailed speed or travel time data should be collected with vehicles equipped with distance measuring instruments (DMI) which can collect instantaneous speed and distance data. With new models suitable for using the detailed speed data the reductions in fuel consumption and emissions should be able to be estimated. The reduction in fuel consumption with bottleneck removals should be at least the same or higher than the average speed method, up to 42%, depending upon the level of traffic flow improvements obtained with the bottleneck removal. One methodology used to study the emissions benefit of automated toll collection showed a reduction for volatile organic compounds (VOC) of 84%, a reduction for carbon monoxide (CO) of 72%, and a reduction of nitrogen oxides (NO_X) of 46% for the elimination of a full stop at a toll booth. Whether these findings are applicable to future analysis is unclear; the actual reductions in fuel consumption and emissions may be even higher. However, significant reductions in fuel consumption and emissions with traffic smoothing due to bottleneck removals are indeed possible. Additional research will help identify the magnitude of these reductions.

Acknowledgments

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Tables of Contents

List of Figures Page

List of Tables

Introduction

Bottlenecks on urban freeways cause deterioration in freeway operation and air quality. These overcapacity sections of freeways create congestion and stop-and-go traffic, which increases fuel consumption, emissions and delays to motorists. The Texas Department of Transportation (TxDOT) has funded and implemented many freeway bottleneck improvement projects to reduce these problems. These projects provide significant benefits in terms of increasing speeds and reducing delays; however, little information exists on quantifying energy and air quality benefits from implementation of bottleneck removal projects. If the congestion is reduced and if the stop-and-go traffic is eliminated, vehicles will be able to operate at a more uniform speed closer to free-flow operation. This, in turn, should reduce fuel consumption and vehicle emissions such as volatile organic compounds (VOC) or hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x). The primary goal of this study is to determine a method to estimate the anticipated decrease in fuel consumption and emissions for any freeway bottleneck removal project. It is essential that transportation agencies in nonattainment areas are able to estimate the energy and air quality benefits from reduced congestion in order to qualify for Congestion Mitigation and Air Quality funds and to meet air quality goals.

Freeway bottlenecks result from some element of the facility having higher demand than capacity. What differentiates these sections from overcapacity freeway corridors is that often a low cost improvement over a short section of the freeway, such as restriping a merge or converting a shoulder to add an additional lane, can significantly relieve congestion. TTI has studied several bottleneck improvement projects implemented by TxDOT. Volume and travel time data exists at these study locations prior to and after project implementation.

This before and after volume and travel time data has been reduced to determine the travel time savings realized by the motorists, which is the primary benefit from freeway bottleneck improvement projects. It was assumed that this before and after volume and travel time data would also be suitable to estimate the secondary benefits of reduced energy consumption and vehicle emissions.

Literature Review

The first objective of this study was to assemble a comprehensive summary of studies that relate levels of fuel consumption and emissions to vehicle parameters such as travel time, speed, and vehicle classification. Information on variables such as cold starts, hot soaks, idle time, acceleration time, deceleration time, temperature, and humidity was also investigated. It was hoped that information from the literature review would reveal several methods of analyzing fuel consumption and vehicle emissions, as well as studies that have compared the various manual methods and computer models.

The literature review did not reveal a specific method for estimating the fuel consumption or emissions reductions from bottleneck improvements. Several planning level methods for estimating the air quality benefits of the Congestion Mitigation and Air Quality (CMAQ) Improvement Program project proposals have been developed to allow different types of projects to be judged on an equal basis. However, no specific method for quantitative analysis of the air quality improvements of CMAQ project proposals exists, although the Federal Highway Administration (FHWA) requires that all CMAQ project proposals should be analyzed for air quality benefits (1).

The primary computer models for estimating mobile source emissions are the MOBILE model from the Environmental Protection Agency (EPA) and EMFAC from the California Air Resources Board (CARB). Both these models relate the vehicle distance of travel (VDT) and average speed to an emission rate, which are derived from specific driving cycles that can be duplicated on dynamometers. Most other models are based on the outputs from the MOBILE and EMFAC models (2).

One methodology suitable for using the MOBILE emission rates and the existing bottleneck data is the average speed method, though this method is generally more suited to larger area wide or regional planning level analysis; the form of the existing data would not allow for a more detailed analysis. This method uses a fuel consumption rate or an emission rate, for a specific average speed, multiplied by vehicle miles of travel to give the total fuel consumption or emissions. The existing before and after data consisted of travel times and volume counts for several bottleneck sites. Since MOBILE does not output fuel consumption rates, these were obtained from a report discussing FREQ10 (3). This report presents the consumption rates for a 1990 California vehicle mix for three vehicle classes (autos, medium trucks, and heavy trucks) used in the FREQ10 model. Emissions rates were obtained from the North Central Texas Council of Governments (NCTCOG). NCTCOG provided a MOBILE5a base year run for 1993 for Dallas and Tarrant County freeways which presents the basic emissions rate for nine vehicle types and an all-vehicle composite at a specific speed for a typical summer day. It was felt that both the fuel consumption rates and emission rates would be suitable for estimating the relative changes in air quality and fuel consumption expected from bottleneck improvements. However, the results of this methodology, which are discussed below, were not satisfactory. Additional literature was reviewed to try and find a better methodology for estimating fuel consumption and emissions.

Most transportation officials agree that VOC and CO emissions from mobile sources are significantly underestimated by existing mobile source models (4). Two possible reasons why the existing models underestimate emissions are miscalculating the impact of cold starts to not fully representing high-emitters in the study fleet. A vehicle's emissions system does not work efficiently until it is fully warmed up, hence the term "cold start." This warm up period is a major source of emissions for most trips. High emitters are vehicles that do not possess a proper emission control system due to damage from mechanical failure or tampering. This mechanical failure or tampering may also result in higher fuel consumption. However for the purposes of this study the effect of cold starts and the percentage of high-emitters in the traffic stream were ignored since both factors can be assumed to be constant for before and after conditions on freeway corridors.

Another significant source of an emissions underestimation is that the test procedures to develop the emissions rates do not fully represent actual driving conditions. The federal test procedure (FTP) driving cycle used to develop the MOBILE models specifically does not include high speeds or sharp accelerations (4). When most vehicles accelerate, their engines operate in an enriched state that is a state higher than stoichiometric fuel/air ratios. Recent research has shown that enrichment events result in much higher emissions compared to stoichiometric conditions (5). The off-cycle driving patterns not included in the FTP often result in enrichment conditions. Enrichment events have been shown for one specific vehicle to increase CO emissions by about 2,500 times and HC emissions by 40 times over the stoichiometric emission rates (5). Research to improve mobile source emission models is being done at the Georgia Institute of Technology and the University of California Riverside (6,7). Additionally the Pike Pass electronic toll collection system used in Oklahoma showed reduced emissions for vehicles bypassing a toll-gate stop (8). This will be discussed further below.

Additional literature concerning fuel consumption models was also reviewed. A large amount of research on vehicular fuel consumption was performed in the mid 1970's to early 1980's and several well-validated models were found (9). However, all these models were calibrated for specific locations and vehicle fleets and would be inappropriate for existing conditions. The additional literature review also revealed the fuel consumption model ARFCOM (ARRB Road Fuel Consumption Model) from the Australian Road Research Board which can be used on a personal computer (10). The ARFCOM model is a detailed power model. It estimates the power needed by a vehicle to overcome the forces acting at its wheels given vehicle speed and road geometry. All the power components are summed, and a fuel-to-power efficiency factor is used to calculate fuel consumption. The model can be used with several input data levels from instantaneous speed traces to average speed or running speed over a section of roadway. ARFCOM requires several vehicle parameters and road geometry data as inputs, though default values are supplied for most parameters. The model has been validated with instantaneous speed data and known parameters to estimate fuel consumption to within 5% of measured values. Using only the minimum required vehicle parameters, errors are within 15% of measured values (11). The ARFCOM model was used to develop fuel consumption rates for the average speed methodology as well as fuel estimates using instantaneous speed data obtained from Houston.

Description of Study Sites

Three bottleneck improvement projects implemented by the Dallas District of TxDOT were selected to be studied for changes in emissions and fuel consumption. Each project had good before and after volume and travel time data. The first project selected was implemented on Stemmons Freeway-IH35E, between the Loop 12/IH35E interchange and the LBJ-IH635/IH35E interchange. Figure 1 shows the northbound lanes of IH35E with peak hour volumes, and Figure 2 shows the southbound lanes of IH35E with peak hour volumes. The primary improvement consisted of a fifth lane being created on the inside shoulders of both the northbound and southbound main lanes of IH35E between the interchanges. Other improvements consisted of restriping the southbound lanes of IH35E north of the IH635 interchange to allow three through lanes, as well as eliminating the inside merges in both interchanges. The travel time analysis of this bottleneck improvement showed a benefit to cost ratio of 36 to 1.

The second bottleneck improvement project selected was located at the IH20 and Spur 408 interchange. Figure 3 shows the eastbound IH20 connection to the northbound lanes of Spur 408, and Figure 4 shows the southbound Spur 408 connection to the westbound lanes of IH20. The one lane ramp from southbound Spur 408 to westbound IH20 was restriped to provide a two-lane ramp with a longer merge onto IH20, and the outside lane of westbound IH20 was striped out to provide an entrance-only lane for the new two-lane ramp. The exit lane from eastbound IH20 was widened to two lanes to provide a climbing lane prior to the bridge structure over IH20. These improvements resulted in travel time benefits for the eastbound to northbound movement in the morning peak period and the southbound to westbound movement for the evening peak period. The travel time analysis of this bottleneck improvement showed a benefit to cost ratio considering delay savings of 5.2 to 1.

The third project analyzed was implemented at the US75 and IH635 interchange. Figure 5 shows the eastbound lanes of IH635, and Figure 6 shows the westbound lanes of IH635. The inside shoulder of eastbound IH635 was converted into a main lane between the US75 southbound exit and the US75 northbound exit, and the US75 northbound exit was converted into a two-lane exit ramp. The entrance ramp from US75 to westbound IH635 was converted from one lane into two lanes and the inside shoulder of IH635 downstream of the entrance was converted to a travel lane to allow both lanes from the entrance ramp to continue. The fifth main lane ends as an exit only ramp to Preston Road. The travel time analysis for this project showed a benefit to cost ratio of 25 to 1.

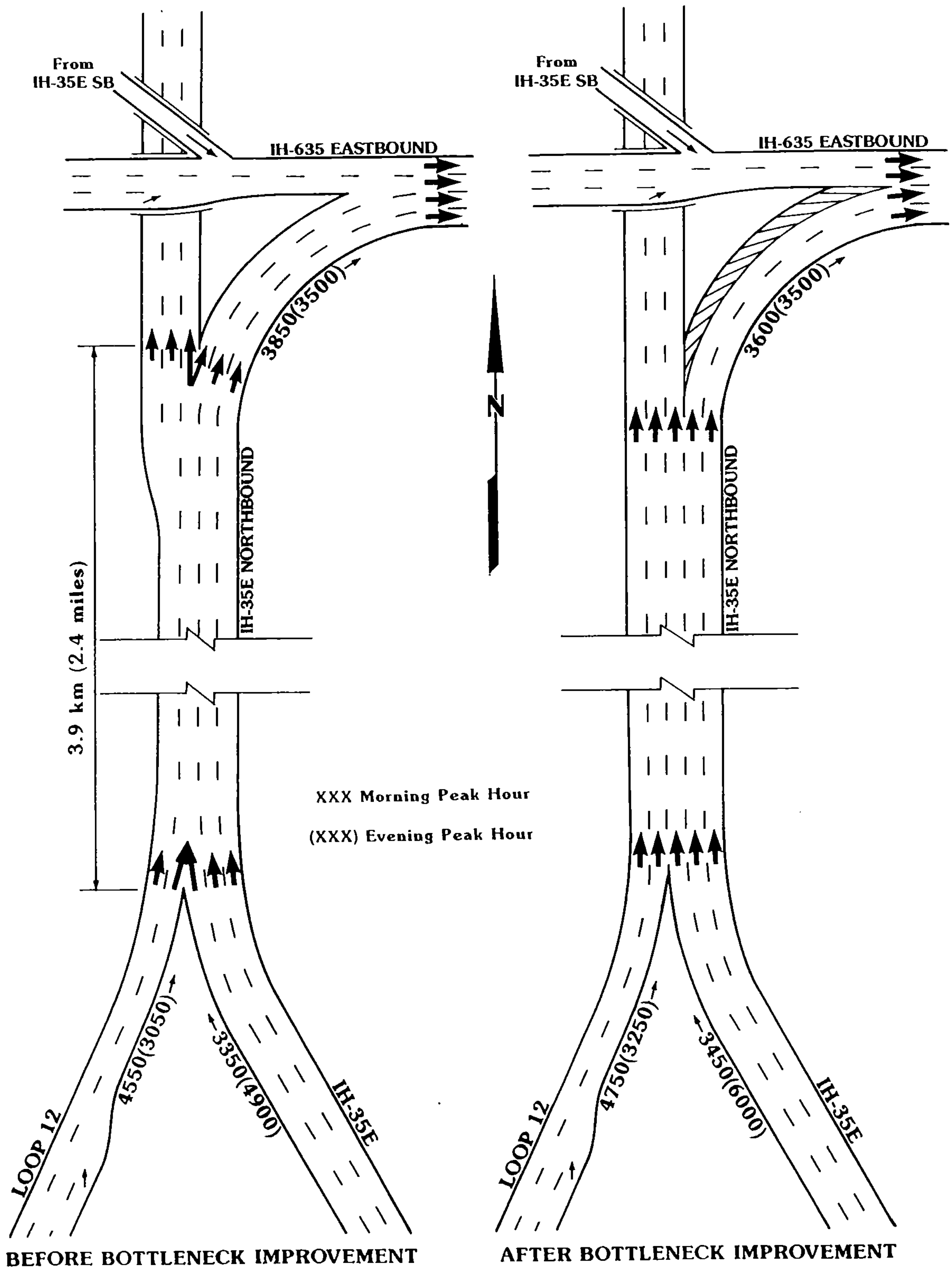


Figure 1. IH35E Northbound Bottleneck Improvement

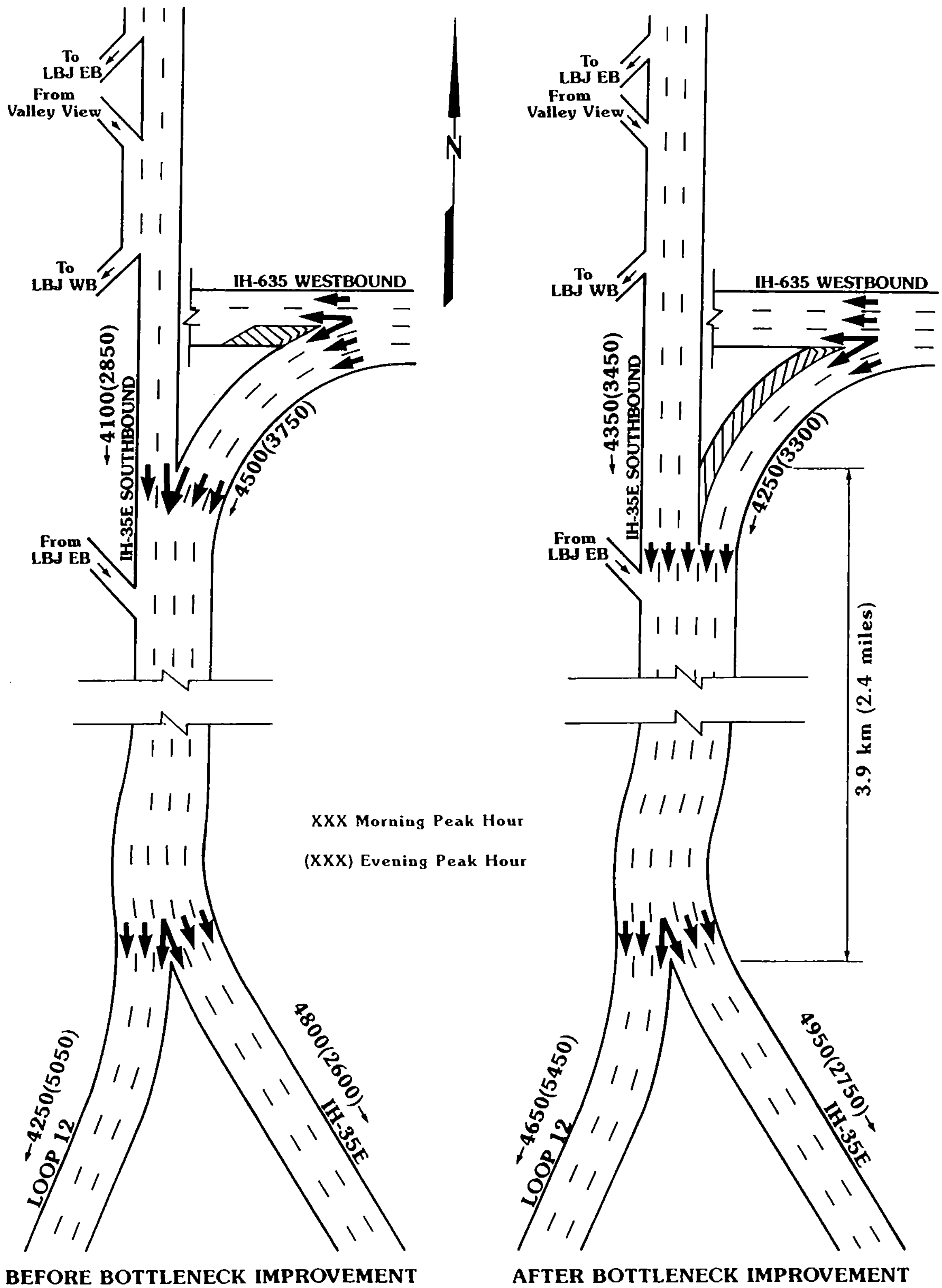
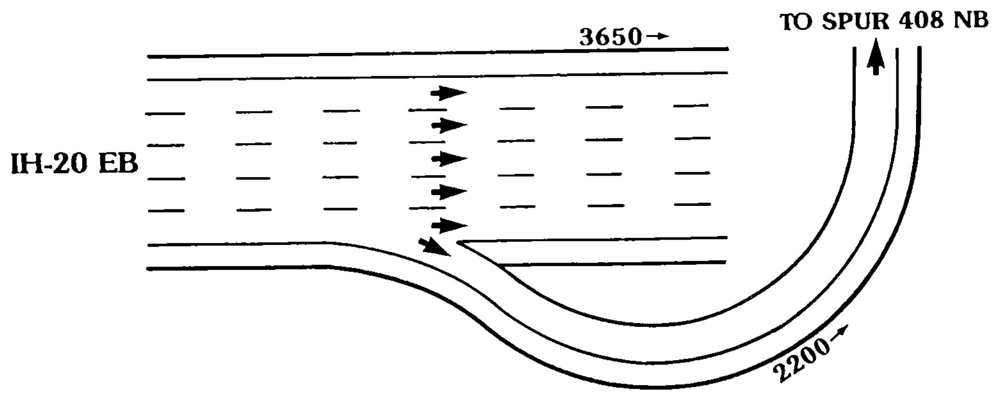


Figure 2. IH35E Southbound Bottleneck Improvement



BEFORE BOTTLENECK IMPROVEMENT

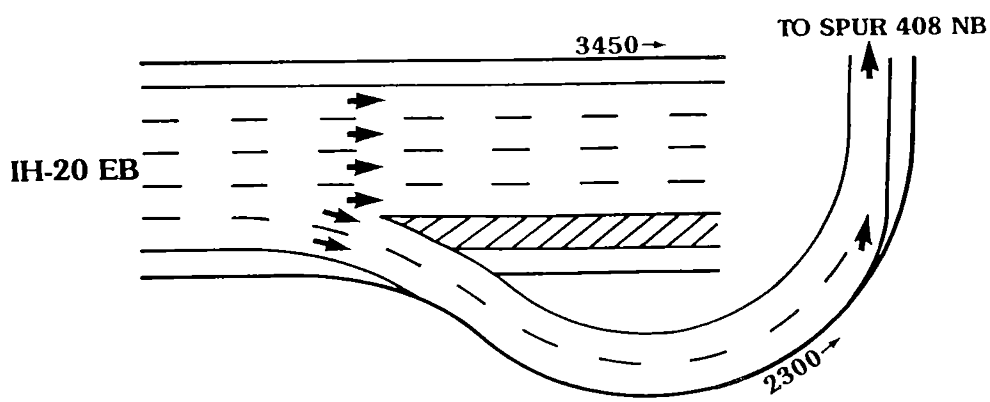


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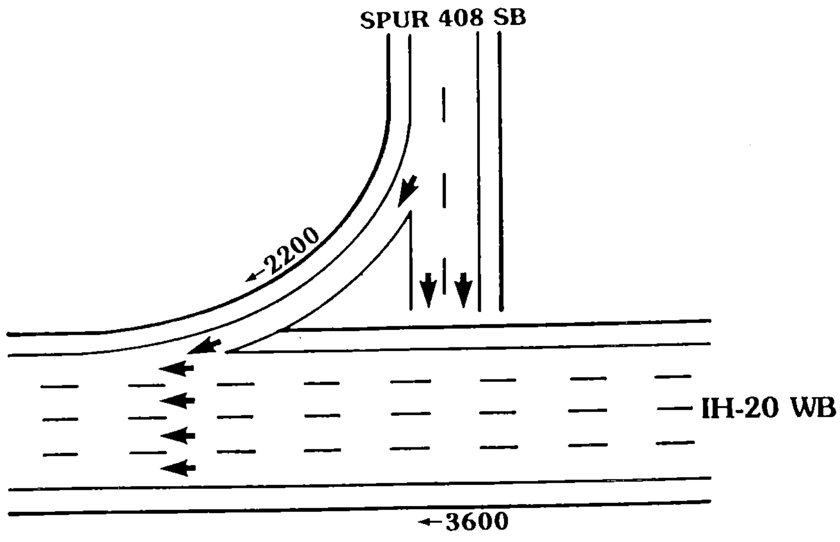
Figure 3. IH20 Eastbound to Spur 408 Northbound Morning Peak Hour Bottleneck Improvement



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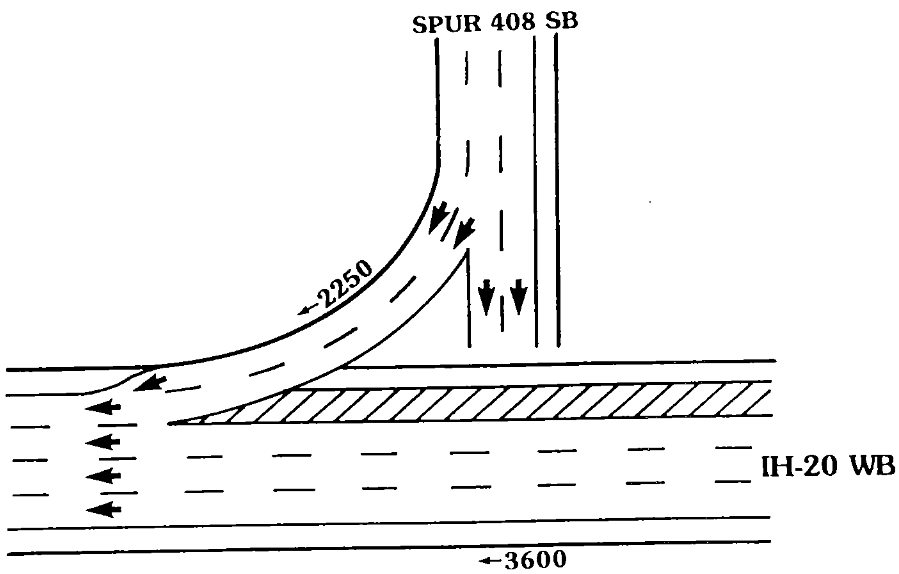


AFTER BOTTLENECK IMPROVEMENT

Figure 4. Spur 408 Southbound to IH20 Westbound Evening Peak Hour Bottleneck Improvement

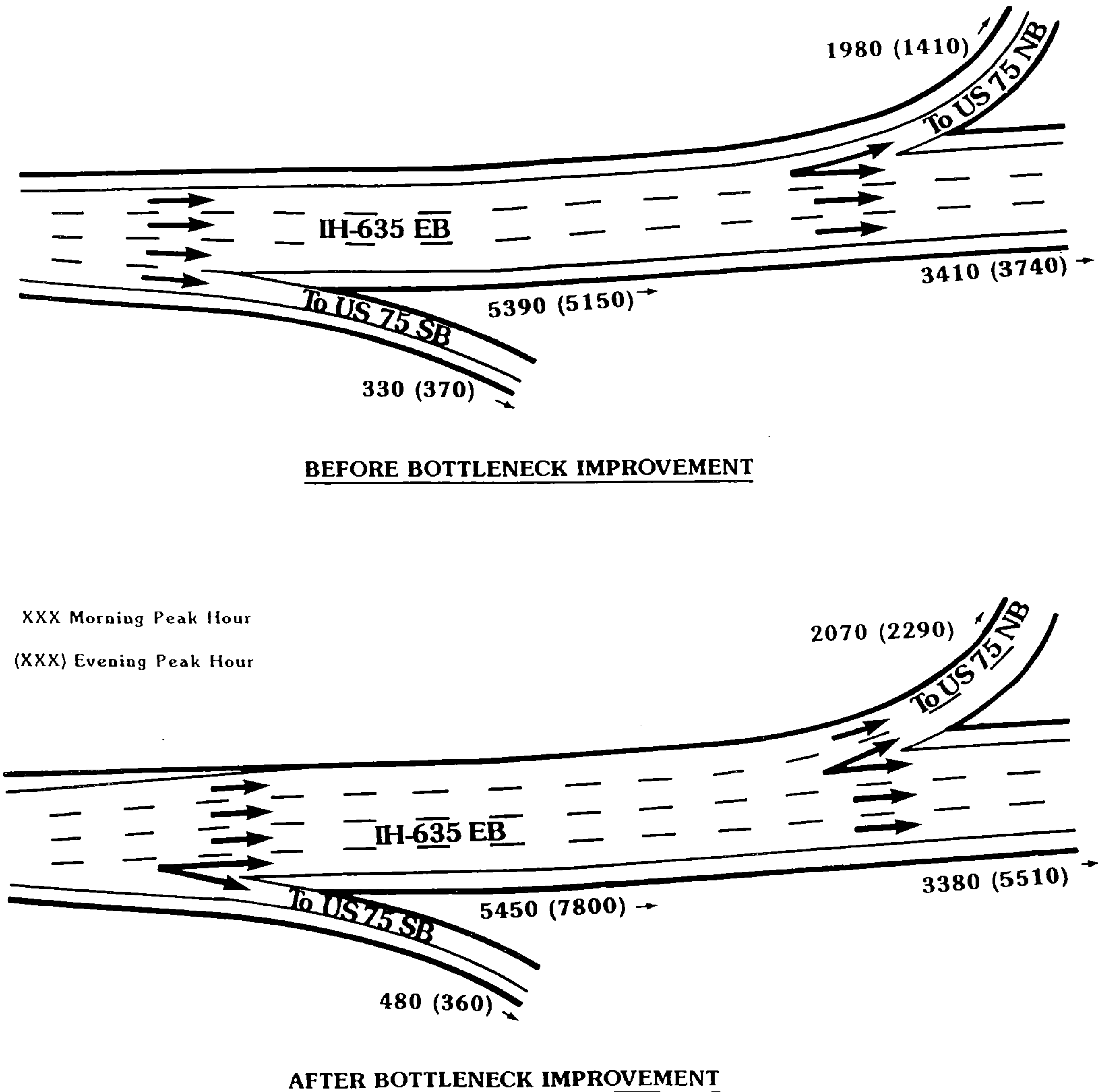
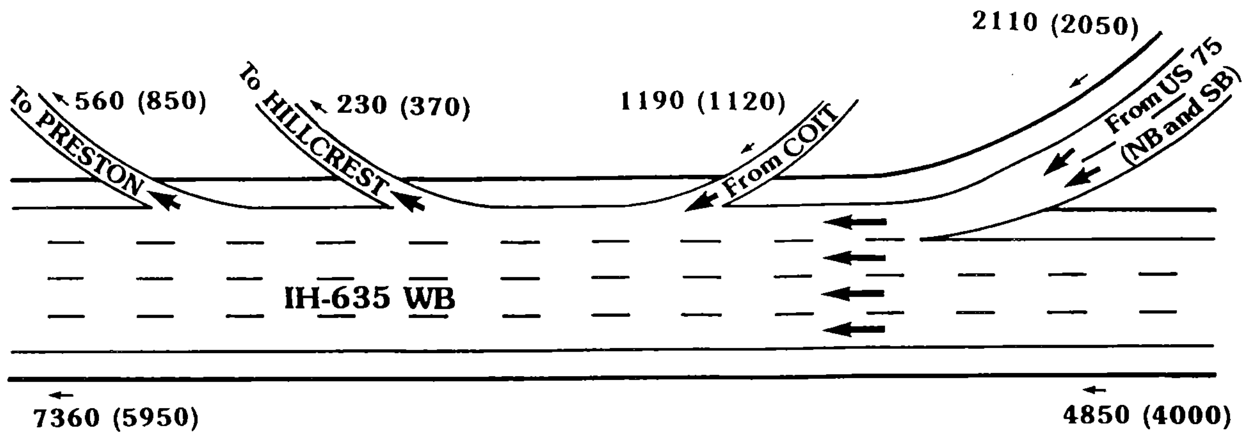


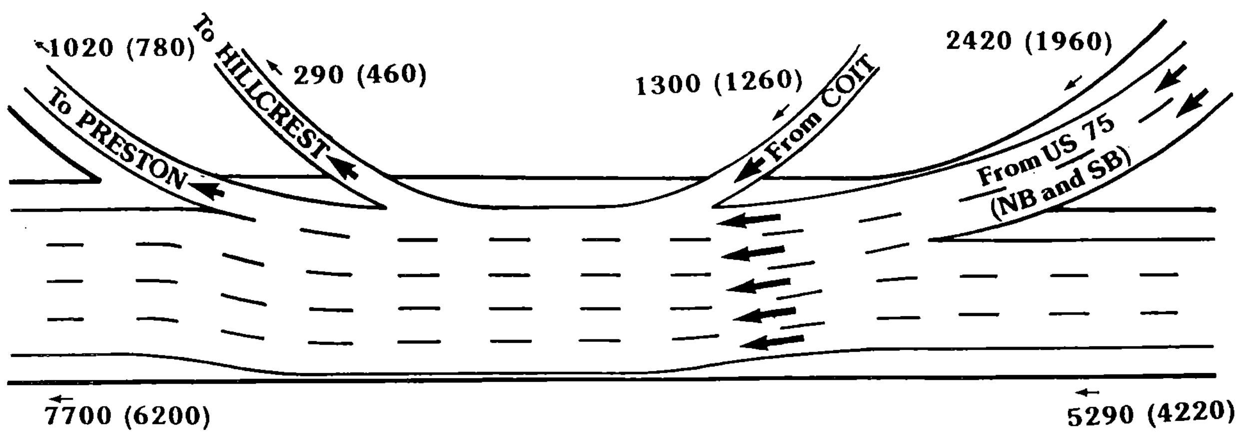
Figure 5. IH635 Eastbound Bottleneck Improvement



BEFORE BOTTLENECK IMPROVEMENT

XXX Morning Peak Hour

(XXX) Evening Peak Hour



AFTER BOTTLENECK IMPROVEMENT

Figure 6. IH635 Westbound Bottleneck Improvement

The before and after volume and travel time data was collected to determine the time savings of the bottleneck improvement projects during the morning and evening peak periods. The travel times were determined using a single vehicle traveling in the traffic stream, which would record the travel time through the corridor every 15 to 30 minutes. Using the known distance between travel time checkpoints, the average speed of a traffic stream was then calculated.

The volume through each corridor was determined with manual and automatic counts. The volume on the main lanes of a corridor was manually counted during peak periods, and the downstream or upstream mainlane volume was calculated using the automatic counts on the entrance and exit ramps along the corridor. Volumes were counted and recorded every 15 minutes for both the morning and evening peak periods.

Each project was divided into separate corridors for the purpose of the fuel consumption and emissions analysis. The IH35E project was separated into northbound and southbound movements for the morning and evening peak periods. The IH20 and Spur 408 project had data only for the peak direction in the morning and evening peak periods and was separated into two corridors. The IH635 project was also separated into four corridors for the eastbound and westbound movements for the morning and evening peak periods. Though there is not enough data to perform a full statistical analysis it is believed that the change in travel time for the IH35E northbound morning movement and the IH635 westbound morning movement was insignificant or minimal, and these movements were not considered for further analysis.

The eight corridor movements analyzed are listed below:

1. IH35E northbound evening
2. IH35E southbound morning
3. IH35E southbound evening
4. IH20 eastbound to Spur 408 northbound morning
5. Spur 408 southbound to IH20 westbound evening
6. IH635 eastbound morning
7. IH635 eastbound evening
8. IH635 westbound evening

In order to analyze the energy consumption and air quality impacts of the bottleneck improvement projects each corridor was divided into several sections for the purpose of recording the travel time and changes in volume. The sections for each corridor were defined by the existing checkpoints used for recording the travel time data. The checkpoints are also located where changes in volume occur. Each section was about 1.0 km (0.6 miles) in length. The average speed and volume for each section were determined in 15-minute time periods. A shorter time period may provide more accurate results, but it would require more detailed data collection. By knowing the before and after conditions of each section, changes in fuel consumption and emissions can theoretically be estimated using the average speed methodology.

Quantify Changes in Fuel Consumption

The second objective was to quantify the change in fuel consumption and emissions from implementation of freeway bottleneck improvement projects. The changes in fuel consumption and emissions for each bottleneck improvement project were estimated using an average speed model methodology. The total fuel consumption for each section of each corridor for a 15-minute period was estimated by multiplying the fuel consumption rate for a specific average speed by the known distance and the 15-minute volume of the section.

Fuel Consumption Rate x Distance x Volume = Total Fuel Consumption

The fuel consumption rates were estimated with the ARFCOM model. Parameters for five of the eight vehicle classes used in the MOBILE5a program were defined for input to the ARFCOM program. Light duty diesel vehicles, light duty diesel trucks and motorcycles, which only make up 2% of the vehicle mix for freeways in Dallas and Tarrant counties, were not considered in the composite fuel rate. This vehicle mix was used to calculate the composite fuel consumption rate. The curves for the five vehicle classes and the composite vehicle are shown in Figure 7. A vehicle composite mix was used since the actual vehicle mix was not known for any of the bottleneck projects. The application of these curves in the determination of fuel consumption under stop and go driving conditions is not clear.

The ARFCOM running speed model was used to estimate the fuel consumption for each of the five vehicle types at average speeds in intervals of 8 kph (5mph) from 8 kph (5 mph) to 113 kph (70 mph). A running speed higher than the average speed was assumed to reflect freeway travel conditions up to 80 kph (50 mph) for each average speed. At 80 kph (50 mph) and above the average speed was assumed to equal the running speed. The model calculates the idle time and travel time based on the given average speed and running speed. Since this analysis was used to create fuel rates for use at several locations the factors for windspeed and roadway grade were assumed to be zero. An important factor in the running speed model is the change in positive kinetic energy, E_{k+}, which is a measure of the amount of speed fluctuation for a given running speed. Default values of E_{k+} are provided for two types of urban areas in the ARFCOM model. However if known values can be calculated for E_{k+}, the accuracy of the model can be improved since these values have been found to vary considerably between cities (11). Using detailed travel data taken on a Houston freeway values for E_{k+} were obtained for freeway conditions from stop-and-go to freeflow driving, which is described in more detail below. Figure 8 compares the composite fuel consumption rate curve derived from the ARFCOM model with the composite fuel consumption rate curve from FREQ10.

Table 1 shows the fuel consumption analysis results from the average speed methodology. The average fuel consumption per vehicle and the total fuel consumption decrease for all but one bottleneck corridor. The total fuel consumption was calculated using the same volume per section of corridor for both the before and after conditions. The per vehicle and total percent change in fuel consumption are different because the per vehicle calculations do not consider the volume in each section of a corridor while the total calculation is the product of the per vehicle change and the section volume. Since the volume of each section is different, the sections with high volumes are essentially being more heavily weighted. The most significant change in fuel consumption per vehicle occurs on IH635 in the westbound direction for the evening peak period, a decrease of 7.4%. The change in fuel consumption per vehicle ranges from 1.6% to -7.4%. The largest decrease in total fuel consumption also occurs on IH635 in the westbound direction for the evening peak period, a decrease of 5.2%. The change in total fuel consumption ranges from zero to -5.2%. Most of the corridors show a small change in fuel consumption primarily due to average speeds in excess of 80 kph (50 mph) after the improvement.

Table 2 shows the results of the average speed methodology if all the average speeds above 88 kph (55 mph) are assumed to be 88 kph (55 mph).* The table shows greater potential decreases in fuel consumption for all but one of the corridors if the 88 kph (55 mph) speed limit is observed. The greatest change in fuel consumption per vehicle occurs on IH35E in the northbound direction for the evening peak period, a decrease of 7.4%. The change in fuel consumption per vehicle ranges from -1.4% to -7.4%. The largest decrease in total fuel consumption also occurs on IH35E in the northbound direction for the evening peak period, a decrease of 6.5%. The change in total fuel consumption ranges from -1.1% to -6.5%.

Most bottleneck improvements result in an increase in traffic volume through the bottleneck. The increase in traffic volume can be attributed to either a shift from alternative routes or a temporal shift from the shoulder hours of the peak period. For example the corridor which showed the largest increase in VDT, IH635 eastbound evening, only had data collected for a two-hour peak period, and the time periods before and after the peak period, the shoulder hours, may have shown a decrease in VDT due to the reduced congestion in the peak period. In either case, the change in fuel consumption for the traffic shifted from alternative routes or the shoulder hours is unknown, though it can be assumed to decrease since traffic would not have shifted from alternative routes or the shoulder hours if there was not a benefit to shift, such as a decrease in travel time during the peak period. A more thorough study of a bottleneck improvement would include data collection on alternative routes as well as over a longer time period.

In summary, reductions in fuel consumption using the average speed methodology seems to occur in an order of magnitude of 5%, where significant delay reductions occur. However, it should be noted that more precise speed measurements in stop and go driving could possibly result in much higher fuel usage in the before condition, as shown in the fuel usage curve of Figure 7 for slower speeds. This cannot be quantified for our examples because this type of data was not available.

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*All data was taken while speed limits were 55 mph throughout the Dallas area.

Figure 7. Average Speed Fuel Rates
ARFCOM Model Results

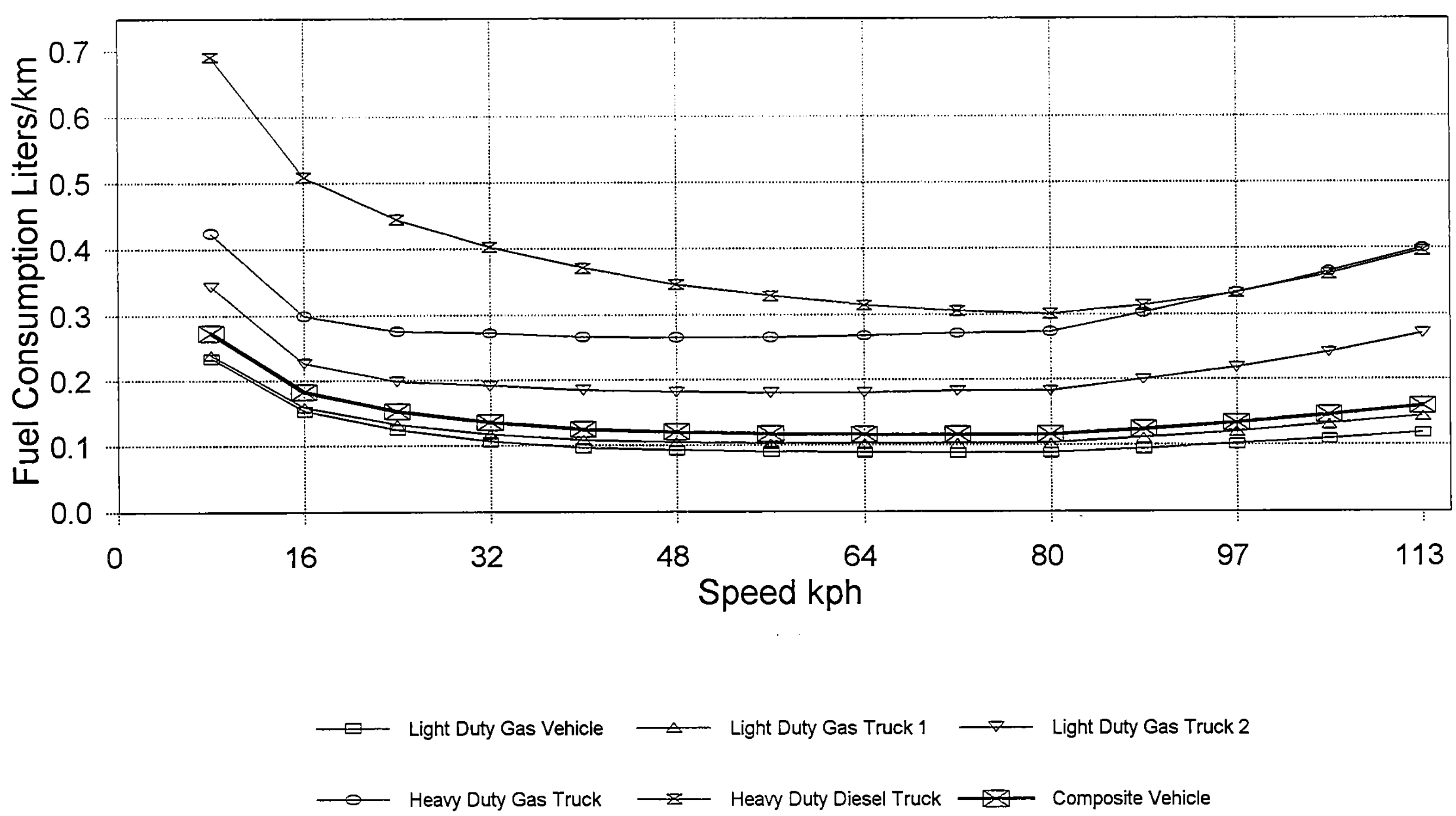


Figure 8. Fuel Consumption Rates

Composite Vehicle

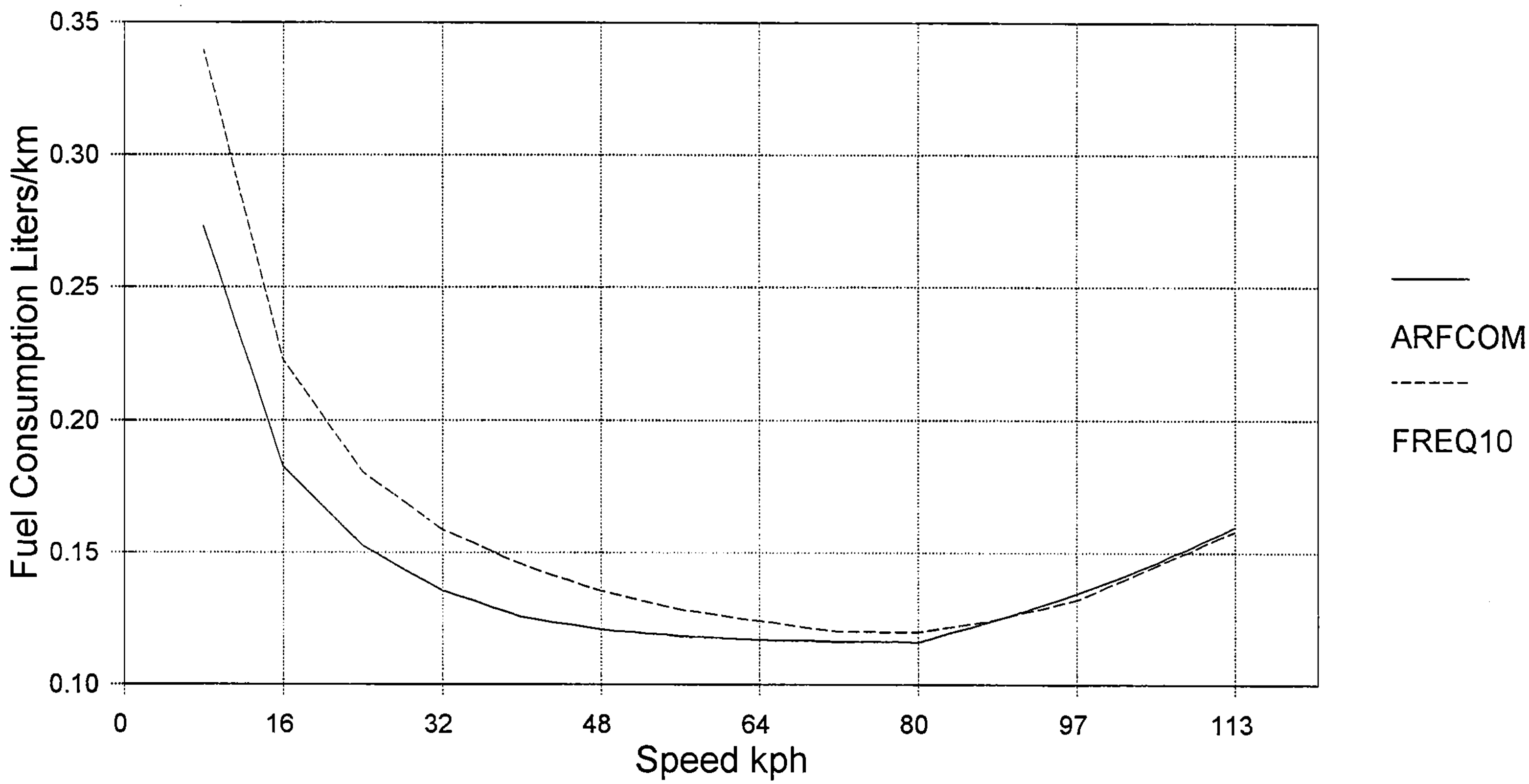


Table 1: **Fuel Consumption Analysis**

Average Fuel Consumption Per Vehicle

Bottleneck Projects		Before Improvement Liters (Gallons)	After Improvement Liters (Gallons)	Change Liters (Gallons)	% Change
1	IH35E NB PM	1.34 (0.35)	1.28 (0.34)	-0.06 (-0.01)	-4.9%
2	IH35E SB AM	1.63 (0.43)	1.63 (0.43)	-0.00 (-0.00)	-0.2%
3	IH35E SB PM	1.93 (0.51)	1.90 (0.50)	-0.03 (-0.01)	-1.3%
4	IH20/408 AM	0.47 (0.12)	0.46 (0.12)	-0.01 (-0.00)	-0.6%
5	IH20/408 PM	0.46 (0.12)	0.46 (0.12)	-0.00 (-0.00)	-1.0%
6	IH635 EB AM	0.62 (0.16)	0.63 (0.17)	0.01 (0.00)	1.6%
7	IH635 EB PM	0.59 (0.16)	0.57 (0.15)	-0.02 (-0.01)	-3.3%
8	IH635 WB PM	0.72 (0.19)	0.66 (0.18)	-0.06 (-0.01)	-7.4%

Total Fuel Consumption

Bottleneck Projects		Before Improvement Liters (Gallons)	After Improvement Liters (Gallons)	Change Liters (Gallons)	% Change
1	IH35E NB PM	22,670 (5,990)	21,790 (5,760)	-880 (-230)	-3.9%
2	IH35E SB AM	23,720 (6,270)	23,650 (6,250)	-70 (-20)	-0.3%
3	IH35E SB PM	24,210 (6,400)	23,830 (6,300)	-380 (-100)	-1.6%
4	IH20/408 AM	3,940 (1,040)	3,930 (1,040)	-10 (-0)	-0.3%
5	IH20/408 PM	4,820 (1,270)	4,780 (1,260)	-40 (-10)	-1.0%
6	IH635 EB AM	5,600 (1,480)	5,600 (1,480)	-0 (-0)	-0.0%
7	IH635 EB PM	7,230 (1,910)	6,860 (1,810)	-370 (-100)	-5.1%
8	IH635 WB PM	8,280 (2,190)	7,850 (2,070)	-430 (-110)	-5.2%

Table 2: Fuel Consumption Analysis with Maximum Speed Set at 88 kph (55 mph)

Average Fuel Consumption Per Vehicle

Bottleneck Projects		Before Improvement Liters (Gallons)	After Improvement Liters (Gallons)	Change Liters (Gallons)	% Change
1	IH35E NB PM	1.30 (0.34)	1.20 (0.32)	-0.10 (-0.02)	-7.4%
2	IH35E SB AM	1.61 (0.42)	1.57 (0.41)	-0.04 (-0.01)	-2.5%
3	IH35E SB PM	1.85 (0.49)	1.79 (0.47)	-0.06 (-0.01)	-3.1%
4	IH20/408 AM	0.46 (0.12)	0.45 (0.12)	-0.01 (-0.00)	-1.8%
5	IH20/408 PM	0.45 (0.12)	0.44 (0.12)	-0.01 (-0.00)	-1.4%
6	IH635 EB AM	0.61 (0.16)	0.60 (0.16)	-0.01 (-0.00)	-2.5%
7	IH635 EB PM	0.59 (0.16)	0.57 (0.15)	-0.02 (-0.01)	-3.7%
8	IH635 WB PM	0.69 (0.18)	0.64 (0.17)	-0.05 (-0.01)	-7.1%

Total Fuel Consumption

Bottleneck Projects		Before Improvement Liters (Gallons)	After Improvement Liters (Gallons)	Change Liters (Gallons)	% Change
1	IH35E NB PM	22,150 (5,850)	20,710 (5,470)	-1,440 (-380)	-6.5%
2	IH35E SB AM	23,420 (6,190)	22,840 (6,030)	-580 (-160)	-2.5%
3	IH35E SB PM	23,370 (6,170)	22,490 (5,940)	-880 (-230)	-3.8%
4	IH20/408 AM	3,890 (1,030)	3,790 (1,000)	-100 (-30)	-2.5%
5	IH20/408 PM	4,610 (1,220)	4,560 (1,200)	-50 (-20)	-1.1%
6	IH635 EB AM	5,570 (1,470)	5,320 (1,400)	-250 (-70)	-4.6%
7	IH635 EB PM	7,150 (1,890)	6,780 (1,790)	-370 (-100)	-5.2%
8	IH635 WB PM	8,010 (2,120)	7,630 (2,020)	-380 (-100)	-4.7%

Quantify Changes in Emissions

The emission changes for each bottleneck improvement project were quantified in the same manner as the changes in the fuel consumption. The total emissions for each movement were estimated by multiplying the emission rate for a specific average speed by the known distance and the 15-minute volume of the section.

$$\text{Emission Rate} \times \text{Distance} \times \text{Volume} = \text{Total Emissions}$$

These emissions rates were given in grams per mile for eight vehicle types and all vehicle composite. The all vehicle composite reflects the Dallas and Tarrant Freeway vehicle mix and was used for all the emissions analyses for this study.

Figure 9 shows the curves for volatile organic compounds. The operating VOC emission rates include the exhaust component and running components of VOC. The exhaust component curve shown in the figure consists of the VOC emissions released through the tailpipe. The running component consists of the evaporative losses while the engine is running. From the figure it can be seen that the running evaporative emissions are a major portion of the operating VOC emissions particularly at low speeds. The optimum VOC emission rate occurs at 88 kph (55 mph). Additional VOC components are given with the MOBILE5a output, however the Evaporative and Resting losses which occur after the engine is shut off were ignored for the purposes of estimating the changes in VOC emissions.

Figure 10 shows the emission rate curve for carbon monoxide. It is similar to the VOC emission curve, but it rises more sharply at speeds in excess of 88 kph (55 mph). The optimum speed for CO emissions occurs at 77 kph (48 mph). Figure 11 shows the emission rate curve for nitrogen oxides (NO_x). This curve differs considerably from the other emission curves as well as the fuel consumption curve. The optimum speed occurs at 40 kph (25 mph), and the curve is almost linear and constant between 32 kph (20 mph) and 77 kph (48 mph). At speeds above 77 kph (48 mph) the emission rate rises sharply.

Table 3 shows the emissions analysis for VOC emissions. The VOC emissions decrease for each bottleneck improvement though greater reductions were expected. The change in VOC emissions per vehicle ranges from -6.6% to -31.1%, and the total VOC emissions ranges from -7.2% to -29.0%. Similarly to the fuel consumption analysis, greater reductions in VOC emissions will result if the speed is limited to 88 kph (55 mph). Table 4 shows the emissions analysis for VOC emissions when the maximum speed is held to 88 kph (55 mph). The change in VOC emissions per vehicle ranges from -9.7% to -34.1%, and the change in total VOC emissions ranges from -8.4% to -32.8%.

Table 5 and 6 show the quantified CO emissions. The change in CO emissions per vehicle ranges from 15.2% to -25.6%, and the change in total CO emissions ranges from 15.7% to -26.5%. If the speed is limited to 88 kph (55 mph) each corridor shows a decrease in CO emissions. The change in CO emissions per vehicle ranges from -5.8% to -28.0%, and the change in total CO emissions ranges from -5.4% to -28.3%. The sharp increase in the CO emission rate per vehicle at speeds above 88 kph (55 mph) is clearly reflected in the results shown in table 5 and 6. The morning eastbound movement of IH635 shows a percent increase in CO emissions per vehicle of 15.2%. The morning eastbound movement of IH635 shows a change in CO emissions of -16.5% when the speed limit is observed. Recent research has shown that CO emissions are greatly affected by enrichment events which are not being modeled by the average speed methodology. So any improvement that eliminates stop-and-go driving and creates smoother traffic flow should result in greater reductions of CO emissions than what is seen in this analysis.

Table 7 and 8 show the results of NO_x emissions analysis. The amount of NO_x emissions increased for every movement. The change in NO_x emissions per vehicle ranges from 29.4% to 5.8%, and the change in total NO_x emissions ranges from 31.0% to 4.3%. If the speed is limited to 88 kph (55 mph) the NO_x emissions show a smaller increase. The change in NO_x emissions per vehicle ranges from 20.4% to 5.9%, and the change in total NO_x emissions ranges from 20.8% to 4.5%. For most of the sections in each movement the average speeds for the before and after conditions were well above 40 kph (25 mph), and any increase in average speed for these sections due to the implementation of the bottleneck improvements results in higher NO_x emissions. The same research that showed the CO and VOC emissions increasing with enrichment events showed that NO_x emissions do not increase with enrichment. However, the MOBILE5a NO_x emission rate increases as speeds decrease below 32 kph (20 mph). With the average speed methodology the low speeds which would show higher emissions are lost within the average speed of a section of freeway.

Figure 9. VOC Emission Rates

1993, Dallas/Tarrant Freeways

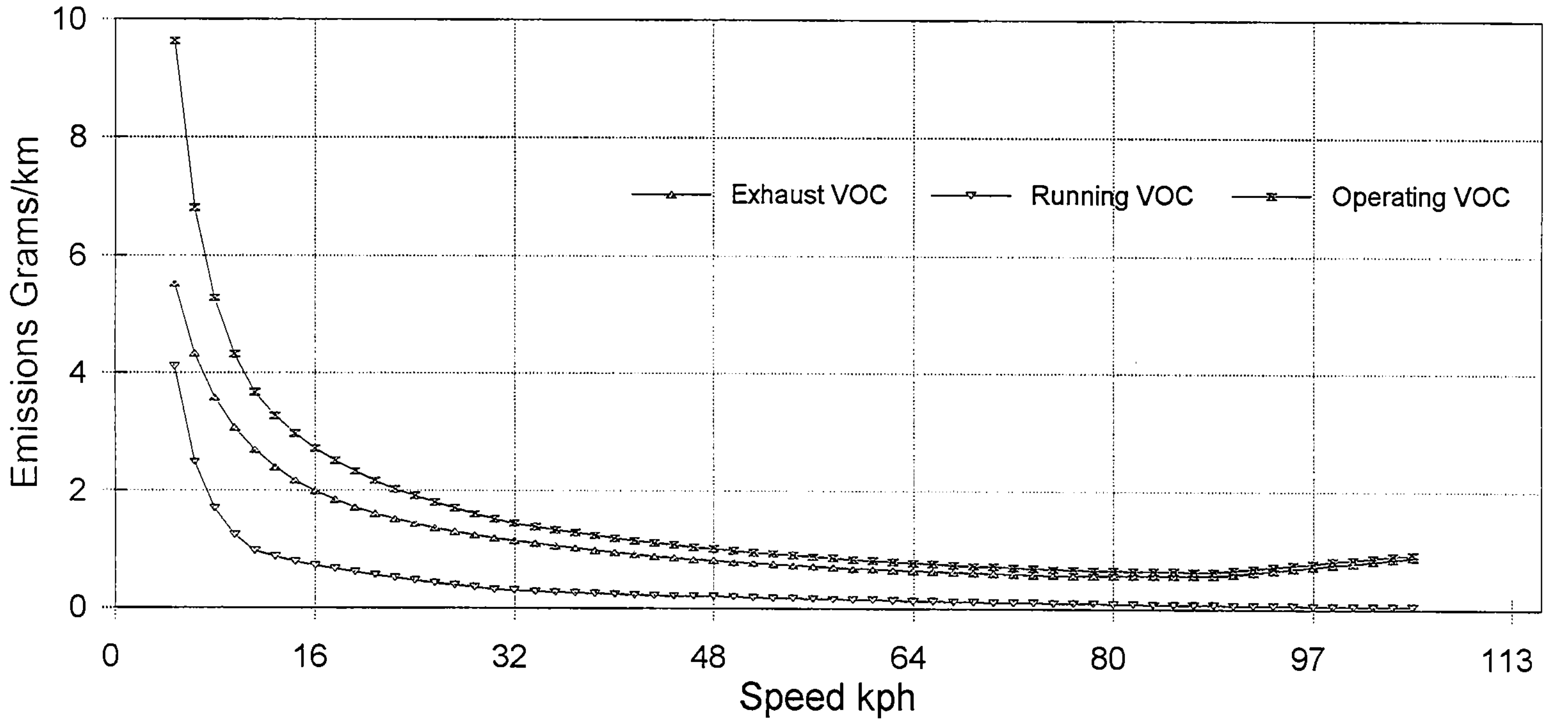


Figure 10. CO Emission Rates

1993, Dallas/Tarrant Freeways

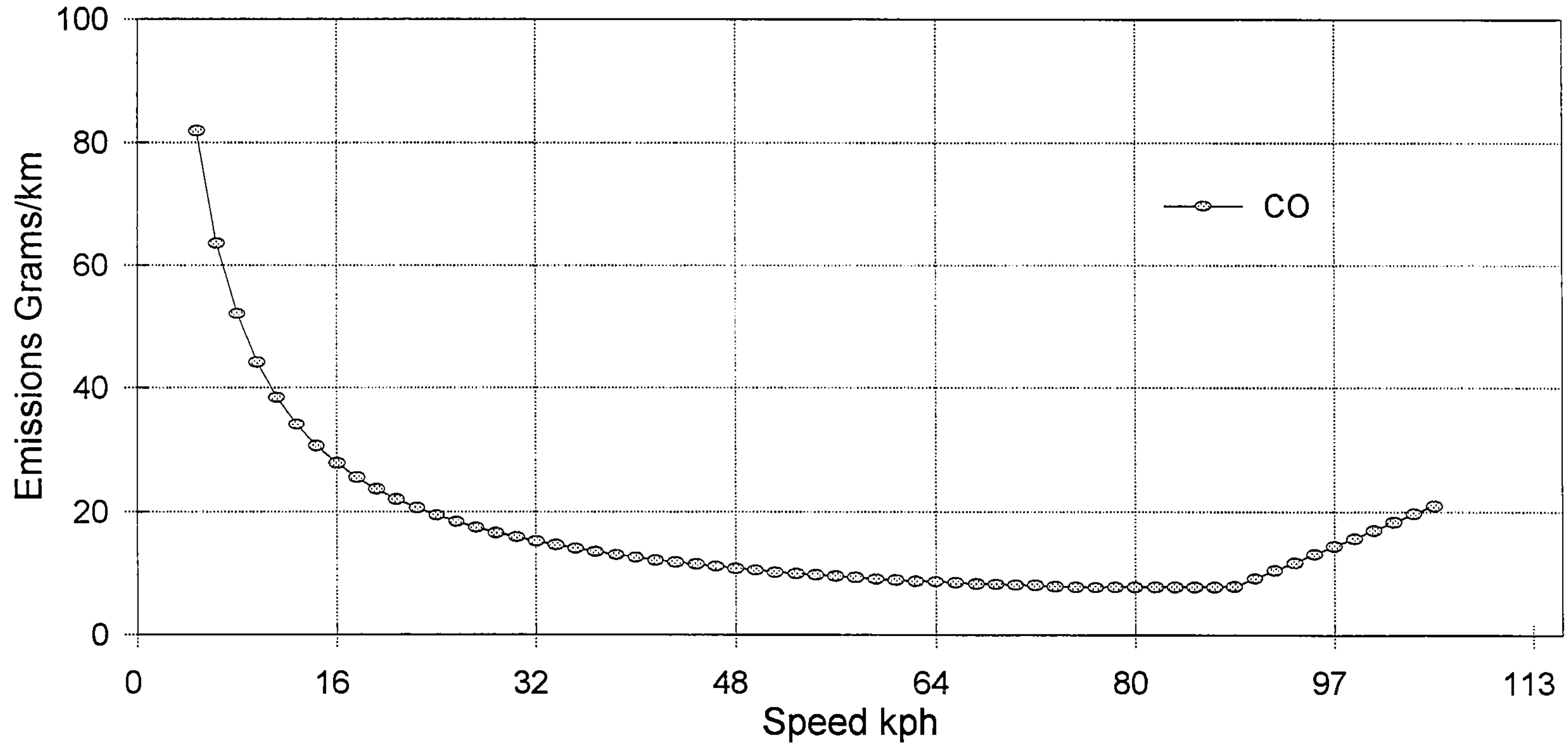


Figure 11. NOx Emission Rates
1993, Dallas/Tarrant Freeways

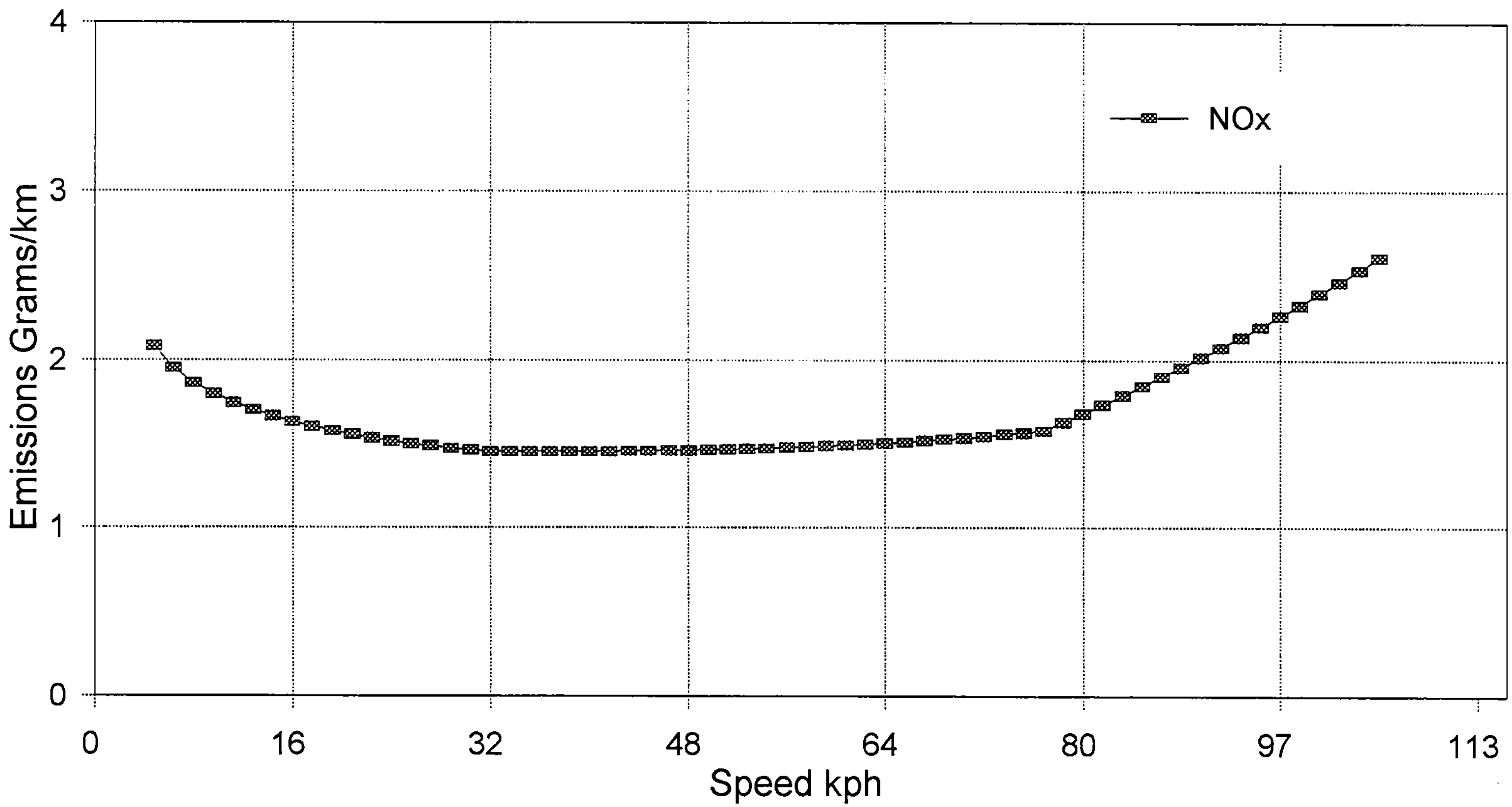


Table 3: **Emissions Analysis**

Average VOC Emissions Per Vehicle for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	10.79	7.80	-2.99	-27.7%
2	IH35E SB AM	10.26	9.02	-1.24	-12.1%
3	IH35E SB PM	12.45	10.67	-1.78	-14.3%
4	IH20/408 AM	2.69	2.52	-0.18	-6.6%
5	IH20/408 PM	2.71	2.50	-0.21	-7.8%
6	IH635 EB AM	4.13	3.49	-0.63	-15.4%
7	IH635 EB PM	4.80	3.34	-1.46	-30.4%
8	IH635 WB PM	5.40	3.61	-1.79	-33.1%

Total VOC Emissions for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	176,700	132,400	-44,300	-25.1%
2	IH35E SB AM	149,900	131,100	-18,800	-12.5%
3	IH35E SB PM	162,900	133,500	-29,400	-18.0%
4	IH20/408 AM	23,600	21,500	-2,100	-9.0%
5	IH20/408 PM	28,500	26,400	-2,100	-7.2%
6	IH635 EB AM	37,900	31,200	-6,700	-17.7%
7	IH635 EB PM	59,800	40,500	-19,300	-32.2%
8	IH635 WB PM	59,800	42,400	-17,400	-29.0%

Table 4: Emissions Analysis with Maximum Speed Set at 88 kph (55 mph)

Average VOC Emissions Per Vehicle for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	10.23	6.76	-3.48	-34.0%
2	IH35E SB AM	9.91	8.21	-1.70	-17.1%
3	IH35E SB PM	11.42	9.20	-2.21	-19.4%
4	IH20/408 AM	2.59	2.33	-0.26	-9.9%
5	IH20/408 PM	2.48	2.24	-0.24	-9.7%
6	IH635 EB AM	4.06	3.09	-0.97	-23.9%
7	IH635 EB PM	4.73	3.24	-1.48	-31.4%
8	IH635 WB PM	5.12	3.37	-1.74	-34.1%

Total VOC Emissions for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	170,000	117,000	-53,000	-31.2%
2	IH35E SB AM	145,600	120,200	-25,400	-17.5%
3	IH35E SB PM	151,400	115,500	-35,900	-23.7%
4	IH20/408 AM	23,000	19,600	-3,400	-14.7%
5	IH20/408 PM	25,400	23,300	-2,100	-8.4%
6	IH635 EB AM	37,500	27,400	-10,000	-26.8%
7	IH635 EB PM	58,600	39,400	-19,200	-32.8%
8	IH635 WB PM	56,400	39,500	-16,900	-29.9%

Table 5: **Emissions Analysis**

Average CO Emissions Per Vehicle for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	137.55	127.53	-10.02	-7.3%
2	IH35E SB AM	129.77	135.75	5.98	4.6%
3	IH35E SB PM	178.63	179.08	0.45	0.3%
4	IH20/408 AM	34.95	36.77	1.82	5.2%
5	IH20/408 PM	40.07	39.49	-0.58	-1.4%
6	IH635 EB AM	48.53	55.93	7.39	15.2%
7	IH635 EB PM	54.53	42.01	-12.52	-23.0%
8	IH635 WB PM	69.58	51.77	-17.81	-25.6%

Total CO Emissions for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	2,173,500	2,084,900	-88,600	-18.4%
2	IH35E SB AM	1,868,000	1,950,100	82,100	4.4%
3	IH35E SB PM	2,240,900	2,234,300	-6,600	-0.3%
4	IH20/408 AM	295,200	326,500	31,300	10.6%
5	IH20/408 PM	440,200	428,100	-12,100	-2.8%
6	IH635 EB AM	438,300	507,300	69,000	15.7%
7	IH635 EB PM	683,200	502,000	-181,200	-26.5%
8	IH635 WB PM	785,800	614,200	-171,600	-21.8%

Table 6: Emissions Analysis with Maximum Speed Set at 88 kph (55 mph)

Average CO Emissions Per Vehicle for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	112.87	81.26	-31.61	-28.0%
2	IH35E SB AM	114.36	100.18	-14.18	-12.4%
3	IH35E SB PM	132.85	114.18	-18.67	-14.1%
4	IH20/408 AM	30.38	28.61	-1.78	-5.8%
5	IH20/408 PM	29.64	27.79	-1.85	-6.2%
6	IH635 EB AM	45.38	37.91	-7.47	-16.5%
7	IH635 EB PM	51.24	37.69	-13.55	-26.4%
8	IH635 WB PM	57.13	41.18	-15.95	-27.9%

Total CO Emissions for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	1,874,400	1,402,500	-471,900	-25.2%
2	IH35E SB AM	1,677,900	1,465,500	-212,400	-12.7%
3	IH35E SB PM	1,733,400	1,433,500	-299,900	-17.3%
4	IH20/408 AM	265,500	240,800	-24,700	-9.3%
5	IH20/408 PM	306,100	289,400	-16,700	-5.4%
6	IH635 EB AM	417,300	338,200	-79,100	-19.0%
7	IH635 EB PM	634,100	454,900	-179,200	-28.3%
8	IH635 WB PM	634,900	484,900	-150,000	-23.6%

Table 7: **Emissions Analysis**

Average NO_x Emissions Per Vehicle for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	17.29	19.89	2.60	15.1%
2	IH35E SB AM	21.80	24.52	2.72	12.5%
3	IH35E SB PM	27.65	30.60	2.95	10.7%
4	IH20/408 AM	6.30	7.02	0.72	11.5%
5	IH20/408 PM	6.81	7.24	0.43	6.3%
6	IH635 EB AM	7.51	9.72	2.21	29.4%
7	IH635 EB PM	6.93	7.56	0.63	9.1%
8	IH635 WB PM	9.38	9.93	0.54	5.8%

Total NO_x Emissions for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	286,100	334,200	48,100	16.8%
2	IH35E SB AM	315,900	356,400	40,500	12.8%
3	IH35E SB PM	335,900	384,200	48,300	14.4%
4	IH20/408 AM	51,800	60,500	8,700	16.8%
5	IH20/408 PM	73,200	76,300	3,100	4.3%
6	IH635 EB AM	67,300	88,200	20,900	31.0%
7	IH635 EB PM	84,500	89,000	4,500	5.3%
8	IH635 WB PM	109,900	118,900	9,000	8.2%

Table 8: Emissions Analysis with Maximum Speed Set at 88 kph (55 mph)

Average NO_x Emissions Per Vehicle for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	16.09	17.67	1.58	9.8%
2	IH35E SB AM	21.07	22.83	1.76	8.4%
3	IH35E SB PM	25.46	27.52	2.05	8.1%
4	IH20/408 AM	6.08	6.64	0.56	9.1%
5	IH20/408 PM	6.32	6.69	0.38	5.9%
6	IH635 EB AM	7.36	8.86	1.50	20.4%
7	IH635 EB PM	6.77	7.36	0.59	8.7%
8	IH635 WB PM	8.78	9.42	0.64	7.3%

Total NO_x Emissions for All Vehicle Types

Bottleneck Projects		Before Improvement (Grams)	After Improvement (Grams)	Change (Grams)	% Change
1	IH35E NB PM	271,600	301,700	30,100	11.1%
2	IH35E SB AM	306,900	333,400	26,500	8.7%
3	IH35E SB PM	311,600	346,300	34,700	11.1%
4	IH20/408 AM	50,400	56,500	6,100	12.0%
5	IH20/408 PM	66,800	69,800	3,000	4.5%
6	IH635 EB AM	66,300	80,100	13,800	20.8%
7	IH635 EB PM	82,100	86,800	4,700	5.7%
8	IH635 WB PM	102,500	112,700	10,200	9.9%

Alternative Methods

There are two primary problems with the average speed method for estimating the changes in emissions. The first problem is the fact that major fluctuations in speed and accelerations or decelerations reflected in off-cycle driving patterns are not recognized when only the average speed in a section of freeway or through a corridor is used to characterize driving behavior. The second problem is the lack of a full range of representative driving cycles or off-cycle driving patterns used to develop the emission rates in the MOBILE5a model. Both problems will tend to under-estimate changes particularly where a transportation improvement removes stop-and-go driving conditions.

These problems for estimating emissions are clearly demonstrated by the results of an analysis of the benefits of electronic toll collection systems over traditional toll gate collection methods. The Northeast States for Coordinated Air Use Management used the Oklahoma Pike Pass system to calculate the potential emission changes for implementing an electronic toll collection system on tollways in New Jersey and Massachusetts (8). Typical driving profiles for three different toll collection alternatives were determined by videotaping traffic in Oklahoma. The three alternatives consisted of a traditional toll-gate alternative where each vehicle came to a stop, a modified Pike Pass alternative where each vehicle decelerated only to 48 kph (30 mph), and a full Pike Pass alternative where each vehicle maintained a cruise speed of 105 kph (65 mph) - the speed limit at the Oklahoma site.

The three different driving profiles were duplicated with ten passenger vehicles on a dynamometer to get reliable samples of actual tailpipe emissions. The emissions of HC, CO, and NO_X were measured for each vehicle, and an average for each toll collection driving profile was determined. The average results per vehicle are shown in Table 9 below along with the results if the average speed method is used for the same driving profiles with emission rates developed for the Dallas Fort Worth freeways for a light-duty gasoline vehicle from MOBILE5a.

Table 9 Pike Pass Project compared to the Average Speed Method

	Toll Gate Stop	Average Speed 35 kph	Modified Pike Pass	Average Speed 72 kph	Full Pike Pass	Average Speed 105 kph
HC (grams/km)	0.75	0.88	0.62	0.50	0.12	0.75
CO (grams/km)	19.0	12.0	12.4	6.78	5.28	17.6
NO_X (grams/km)	0.68	0.96	0.56	1.03	0.37	1.75

The results of the Pike Pass project clearly show the benefits for transportation improvements which smooth traffic flow even at high speeds. The average speed method came closest to estimating actual measurements at the slowest average speed of 35 kph (22 mph). The average speed method overestimated and was further off from the actual measurements at the highest speed of 105 kph (65 mph). However, the most important observation is that the actual measurements showed a decrease for each emission as the average speed increased, where as the MOBILE5a emission rates all show a steady increase at high speeds.

Dynamometer tests may be the best way to get actual measurements of emissions if the vehicle driving profiles can be duplicated on the dynamometer. However, the method used with the Pike Pass project would probably be prohibitively expensive for measuring the benefits of other transportation flow improvements such as bottleneck removal projects. Unlike the driving profiles at toll booths, every freeway bottleneck has different driving profiles, varying with the time of day and the level of congestion. A model to accurately estimate the emissions through a bottleneck needs to be responsive to the changes in the driving profile. This type of model is known as a drive-mode model or a modal emissions model.

A drive-mode or modal emissions model considers the driving mode or changes in the driving cycle to estimate emissions. The driving modes usually considered for a modal model are idle, cruise, acceleration, and deceleration. There are several approaches to developing a modal emissions model. Two approaches that have been used recently to develop models are the speed-acceleration matrix and the emissions mapping approaches. An approach that attempts to avoid the problems associated with these two approaches is being developed at the University of California Riverside. The power-demand modal modeling approach is based on a parameterized analytical representation of emissions production. The model is deterministic in nature and requires emissions and operations data from a wide range of vehicles (7). The first phase of literature and data collection for the development of this model - a three year project - has been completed.

The operational data required for modal models depends on the detail of the model, but the travel time and the vehicle volume as collected for the bottleneck improvement projects are not enough. To calculate the acceleration or deceleration rates the changes in speed must be recorded. The most effective way to do this is to record the spot speed and distance with an automatic travel data recorder at a fixed time interval such as every second; from this data a speed-time profile can be constructed which will show the changes in speed over time. The estimates of any model will be more accurate if the travel-runs used to develop the driving profiles can be completed as often as possible. The fuel consumption or emission estimates for any model are based on the assumption that the driving profile is typical for each vehicle in the traffic stream.

A simplified version of the drive-mode element model was tested during the course of this research. Since fuel consumption and emission rates for acceleration and deceleration were not available, the simplified model used only the idle mode and a running mode which used an average speed minus the idle time in place of the cruise, acceleration, and deceleration modes. A travel data recorder calibrated for a specific vehicle was used to gather more accurate travel time, travel distance and spot speed data. Previously only travel time data was collected for analyzing any freeway improvements and the time spent idling in a stop and go traffic or the idle time was ignored. With the data recorder it was hoped that the idle time could be accurately recorded and that a speed-time profile could be prepared from which it would be possible to determine acceleration and deceleration rates.

Six separate runs were performed on a section of IH635 from the Luna Road entrance ramp eastbound to the Josey Lane exit ramp that routinely has stop and go driving conditions in both the morning and evening peak periods. Four runs were performed in the morning peak period and two runs were performed in the evening peak period. The collected data was analyzed using the average speed method and the simplified drive-mode method.

Idle emissions were calculated for the total idle time for each run. Idle emission rates consistent to the regular emission rates used from MOBILE5a were obtained from NCTCOG. The emissions from the running mode were determined using the average speed minus the idle time. This gave a slightly higher average speed than the average speed method. The MOBILE5a emissions factors used in the average speed model were also used in calculating the running mode emissions.

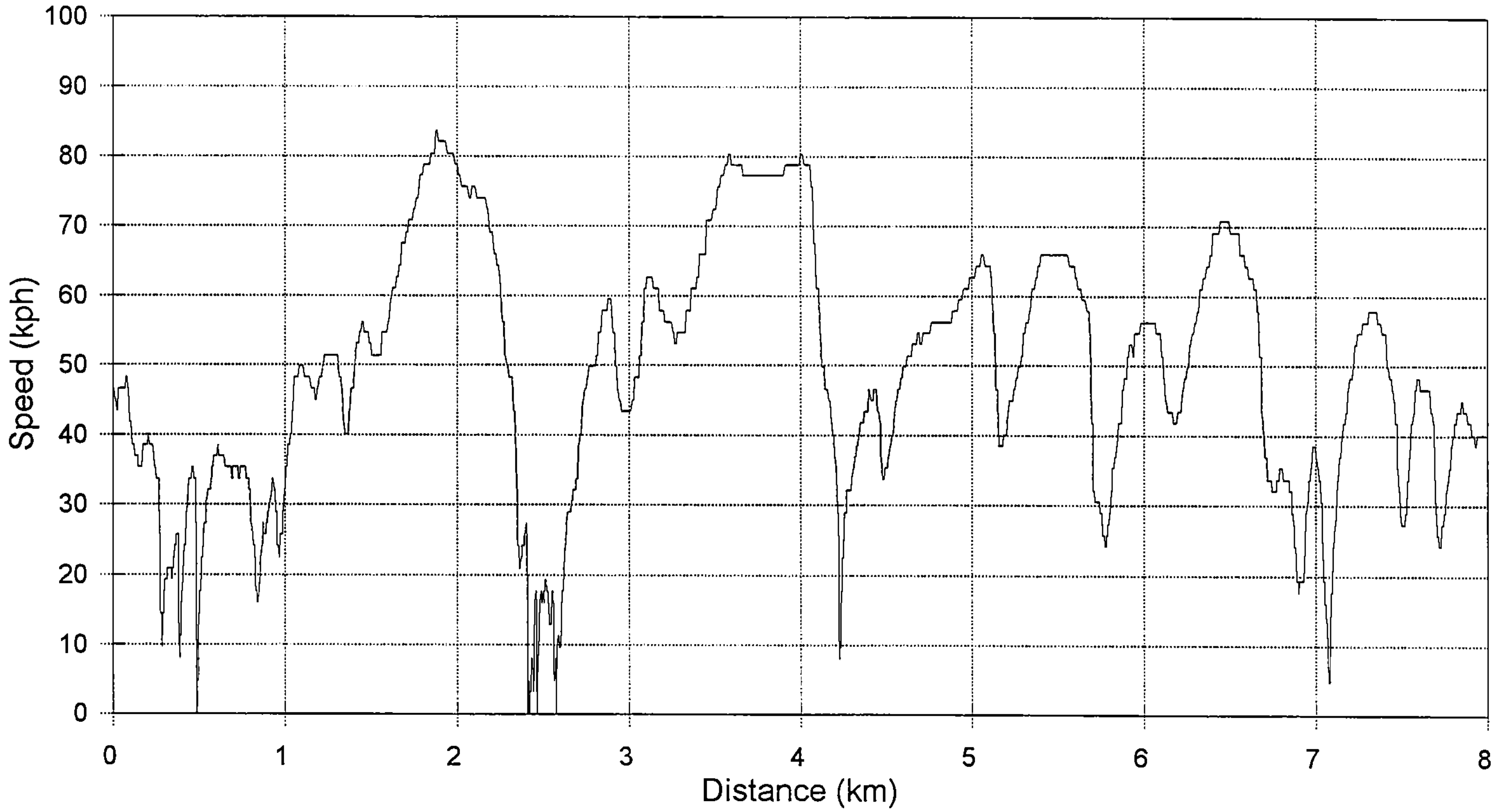
Each method is a different way of looking at the same data. The emission estimates for each method vary only slightly for each run. The simplified drive-mode method was expected to result in higher emissions estimates than the average speed method, though for this data the drive-mode method estimates are slightly lower. It was determined from this data that a full modal model using acceleration and deceleration rates needs to be used to estimate the increased emissions that are a result of stop and go driving. From this test it was also determined that a more precise travel data recorder - one not requiring human input during the travel run - would be more suitable for collecting the travel time, travel distance and spot speed data. This would allow for a better determination of the acceleration and deceleration rates, and the idle time needed for a modal model.

The Houston office of TTI has installed distance measuring instrumentation (DMI) on four vehicles for detailed modal data collection. The data is collected in the same manner as the traditional travel time data with a single vehicle moving with the traffic stream or following a randomly selected vehicle. However, only the driver is needed to operate the DMI equipment. Detailed travel data is collected automatically once the DMI is initiated by the driver at a particular checkpoint to start the travel time run. The DMI collects the cumulative distance, the spot speed in mph, and the travel time and interval time to the closest half second interval. The data is saved in a laptop computer, which is connected to the DMI, with software developed by the Houston office of TTI.

Several travel time runs collected with the DMI equipped vehicles were obtained from the Houston office of TTI for use with the ARFCOM fuel consumption model. An example of the detailed travel time data is plotted in Figure 12. The DMI equipment was set to collect data at half second intervals. The most accurate level of the ARFCOM model, the instantaneous speed

Figure 12. Detailed Travel Time Run

DMI Data from Houston



program, requires second by second speed data of a vehicle to estimate that vehicle's fuel consumption. Other parameters such as wind speed and roadway geometry can be included in the model, but are not necessary. Nine runs all performed on 31.5 km (19.6 miles) of the eastbound lanes of the Katy Freeway in Houston in the morning peak period were analyzed. The nine runs were divided into 42 segments to provide a range of average speeds from 8 kph (5 mph) to 103 kph (64 mph). Most segments were about 8 km (5 miles) in length, however shorter segments were necessary where speeds were slow due to the large amount of data points. The segments varied in length from 9.05 km (5.62 miles) to 1.60 km (0.99 miles), and in travel time from 16 minutes to 1.6 minutes. The ARFCOM model calculated from the speed data the distance traveled, the travel time, the idle time, the average speed, the running speed and the speed fluctuations (E_{k+}) for each segment. From this the model estimated the fuel consumption of a specified vehicle for each of the 42 segments. Table 10 shows a summary of the ARFCOM results of the nine runs plus a hypothetical run in which the speed was held constant at 88 kph (55 mph).

Table 10. Summary of ARFCOM Results

Run	Average Speed kph (mph)	Fuel Consumption Rate km/L (mpg)	Average E_{k+} m/sec^2 (ft/sec^2)	% Difference in Fuel Consumption Rate[1]
1	68.1 (42.3)	10.3 (24.2)	0.119 (0.389)	7.07%
2	29.3 (18.2)	7.72 (18.2)	0.203 (0.665)	42.5%
3	25.5 (15.6)	8.16 (19.2)	0.169 (0.554)	34.8%
4	71.5 (44.4)	10.3 (24.2)	0.103 (0.337)	7.01%
5	41.7 (25.9)	8.44 (19.9)	0.276 (0.906)	30.3%
6	93.1 (57.9)	9.90 (23.3)	0.072 (0.235)	11.1%
7	51.6 (32.0)	9.03 (21.3)	0.154 (0.506)	21.8%
8	64.2 (39.9)	8.87 (20.9)	0.134 (0.440)	24.0%
9	99.7 (62.0)	9.05 (21.3)	0.084 (0.273)	21.5%
Hypothetical	88.0 (54.7)	11.0 (25.9)	0.000 (0.000)	0

1. The potential change in fuel consumption as compared with a constant speed of 88 kph (55 mph)

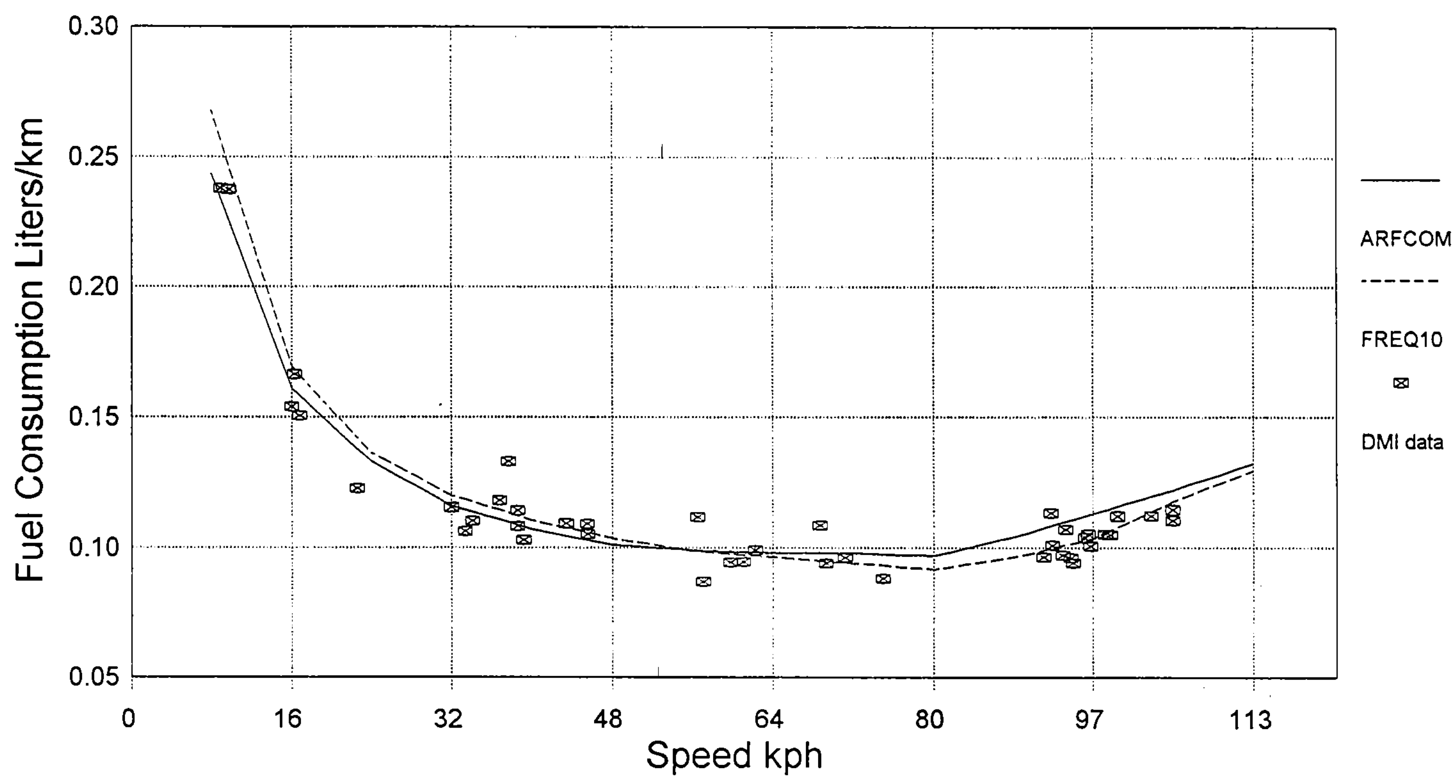
The results presented in the table clearly show how fuel consumption varies with speed and how fuel consumption is influenced by the speed fluctuations. For example run 2 has a lower fuel consumption rate than run 3, despite a slightly higher average speed, due to the greater amount of speed fluctuations. The hypothetical run allows a comparison to show what change in fuel consumption might be achieved with smoothing the flow of traffic.

The vehicle specified for this analysis was a composite of the light duty gas vehicle and the light duty gas trucks which had been defined for the ARFCOM model to be equivalent to the MOBILE5a vehicle classes of the same name. The light composite vehicle is basically equivalent to the automobile class used with the FREQ10 fuel consumption rates. The automobile class used in FREQ10 is a composite of all four wheel vehicles (3). Figure 13 shows the fuel consumption for each segment in liters/km plotted versus average speed in kph. Figure 13 also shows the FREQ10 freeway fuel consumption rate curve for autos and the fuel consumption rate curve derived with the ARFCOM running speed model for the light composite vehicle. The similarity of the FREQ10 freeway fuel consumption rate with the fuel consumption results of the DMI data using ARFCOM indicate that the average speed methodology is adequate for freeway fuel consumption analysis for freeway transportation improvement projects. This stands to reason, since actual fuel consumption for any vehicle can be easily measured for use in validating a model.

However, the average speed methodology and the modal methods discussed above would still be an estimation based on the performance of a single vehicle or floating point in the traffic stream. For many locations it may be feasible to perform actual measurements of emissions, though not fuel consumption, from a traffic stream. It was proposed that a field test using emissions monitoring equipment from the Department of Electrical Engineering's Wave Scattering Research Center at the University of Texas at Arlington be utilized for measurement of vehicle emissions analysis. The equipment consists of advanced open-path infrared (IR) and ultraviolet (UV) spectrometers which can detect in real time CO, CO_2, O_3, NO, NO_2 and individual VOC's. However this proposal could not be implemented under this project, due to restrictions associated with the funding source.

Figure 13. Fuel Consumption Rates

Light Composite Auto



Identify Energy Savings

One of the anticipated secondary benefits of bottleneck improvement projects is a reduction in fuel consumption. The average speed model methodology was used to estimate the fuel consumption of the three bottleneck improvement projects. The estimated change in fuel consumption per vehicle and the total estimated change in fuel consumption for each corridor as shown in Table 1a is low for the peak periods. The fuel consumed per vehicle ranges from an increase of 1.6% for the morning eastbound IH635 corridor to a reduction of 7.4% for the evening westbound IH635 corridor. However, the travel time per vehicle ranged from a change of -14.3% for the evening southbound Spur 408 to westbound IH20 corridor to a change of -40.5% for the evening westbound IH635 corridor. The morning eastbound IH635 corridor which had an increase in fuel consumption per vehicle had a travel time change of -33.2%. Table 11 shows the travel time savings for each corridor. From these results it is evident that other factors other than travel time may help identify energy savings. However, other factors are not easily quantified such as speed and acceleration. From Figures 7,8, and 13 it can be seen that the fuel consumption of any vehicle increases at speeds more than 80 kph (50 mph) primarily due to the increasing influence of air resistance at higher speeds. When speeds in each corridor are assumed not to exceed the limit of 88 kph (55 mph) the potential fuel consumption per vehicle and the total fuel consumption for both the before and after conditions for each improvement decreases.

The travel time data for each bottleneck improvement was collected every 15 minutes during the peak period, and was used to estimate the fuel consumption. Figure 14 shows the plot of the estimated fuel savings per vehicle for each 15 minute data period for each corridor related to the travel time savings. There is a total of 91 data points or observations in the plot. If there is no change in travel time during a time period then there is assumed to be no change in fuel consumption. A linear regression through the origin was performed on the data points to determine a linear relationship between travel time savings and the estimated reductions in fuel consumption. The line through the origin has an R^2 value of 0.2. This does not indicate a strong linear relationship, though a positive linear relationship is evident. If the data points with an increase in travel time or an increase in fuel consumption are removed from the plot the relationship between fuel savings and travel time savings remains largely the same. This relationship is shown in Figure 15. Obviously other factors such as the relative change in average speeds or accelerations would help to predict fuel savings.

Table 11: **Travel Time Analysis**

Average Travel Time Savings Per Vehicle

Bottleneck Projects		Before Improvement Minutes	After Improvement Minutes	Change Minutes	% Change
1	IH35E NB PM	9.35	7.83	-1.51	-16.2%
2	IH35E SB AM	11.30	8.66	-2.64	-23.4%
3	IH35E SB PM	12.61	9.25	-3.36	-26.8%
4	IH20/408 AM	2.91	2.46	-0.45	-15.4%
5	IH20/408 PM	2.67	2.29	-0.38	-14.3%
6	IH635 EB AM	4.77	3.19	-1.58	-33.2%
7	IH635 EB PM	5.69	3.68	-2.01	-35.4%
8	IH635 WB PM	6.03	3.59	-2.44	-40.5%

Total Travel Time Savings

Bottleneck Projects		Before Improvement Veh-hours	After Improvement Veh-hours	Change Veh-hours	% Change
1	IH35E NB PM	24,220	20,320	-3,900	-16.1%
2	IH35E SB AM	39,310	29,610	-9,700	-24.7%
3	IH35E SB PM	40,580	29,690	-10,990	-26.8%
4	IH20/408 AM	1,440	1,190	-250	-17.3%
5	IH20/408 PM	1,690	1,430	-260	-15.3%
6	IH635 EB AM	6,540	4,350	-2,190	-33.5%
7	IH635 EB PM	9,970	6,450	-3,520	-35.3%
8	IH635 WB PM	12,110	7,180	-4,920	-40.7%

Figure 14. Bottleneck Improvements

Travel Time Savings vs. Fuel Savings

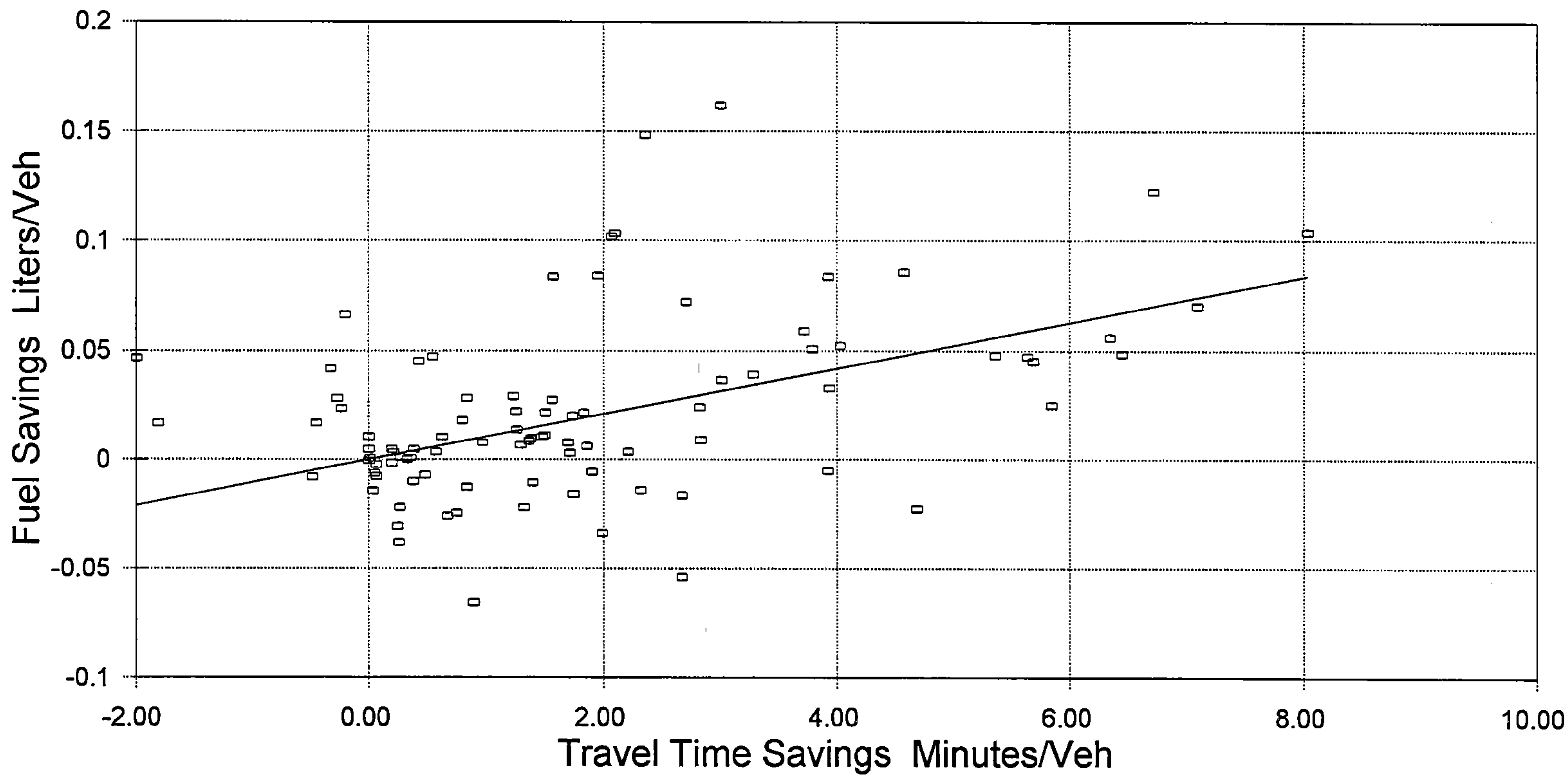
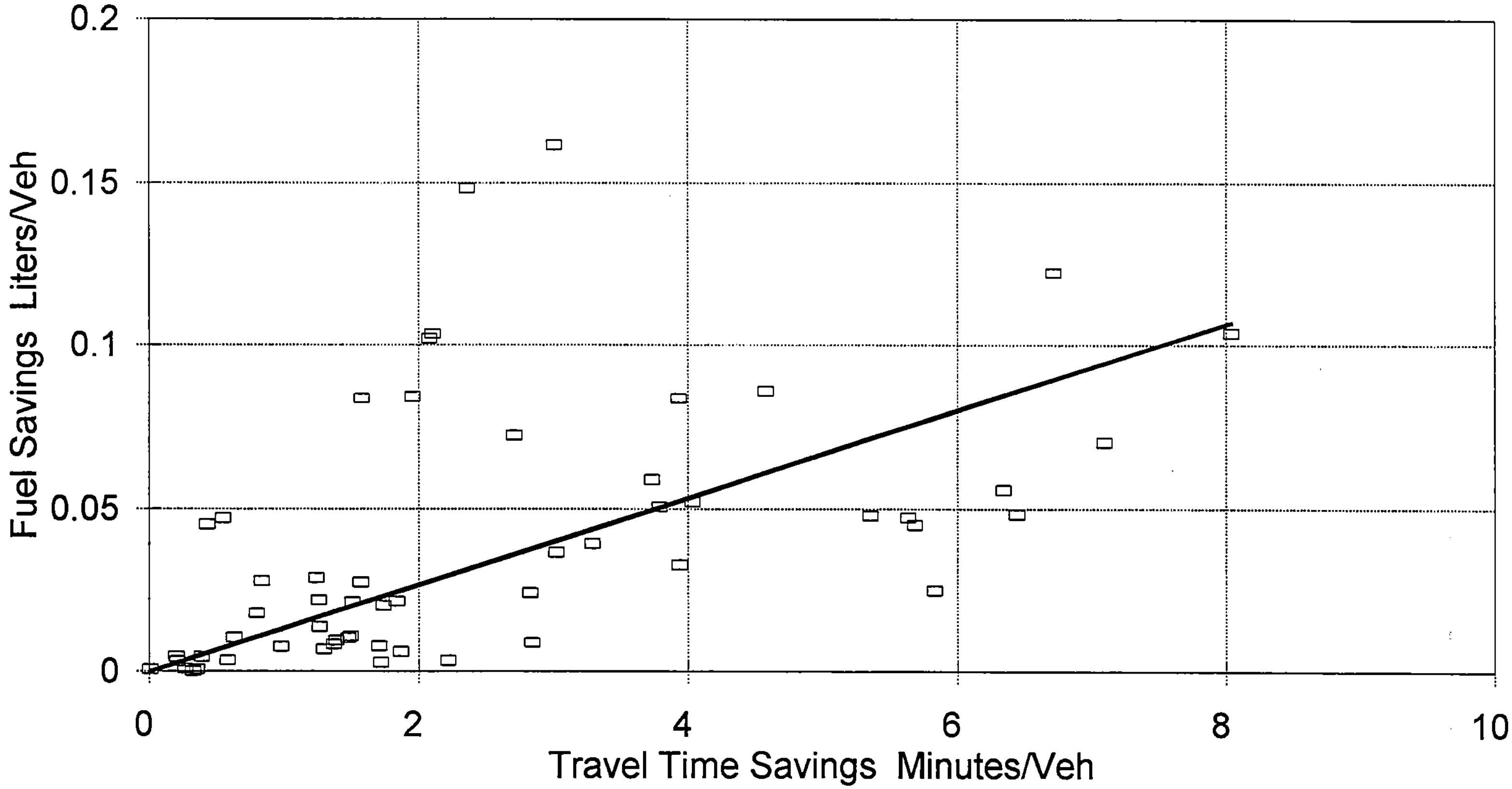


Figure 15. Bottleneck Improvements

Travel Time Savings vs. Fuel Savings



Application of Results

The third objective of this research was to develop guidelines for predicting energy and air quality benefits from implementation of future freeway bottleneck improvement projects. Energy savings will only occur where there is a significant decrease in travel time, though a reduction in travel time does not necessarily result in fuel savings. If the average speed of vehicles increases more than 80 kph (50 mph) an improvement may result in an increase in fuel consumption. The emissions of VOC and CO are more difficult to quantify and there is considerable uncertainty in the rates used with the average speed methodology. However, it is apparent that reductions in these emissions are significant when there is a significant decrease in travel time. It is also apparent that there would be a decrease in these emissions, particularly for CO emissions, where there is a smoothing of the traffic flow or where stop and go driving is reduced without raising the average speed. Of course this is not possible to identify using an average speed methodology. Similarly to fuel consumption, these emissions increase at high average speeds. Emissions of NO_X are produced differently than the VOC and CO emissions. The hard accelerations that occur during enrichment phases common to stop and go driving do not appear to increase NO_X emissions. NO_X emissions only appear to increase with speed, though there is some increase at low speeds less than 32 kph (20 mph). As a result, with any traffic flow improvement that decreases the average travel time significantly an increase in NO_X emissions may be expected. However, the results of the Pike Pass analysis as shown in Table 9 show that the NO_X emissions decrease with higher speeds for the vehicles that were tested in the Pike Pass project. This serves as an illustration of the current uncertainty within the research community at this time. Until future research with actual measured emissions is available for stop and go driving conditions, it is at least speculative to assume an increase in VOC, CO, and NO_X at smoother and higher speeds.

In general a positive relationship appears to exists between reductions in fuel consumption, VOC emissions, and CO emissions, and travel time savings at average speeds below the speed of 88 kph (55 mph). However, the relationship between NO_X emissions and travel time savings is indeterminate at this level of analysis. Due to the uncertainty of emissions models no guidelines are defined for predicting emissions. For fuel consumption a reduction of 0.013 liters (0.0035 gallons) per vehicle can be expected for every minute in travel time savings for a typical bottleneck improvement with significant travel time savings and average speeds that do not exceed the speed of 88 kph (55 mph).

The results of this report will be implemented to reduce energy consumption in Texas by presenting a methodology to transportation officials for predicting the fuel consumption of freeway bottleneck improvement projects as well as other freeway traffic flow improvements. The ability to predict fuel consumption will help determine the best alternative for freeway bottleneck improvements or any freeway traffic flow improvements, and it will help measure the effectiveness of finished freeway improvements which provide significant travel time savings to motorists.

Summary

The primary goal of this study was to determine a method to estimate the anticipated decrease in fuel consumption and emissions for any freeway bottleneck removal project. The first objective to meet this goal was to perform a comprehensive literature review. The literature review failed to reveal a specific method for estimating the fuel consumption or emissions reductions from bottleneck improvements or for any transportation improvement that smooths traffic flow. MOBILE5a is the primary model for estimating mobile source emissions, and emission rates generated by the MOBILE5a model were obtained from the NCTCOG to use in an average speed methodology for estimating emissions. Generally the average speed method is more suited to larger or regional scale analysis than individual project level analysis, but the state of the existing data would not allow for a more detailed analysis. The initial results of this methodology were unsatisfactory, and additional literature was reviewed to find better fuel consumption or emission rates or a more adequate methodology for estimating fuel consumption and emissions. It was found that most transportation officials agree that mobile source models underestimate VOC and CO emissions. Also, a better method of estimating fuel consumption using the ARFCOM model was found.

Three bottleneck improvement projects were selected for analysis with good before and after volume and travel time data. Each project was divided into corridors for a total of eight corridors, and each corridor was divided into as many sections as the data permitted to determine the average speeds. The primary benefit of bottleneck improvement projects is in travel time savings. Each of the eight movements of the three bottleneck improvement projects studied for this analysis resulted in travel time savings for motorists. The travel time savings can be easily quantified and used to determine the average speeds through each corridor

The next objective was to quantify the change in fuel consumption and emissions from implementation of freeway bottleneck improvement projects. The changes were estimated using an average speed model methodology, despite considerable disputes as to the validity of the MOBILE5a model for individual project analysis. The total amount of fuel consumption or emissions was estimated by multiplying the fuel consumption rate or emission rate for a specific average speed by the known distance and the 15-minute volume of the section. All but one corridor improvement showed a decrease in fuel consumption. The change in fuel consumption per vehicle ranged from 1.6 % to -7.4%, and the total change in fuel consumption ranged from -0.0% to -5.2%. Each corridor showed a decrease in VOC emissions. The change in VOC emissions per vehicle ranged from -4.3% to -24.4%, and the total change in VOC emissions ranged from -4.8% to -24.0%. Some corridors showed an increase in CO emissions. The change in CO emissions per vehicle ranged from 15.2% to -25.6%, and the total change in CO emissions ranged from 15.7% to -26.5%. Each corridor showed an increase in NO_X emissions. The change in NO_X emissions per vehicle ranged from 29.4% to 5.8%, and the total change in NO_X emissions ranged from 31.0% to 4.3%.

There are several reasons for the calculated fuel consumption and emissions benefits being lower than expected. One reason is the actual physics which apply under the high speeds for the after conditions of most of the bottleneck conditions. When speeds exceed 80 kph (50 mph) wind resistance becomes a dominant factor and fuel consumption rates increase with speed. If the maximum speed through the bottlenecks is limited to 88 kph (55 mph) and the same volumes are used with the average speed methodology, the fuel consumption is reduced.

The second reason is that the average speed methodology does not effectively estimate the fuel consumption and emissions of stop and go traffic flow conditions. The primary alternative method, a drive-mode element type model, should be more suitable for estimating the fuel consumption and emissions of stop-and-go traffic flow conditions, though modal fuel consumption and emission rates do not exist for this type of model. A simplified version of the drive-mode model was tested and found to be ineffective because accelerations were not accounted for in the before and after data collection. The main problem of the simplified drive-mode model was the data collection equipment, which could be remedied by using automatic DMI equipment similar to that used by the Houston office of TTI. Data collected with the automatic DMI equipment by the Houston office was analyzed with the ARFCOM model. The results of the analysis showed that the average speed methodology may be adequate for estimation of fuel consumption despite the frequent changes in speed created by recurring traffic congestion, if these changes are fully measured and analyzed. However, no acceptable means of calculating the changes in emissions was identified. A comparison was made with a carefully controlled study on emissions at a toll facility in Oklahoma, where stops could be avoided with tolltags. This comparison yielded results in sharp contradiction with the MOBILE5a model which predicts higher emissions in all three pollutants for the nonstop condition; the free-flow condition produced the least emissions.

To identify the energy savings of bottleneck improvement projects the observed travel time savings were compared to the estimated fuel consumption. The percent change in fuel consumption is much lower than the percent change in travel time for each bottleneck improvement analyzed. This indicates that other factors may help better identify energy savings. A linear regression analysis was performed to establish a relationship between travel time savings and fuel consumption. Though a strong linear relationship between travel time savings and fuel consumption is not evident it can still be used to set general guidelines for predicting energy savings. These guidelines can be used to help determine the best alternative for freeway bottleneck improvements or any freeway traffic flow improvements, and it will help measure the effectiveness of finished freeway improvements which provide significant travel time savings to motorists.

Conclusions

The primary goal of this study, to determine a method to estimate the anticipated decrease in fuel consumption and emissions for any freeway bottleneck removal project, was met. The results using the average speed methodology with the emission rates obtained from the MOBILE5a model have been shown to be inaccurate at high average speeds and also at low average speeds when speed fluctuations occur in bottleneck conditions. At high speeds above 88 kph (55 mph) the MOBILE5a model overestimates emissions rates for VOC, CO, and NO_X emissions which is shown in the results of the Pike Pass study. At low average speeds that exist in stop-and-go driving the MOBILE5a model underestimates emission rates for VOC, and CO due to the lack of enrichment events in the FTP drive cycle. This is not to say that the MOBILE5a model is inappropriate for use, but that it is clearly not appropriate for the level of analysis required for comparing before and after conditions of freeway bottleneck improvements. There are several efforts currently underway to improve the MOBILE model as well as to develop various other models for estimating emissions for individual traffic flow improvements. The new models may appear similar to the ARFCOM model used for fuel consumption; that is, they will be suitable for a variety of input data levels, but most accurate using detailed speed data obtained with DMI equipped vehicles. The fuel consumption amounts obtained with the average speed method appear accurate for smooth traffic flows. However, a more detailed analysis with data obtained with DMI equipped vehicles would reflect the increased fuel consumption due to speed fluctuations in bottleneck conditions. The average speed method removes the number and magnitude of speed fluctuations from the model. At low average speeds before bottleneck improvements are made, conditions with stop-and-go driving speed fluctuations are much more frequent.

The average speed methodology as used in this study is not suitable for the level of analysis necessary to compare the before and after conditions of bottleneck improvements. In the meantime, until future models are available, detailed speed or travel time data should be collected with DMI equipped vehicles. With new models suitable for using the detailed speed data the higher anticipated changes in fuel consumption and emissions should be able to be estimated. The reduction in fuel consumption with bottleneck removal should be at least the same or higher than the average speed method, up to 42%, depending upon the level of traffic flow improvements obtained with the bottleneck removal. The method used with the Pike Pass study showed a reduction for VOC of 84%, a reduction for CO of 72%, and a reduction of NO_X of 46% for the elimination of a full stop at a toll booth. Whether these findings are applicable to future analysis is unclear; the actual reductions in fuel consumption and emissions may be even higher. However, significant reductions in fuel consumption and emissions with traffic smoothing due to bottleneck removals are indeed possible. Additional research will help identify the magnitude of these reductions.

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