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Modeling IVHSEmission Impacts. Volume 1: Background Issues And Modeling Capabilities

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Modeling IVHS Emission Impacts

Volume 1:
Background Issues and Modeling Capabilities

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ABSTRACT

The existing motor vehicle emission modeling regime was never developed with the intent of accurately assessing the impacts of transportation strategies at the corridor level. Hence, it should not be surprising that our modeling capabilities are limited when it comes to assessing the potential air quality impacts of intelligent vehicle and highway systems. This paper examines the potential effects of **IVHS** upon important emission-producing vehicle activities and those parameters that affect emission rates. Important emission relationships are identified, a framework for comparative analysis is developed, and the general relationships between **IVHS** technology bundle characteristics and vehicle emission impacts are examined.

The primary **IVHS** emission-related impacts that this project addresses are associated with changes in the average speed and operating mode (acceleration, deceleration, cruise, and idle) characteristics of the vehicle fleet. The emission model algorithms associated with the average speed modeling regime are assessed in the second part of this volume.

KEYWORDS

Intelligent Vehicle and Highway Systems
Motor Vehicle
Emissions
Environmental Impact
Advanced Traveler Information Systems
Advanced Traffic Management Systems
Advanced Vehicle Control Systems
Commercial Vehicle Operations
Advanced Public Transportation Systems

EXECUTIVE SUMMARY

Motor vehicles contribute a large percentage of pollutant emissions in urban areas. **IVHS** technologies are being developed to improve the efficiency of the transportation system, which will have different potential effects on vehicle emissions. However, the exact emission impacts of **IVHS** technologies resulting from the potential improvements in the transportation system are not known. Further, assessing the emission impacts of **IVHS** requires using existing motor vehicle emission models which were never designed to assess impacts on a corridor level. Thus, it is not possible to evaluate **IVHS** impacts without a large degree of uncertainty. This paper examines the potential effects of IVHS upon important emission-producing vehicle activities and those parameters that affect emission rates. Important emission relationships are identified, a framework for comparative analysis is developed, and the general relationships between **IVHS** technology bundle characteristics and vehicle emission impacts are examined. The **5 IVHS** technological bundles examined include: 1) Advanced Traffic Management Systems (ATMS); 2) Advanced Traveler Information Systems (ATIS); **3)** Advanced Vehicle Control Systems (AVCS); **4)** Commercial Vehicle Operations (CVO); and **5)** Advanced Public Transportation Systems (APTS).

The five **IVHS** technology bundles have potential to change emission producing vehicle activities such as VMT, cold and hot engine **starts,** hot soaks, engine idling, diurnal evaporation, refueling, and modal accelerations and decelerations. In looking at these emission producing vehicle activities it is important to consider location, peak and off-peak times, and recurrent and non-recurrent congestion.

The California Air Resources Board's emission rate model (EMFAC7F) and the **US** Environmental Protection Agency's emission rate model **(MOBILE5**.0a) employ an average speed modeling regime to calculate running exhaust emission rates. The average speed algorithms exhibit a large range of uncertainty and the relationship between average speed and emissions is tenuous at best. Speed correction factors used in these empirical models do not account for impacts of vehicle operating modes (such as acceleration and deceleration effects and increased engine load) which adds further to the uncertainty in the assessment **IVHS** emission impacts and may result in an underestimation of modeled **IVHS** emission reduction benefits associated with traffic flow smoothing.

The impact assessment of IVHS-related level of service using the conventional models available today is questionable. The analyses that follow are similar to those previously undertaken by the authors and the qualitative conclusions that we can reach based upon our knowledge of the cause effect relationships at work are identical: 1) where **IVHS** causes automobile vehicle trips and vehicle miles of travel to decline, emission benefits for all pollutants will accrue, to the extent that they are not offset by increased emissions from alternative modes; 2) where **IVHS** reduces congestion and smoothes traffic flow, emission rates per mile of travel will likely decline for carbon monoxide and hydrocarbons, but will likely increase for oxides of nitrogen; **3)** if **IVHS** yields increased vehicle activity at high speeds, in excess of **88.7** kph **(55** mph), emission increases are likely for all pollutants; and **4)** where **IVHS** increases congestion and lowers average operating speeds on local roads, emission rates per mile of travel will likely increase for all pollutants.

To better evaluate the emission impacts of **IVHS** systems: 1) land use models need to be capable of incorporating the influence of new **IVHS** infrastructures; **2)** travel demand models need to be upgraded to consider fundamentally different highway capacity (traffic flow) relationships, to be more sensitive to microscale traffic flow changes, and to incorporate additional feedback loops between the various travel demand model components; and **3)** emissions models need to represent relationships between vehicle operating modes and emissions more accurately. **As** these analytical tools evolve, the impacts of **IVHS** implementation can be better evaluated.

The primary goal of IVHS-related emissions research should be to identify and quantify the important cause-effect relationships at work. To achieve this goal, the effect **of** modal vehicle operations on emissions must be further investigated. Future IVHS-emissions research should be designed **to:** 1) identify important emission related vehicle activities in the **IVHS** and non-**IVHS** vehicle fleets affected by **IVHS** implementation; **2)** develop a modal emission modeling framework, applicable to **IVHS** and non-IVHS vehicle fleets; **3)** improve existing transportation demand models or develop new activity modeling approaches that combine demand and simulation ***so*** that modal activity outputs can be estimated; **4)** develop a new modal emissions model using second-by-second emission testing data now becoming available; and 5) analyze the implications of **IVHS** implementation, in terms of **IVHS** and non-**IVHS** vehicle performance profiles, based upon the emission rate model outputs.

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1.0 INTRODUCTION

Advanced transportation technologies can range widely in their scope, from some of the simpler systems that provide drivers with real-time congestion conditions along their travel routes, to the tremendously complex systems that may eventually provide fully automated vehicle control. Advanced technologies applied to motor vehicles and the infrastructure are generally known as Intelligent Vehicle Highway System (IVHS) technologies. Combinations of these advanced technologies, known as "technology bundles," are being promoted as a means of reducing congestion delay, and also as a means of making vehicle travel "...more energy efficient and environmentally benign (USDOT, 1990). In theory, **IVHS** technologies will increase the efficiency, capacity, and safety of the existing highway system to reduce congestion (Saxton and Bridges, 1991; Conroy, 1990; Shladover, 1991; Shladover, 1989) and as traffic congestion is reduced and traffic flows are smoothed, significant air quality benefits are expected to accrue. On the other hand, increased travel efficiency and reduced trip times may increase trip generation, change travel destinations, increase single occupant vehicle use, and change travel routes. Hence, if IVHS systems lead to increases in the number of trips and vehicle miles traveled, the emissions associated with increased travel may negate some or all of the expected efficiency-related air quality benefits achieved from smoother traffic **flows.**

The five basic **IVHS** "technology bundles" (Jack Faucett Associates, 1993a) include: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), Commercial Vehicle Operations (CVO), Advanced Public and Transportation Systems *(APTS).*[1] Each of these technology bundles is designed to achieve the same general goal; improve the efficiency of the transportation system through the application of technology. However, the efficiency objectives targeted by each technology bundle are distinctly different, and will have different potential effects upon the parameters that effect vehicle emissions.

This paper summarizes earlier papers, addressing the general relationships that are important in determining the potential impacts of **IVHS** systems (Sperling, et al., 1992; Guensler, 1993b; Washington, Guensler, and Sperling, 1993a; Washington, Guensler and Sperling, 1993b; Guensler, Sperling, and Washington, 1993; Lawrence, 1993; Jack Faucett Associates, 1993b). These papers noted problems in the capabilities of existing models to estimate IVHS emissions impacts. The papers also explored the emissions implications of deploying IVHS "technology bundles" by examining potential effects upon important emission-producing vehicle activities and the parameters affecting vehicle emission rates. Specific discussions and analyses related to modeling these emissions are included in this work.

Given the vehicle activity and emission rate modeling shortfalls that currently exist, evaluating the air quality impacts of IVHS impacts with today's modeling tools will be highly uncertain and impossible to determine in a definitive manner. What is possible, and what we do in this

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[1] Emergency Vehicle Services (EVS) is considered by many to constitute a separate **IVHS** technology bundle. EVS would include such approaches as preferential signal timing, automated accident identification and emergency response systems, etc. Because all of the EVS systems and approaches are limited subsets of the other technology bundles, EVS is not discussed as a separate bundle in this report.

paper, is **to:** I) identify the important emission relationships, 2) discuss the general framework used to compare emission impacts, **3)** examine the general relationships between the characteristics of **IVHS** technology bundles and how these characteristics are likely to positively or negatively impact vehicle emissions. Then, the current emission modeling algorithms associated with changes in vehicle operating modes (expressed specifically as changes in average operating speed) are assessed. Based upon the literature review and results of analyses, model improvements that are needed for proper evaluation of **IVHS** implementation scenarios are summarized.

2.0 IVHS TECHNOLOGY BUNDLES

Based upon literature review prepared for the Faucett study (Jack Faucett Associates, 1993a), five **IVHS** technology bundles are discussed: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), Commercial Vehicle Operations (CVO), and Advanced Public Transportation Systems (APTS) (sometimes Emergency Vehicle Services **(EVS)** is treated as a separate technology bundle). Each of these technology bundles is designed to achieve the same general goal, i.e. improving the efficiency of the transportation system through the application of technology. However, the efficiency objectives targeted by each technology bundle are distinctly different.

Because the purposes of the technology bundles are different, each bundle will have different potential effects upon the parameters that effect vehicle emissions. However, it will become clear in later discussions that the problems inherent in the current vehicle emissions models are fundamental in nature. Hence the emission modeling problems apply across all of the technology bundles (although not to an equal degree). In fact these problems apply outside of the IVHS arena as well, to such applications as the evaluation of regulatory and market-based transportation control measures.

2.1 Advanced Traffic Management Systems (ATMS)

As the name implies, advanced traffic management systems use computer control to optimize transportation flows on the vehicle network. Examples of ATMS technologies would be traffic light network optimization and ramp metering. Both of these computer controlled systems are designed to reduce congestion levels; the first program for city streets and the second program for freeways. ATMS technology bundles would also include: various signal actuation bundles, electronic toll collection, congestion pricing, incident detection, rapid accident response, and integrated traffic management.

The goal of the fuel efficient traffic signal management (FETSIM) program is to minimize stop delay in the signalized network and to thereby improve the fuel efficiency of vehicles by minimizing inertial losses (CEC, 1983; LADOT, 1987; Deakin, et al., 1984). To accomplish the delay reductions, signal timing systems are networked and optimized by computer such that efficient flows of traffic platoons, uninterrupted by stops, can be facilitated. Traffic signal management can reduce the stop delays and idling time on the city grid, as well as improve traffic flow, thereby reducing delay, fuel consumption, and emissions.

Ramp metering is designed to maintain smooth ramp flows, reducing weaving at the freeway merge, maintaining capacity in the right-most lanes, and maintaining smooth flows and higher levels of service on the freeway (TRB, 1985). Again, ramp metering is designed to reduce congestion, fuel consumption, and emissions. However, there is currently a controversy over whether the emissions saved on the freeway segment from flow smoothing and increased average speeds is partially, or completely, offset by the emissions imposed by the higher rate of vehicle acceleration from the ramp queue into the freeway flow.

Congestion pricing is advocated by many in academia, as well as in both the environmental and business communities, as a rational means for reducing congestion in urban areas (TRB, 1994). The implementation of congestion pricing schemes is highly controversial, as motorists have become accustomed to paying for their transportation through other means such as gasoline taxes and hidden charges such as sales and property taxes (TRB, 1994). The ability to implement congestion pricing through the application of advanced technologies is considered by many to be the biggest asset of the **IVHS** research. Congestion pricing has the potential to fundamentally change trip making behavior and thereby reduce vehicle hours of delay associated with stop and go driving in urban areas (Harvey, 1994; Guensler and Sperling, 1994). By smoothing traffic flow through congestion pricing the elevated emission rates associated with stop and go driving can be reduced (Guensler and Sperling, 1994). However, as will become evident in the course of this document, .accurate and quantitative estimates of congestion pricing impacts on air quality are not possible at this time because a number of fundamental [emission modeling] problems exist (Guensler and Sperling, 1994)..

2.2 Advanced Traveler Information Systems (ATIS)

The purpose of advanced traveler information systems is to provide information to individuals about routes and system conditions ***so*** that individual travel decisions can be optimized. The provision of additional information to the consumer is thought to be a step toward improving travel efficiency. For example, ATIS technologies include onboard maps and onboard computerized route guidance assistance. Route guidance systems are designed to prevent traveler from becoming lost, making trips more efficient. With active information exchange between vehicles and roadside computers, route guidance systems will also provide network congestion information to the operator ***so*** that alternative routes (perhaps somewhat longer in distance but greatly shorter in time) can be selected. Various ATIS system would include: onboard navigation, electronic route planning, radio data systems, externally linked route guidance systems, vehicle condition warning systems, emergency mayday beacons, changeable message signs, ridesharing information availability.

2.3 Advanced Vehicle Control Systems (AVCS)

Advanced vehicle control systems range from technologies designed to control the lateral and longitudinal separation of vehicles for safety purposes to comprehensive systems that would control the entire operation of the vehicle from the beginning to the end of a trip. Various AVCS bundles include: automated headway control, automatic steering control, rural intersection hazard warning, and collision avoidance systems.

In concept, AVCS technologies are being developed so that freeway capacity can be increased without requiring the acquisition of additional right-of-way and constructing additional freeway lanes. Capacity increases are achieved under AVCS in two ways: 1) lane widths are narrowed because computer controls will significantly reduce the need for buffer space on the sides of moving vehicles, and **2)** vehicle gaps, or space between the tail of the lead vehicle and the head of the following vehicle, are reduced because the computer linkage between vehicles will significantly reduce the reaction time for braking maneuvers. Because automated control of steering and braking partially removes the driver from the decision-making loop, the same or better margin of safety can be achieved with shorter separation distances maintained around the vehicle by a computer. Subsequently, driver-induced accidents, bottlenecks, rubbernecking, flow breakdowns, stop-and-go commuter traffic, and other factors restricting capacity can theoretically be minimized or eliminated.

2.4 Commercial Vehicle Operations (CVO)

Commercial vehicle operations are technologies designed to improve the efficiency of freight transportation, primarily by minimizing time lost during demonstration of regulatory compliance. For example, computerized weigh-in-motion systems are designed to determine compliance with axle load requirements while the vehicle is in motion. At the same time, electronic bills of lading and driver credentials can be verified by state authorities without delaying the vehicle at a weigh station. Examples of other CVO technologies include: driver log monitoring, safety inspection monitoring, hazardous material tracking, automated fleet locator systems, and electronic mileage reporting. A number of these systems have been implemented in the CRESCENT program, serving the major truck route from Washington state to Texas, along the coastal crescent (passing through Oregon, California, Arizona, and New Mexico).

2.5 Advanced Public Transportation Systems (APTS)

Intelligent public transit systems could range in scope from computerized rideshare matching (perhaps even in-vehicle matching) to personal rapid transit systems. Technologies could also include: computerized or video transit schedule displays, automated information onboard transit regarding destinations, interactive kiosks at transit terminals, electronic billing, automated fleet maintenance and tracking, and automated HOV lane enforcement. These systems would be designed to make carpooling and transit easier and more convenient for individuals, lowering the actual and perceived costs of alternative modes, and improving the likelihood that the alternative modes will be selected over the single occupant vehicle.

2.6 Emergency Vehicle Services (EVS)

Emergency vehicle services would include systems designed to give priority to vehicles responding to an emergency situation, such as fire trucks and ambulances. Such systems might also include rapid accident response systems (designed to remove accidents quickly and reduce congestion duration and air quality impacts). However, we have chosen to include rapid accidents response in the advanced traffic management system. Because emergency vehicle services other than rapid accident response are not likely to impact motor vehicle emissions, these systems will not be included in the discussions that follow throughout the document.

3.0 MOTOR VEHICLE EMISSIONS

Motor vehicles account for the lion's share of air pollutant emissions in urban areas; typically more than 50% of volatile organic compound (VOC) and oxides of nitrogen (NOx) emissions, both of which are precursors to ozone formation, and more than 80% of carbon monoxide (CO) emissions. Of course, estimated transportation contributions of these pollutants vary from area to area (see table 1).

Table 1: Emissions from On-Road Vehicles in California's Urban Areas (Percent of Total 1987 Emission Inventory)

	Air Pollution Control District			
Pollutant	**Bay Area**	**Sacramento**	**San Diego**	**South Coast**
Volatile Organic Compounds (VOC)	46%	42%	56%	46%
Oxides of Nitrogen (NOx)	60%	66%	59%	60%
Carbon Monoxide (CO)	80%	63%	92%	86%

VOCs are those hydrocarbons that participate in ozone-forming chemical reactions in the atmosphere

Recent studies clearly indicate that motor vehicles emissions are even higher than reported by the US Environmental Protection Agency (USEPA) and California Air Resources Board (CARB); perhaps by as much as a factor of two to four for hydrocarbons and carbon monoxide (NRC, 1991; Bagues, 1991; Bradow, 1992). On one hand, the underestimation of on-road motor vehicle emissions probably means that additional motor vehicle emission control strategies need to be implemented, on the other hand those emission control strategies that are implemented probably yield much larger emission reductions than are currently estimated by the models (because control strategy effectiveness is often calculated as percentage reductions from baseline emissions). The bottom line is that the actual causes of vehicle emissions must be better understood before emission reduction strategies can be properly evaluated.

Motor vehicle emissions are estimated by quantifying emission-producing vehicle activities and coupling these activities with activity-specific emission rates. Note that this presumes that the analyst knows what activities produce emissions. For example, vehicle miles of travel and engine idling are activities known to produce emissions, and gram/mile and gram/hour emission rates can be developed for these vehicle activities under various operating and environmental conditions. The sections that follow describe the current emission modeling regime.

3.1 Emission-Producing Vehicle Activities (Guensler, 1993b)

Motor vehicles pollute, whether operating on expressways or parked in driveways. For the purposes of estimating emissions, the action being performed by the vehicle (or inaction) at the time the emissions occur is an emission-producing vehicle activity. Table 1 contains the general vehicle activities known to produce vehicle emissions that are often included in the emission inventory modeling process, as well as the type of emissions that are produced:

There are two controlling factors in vehicle emission rates: 1) how much fuel is being burned and therefore how much exhaust gas must be treated, and 2) how efficiently the fuel is being burned and how well the after-treatment devices are functioning.

Fuel consumption rates have been correlated to average vehicle operating speed and the characteristics of trip conditions (Bowyer, et al., 1985). In general, at low average operating speeds fuel consumption is high, and fuel efficiency increases with speed as the engine approaches maximum thermal efficiency. Hence, strategies that increase average operating speed can yield average fuel economy improvements. **As** mentioned earlier, for any given vehicle, if fuel economy is improved, the amount of exhaust gas to be treated is generally reduced. Secondly, under congested traffic conditions of unstable flow (evidencing stop-and-go motion) the repetitive use of braking systems results in energy losses that increase fuel consumption. Typically, on the order of 10% of fuel energy can go toward overcoming inertia, and as inertial requirements increase **so** does fuel consumption. Strategies designed to keep traffic conditions flowing smoothly minimize the number of **starts** and stops, increasing average fuel efficiency (however, at very high speeds fuel efficiency can decrease significantly due to inefficient combustion). Thirdly, operator behavior, or driving style, can affect fuel consumption. **A** recent study indicated that a difference of more than 20% in fuel economy can be experienced by different drivers of the same heavy-duty vehicle (Millican, 1989). Education strategies can be used by heavyduty fleet managers to help drivers understand how high engine speeds can adversely affect fuel consumption and engine life. In fact, one company noted an average 27% increase in fuel economy after implementing an ongoing education program with repetitive driver feedback (Millican, 1989).

Carbon monoxide forms as a result of incomplete combustion, when fuel carbon is not completely oxidized to carbon dioxide. Volatile organic compounds evolve from evaporation of fuel during storage and transfer, or as the result of incomplete combustion. Oxides of nitrogen are formed when elemental nitrogen in the combustion air (N_2 is roughly 78% of ambient air) is passed through the combustion chamber under conditions of high temperature and pressure; the nitrogen combines with oxygen in the combustion air to form NOx. Fine particulate matter (PM_{10}) consists of solid particles and liquid droplets, also resulting from incomplete combustion. Because ambient air has negligible sulfur content, oxides of sulfur are formed by the oxidation of elemental sulfur contained in the fuel. Thus, with the exception of SOx, which is solely fuel dependent, the emissions outlined in table 1 result from either evaporation or incomplete combustion.

The elevated emissions of CO, NOx, PM_{10}, and SOx, noted in table 2 generally result from engine conditions that exacerbate incomplete combustion and from catalytic converter temperatures too low to facilitate efficient control of exhaust gas emissions (Jacobs, et al., 1990; Heywood, 1988; Joy, 1992; Stone, et al., 1990; Pozniak, 1980). When an engine is cold, fuel vaporizes slowly and the fuel/air ratio is adjusted upward to obtain a combustible mixture. Cylinder walls are cold, causing partial quenching of the combustion flame at the wall, increasing CO, VOC and PM_{10} emissions. Engine **starts** cause elevated running exhaust emission rates for the first few minutes of operation, until the engine warms-up and the emission control catalyst reaches light-off temperature and begins to efficiently control tailpipe emissions (Joy, 1992). Studies also indicate that fuel consumption for short trips under cold **start** conditions yield a significant increase in fuel consumption, approximately 25%, compared to warm engines (Stone, et al., 1990; Pozniak, 1980). Increased fuel consumption appears to result primarily because fluids and lubricants in a cold engine are also more viscous. The elevated internal mechanical friction that must be overcome during engine warm-up causes the decrease in fuel efficiency. Decreased fuel efficiency means more fuel must be combusted per mile, increasing the total amount of exhaust gas that must be controlled for a given distance, and typically increasing pollutant emissions (i.e. assuming the same level of control is maintained by the catalytic converter). Plus, because more fuel is combusted, the emissions of fuel-bound sulfur compounds will be slightly elevated.

Two modeling approaches can be used to address elevated emission rates: 1) the cause can be modeled as a discrete emission-producing activity (e.g. an engine **start),** and the emissions treated as a discrete "puff;"or 2) the emission rate for the parent activity (e.g. the running exhaust emissions that are elevated by the cold **start)** can be adjusted upward when the conditions that cause elevated emission rates are noted. The California Air Resources Boards (CARB's) emission rate model (EMFAC7F), for example, treats the elevated engine **start** emissions as a single "puff' (i.e. separate from running exhaust) and multiplies the number of engine starts by a cold **start** emission rate. The US Environmental Protection Agency's (USEPA's) emission rate model (MOBLES0), on the other hand, increases the calculated running exhaust emission rate for vehicles, based upon an assumed fraction of vehicles operating in cold start, hot **start,** and hot stabilized modes.

The empirical models used to develop the speed correction factors for motor vehicle emission rates do not account for modal operations, such as acceleration and deceleration activities that cause enrichment. Unfortunately, modal emission rates and relationships for both the current and future vehicle fleet are relatively unknown at this time, and potential emission tradeoffs associated with changing vehicle flow parameters cannot be evaluated without further analysis of existing and future data. As additional second-by-second emission profiles become available for modern vehicles that are likely candidates for **IVHS** incorporation, these tradeoffs will become more clear (at least for those vehicles for which data become available). However, it is likely that the projected emission effects that result from specific modal operations will play a very important role in determining which vehicles will ultimately be selected for **IVHS** incorporation. Individual vehicle emission behavior and final **IVHS** vehicle fleet profiles are inextricably linked.

Congestion relief is likely to reduce the number of significant acceleration and deceleration events that cause elevated emission rates. Yet, the emission tradeoffs between improved flows on automated freeway links and degraded flows on non-automated connector surfaces is unclear at this time. Better tools are needed to assess the impacts of changes in modal operations, because traffic flow tradeoffs resulting from **IVHS** and other transportation improvement strategies are complex. Consider **for** example the effect on driving conditions of "improving" one part of the highway system: doing so may push congestion elsewhere, and in a complex non-linear manner. For example, ramp metering reduces congestion on the freeway upstream of the onramp but also causes congestion on the freeway onramp itself; congestion

Table 2: Emission-Producing Vehicle Activities and Emissions Produced

Emission-Producing Vehicle Activity	Type of Emissions Produced
Vehicle Miles Traveled	• Running Exhaust (CO, VOC, NOx, PM_{10}, SOx) • Running Evaporative Emissions (VOC)
Cold Engine Starts	• Elevated Running Exhaust Emissions (CO, VOC, NOX, PM_{10}, SOX)
Warm or Hot Engine Starts	• Elevated Running Exhaust Emissions (CO, VOC, NOx, PM_{10}, SOx)
Engine "Hot *Soaks*" (shut-downs)	• Evaporative Emissions (VOC)
Engine Idling	• Running Exhaust Emissions (CO, VOC, NOx, PM_{10}, SOX) • Elevated Evaporative Emissions (VOC)
Exposure to Diurnal and Multi-Day Diurnal Temperature Fluctuation	• Evaporative Emissions (VOC)
Vehicle Refueling	• Evaporative Emissions (VOC)
Modal Behavior (e.g. High Power Demand, Heavy Engine Loads, or Engine Motoring)	o Elevated Running Exhaust Emissions (*CO*, VOC, NOx, PM_{10}, SOx)

CO = Carbon Monoxide; VOC = Volatile Organic Compounds; NOx = Oxides of Nitrogen; PM_{10} = Fine Particulate Matter (less than 10 microns in diameter) ; SOx = Oxides of Sulfur

Source: Guensler, 1993b

that can spill over onto other roadways. In an ongoing study at the University of California at Davis using travel demand models for the Sacramento region, Johnston and Page found that on a systemwide level, automation of freeways appear to result in significantly reduced vehicle-hours of delay on the freeways, but these reductions are coupled with large congestion increases on the onramps, arterials, and collectors that feed into the freeway system (Johnston and Page, 1991). Changes in modal emission contributions are very likely to be significant.

High power and load conditions, such as rapid acceleration or high speed activities, also produce significant emissions (LeBlanc, et al., 1994; CARB, 1991b; Benson, 1989; Groblicki, 1990; Calspan Corp., 1973a; Calspan Corp., 1973b; Kunselman, et al., 1974). Recent laboratory testing indicates that high acceleration rates contribute significantly *to* instantaneous emission rates. One sharp acceleration may cause as much pollution as does the entire remaining trip (Carlock, 1992b) and a small percentage of a vehicle's activity may account for large shares of the vehicle's emissions (LeBlanc, et al., 1994). Recent evidence also indicates that there is a non-linear relationship between the length of an enrichment event and the emissions associated with the event; longer events producing significantly more emissions than an equal sum of shorter events (LeBlanc, et al., 1994). In addition, unloaded vehicle deceleration events appear to be capable of producing significant emissions (Darlington, et al., 1992). In contrast to cold **start** emissions that occur over a period of minutes, acceleration and deceleration related emissions occur over a period of seconds.

With increasing engine load an engine speed, cylinder temperatures rise and the combustion process tends to reduce concentration of CO and unburned VOC in the exhaust gas and increase the concentration of NO emissions in the exhaust gas. Note that both the concentration of each pollutant in the exhaust gas is changing, while the volume of exhaust gas **is** increasing with RPM. Hence, the general trends noted in emission rate models (g/mile) with respect to moderate vehicle speeds seem *to* make sense.

To maintain power at high loads, the combustion mixture is slightly enriched (increasing the fuel/air ratio). However, at very high engine loads, high cylinder and exhaust gas temperatures can lead to valve damage and sintering of catalytic converters. Hence, manufacturers may significantly increase the fuel/air ratio for their vehicles under conditions of high loads to prevent thermal damage and improve driveability (USEPA, 1993). Elevated emission rates under deceleration conditions may be linked to the slight delay in fuel cutoff when power output is no longer required (Bosch, 1986).

Figures 1 and **2** present second-by-second emission estimates for a utility vehicle operating under parts of the Federal Test Procedure (FTP) and the Highway Fuel Economy Test (HFET).[2] Figure 1, test results from a portion of the FTP cycle, clearly illustrates that hydrocarbon and oxides of nitrogen "emission puffs" occur, and are likely associated with either the high rates of acceleration or deceleration (the time delay associated with analytical equipment response is unclear, roughly 4-6 seconds, *so* associating the specific modal event with the resulting emission puffs is not possible from these data). Surprisingly, even vehicle operations at a relatively stable high speed flow show some variability in emission rates (i.e. smaller "puffs") that may be associated with accelerations **and** decelerations, even though the rates of acceleration and deceleration at these speeds are low (figure 2, test results from a portion of the HFET).

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[2] A testing cycle is a set pattern of acceleration, deceleration, cruise, and idle activities that a vehicle follows on a laboratory dynamometer, or computerized vehicle treadmill. The Federal Test Procedure is the standard USEPA emission testing cycle in the Code of Federal Regulations used to determine compliance with new and in-use motor vehicle emission **standards** (grams/mile). The Highway fuel economy test is also employed in the regulatory arena and **used** in part for determining compliance with corporate average fuel economy standards (CAFE).

Figure 1: Second-by-Second Emission Data for a Utility Vehicle Operating Under a Portion of the Federal Test Procedure (FTP)

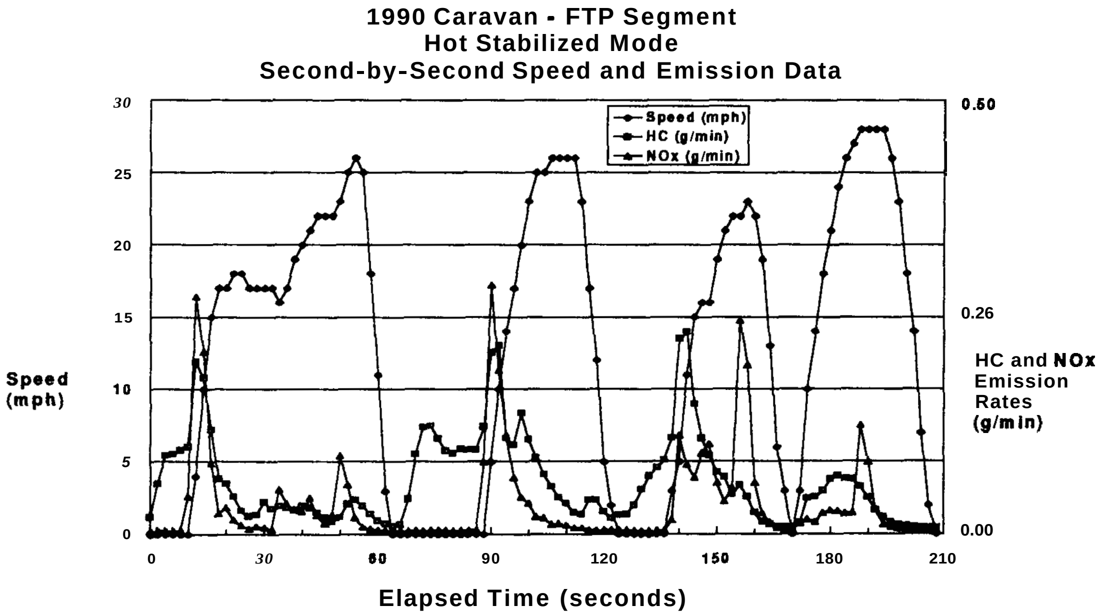
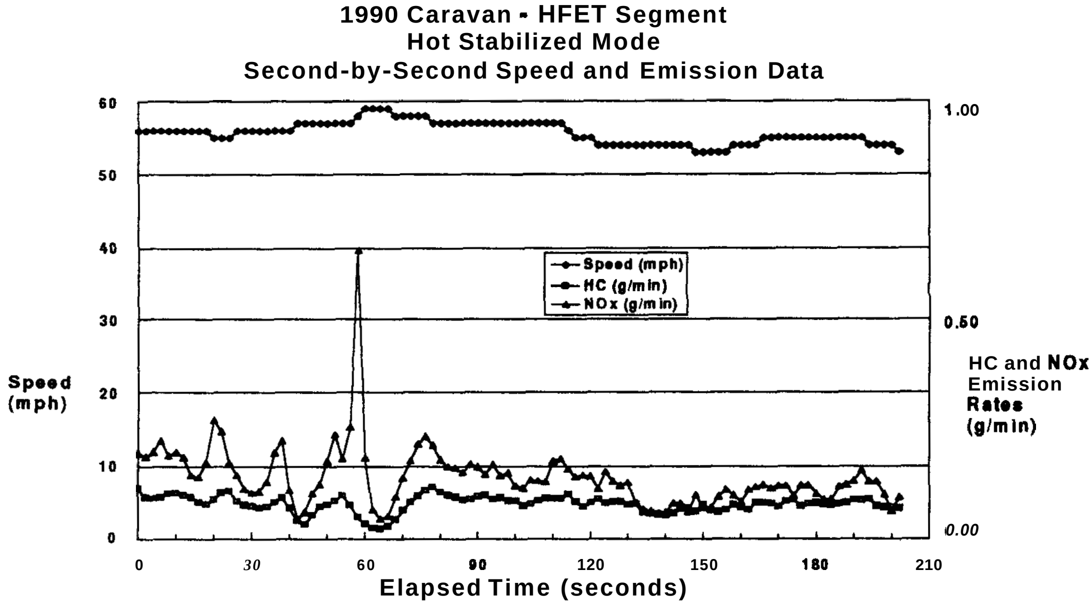


Figure 2: Second-by-Second Emission Data for a Utility Vehicle Operating Under a Portion of the Highway Fuel Economy Test (HFET)



Like engine **starts**, however, acceleration and deceleration activities can be treated as discrete emission-producing events and modeled as emission puffs, provided that emission rates for these activities (as well as any potential factors that may influence the magnitude of the puff) can be determined. Modal activities producing elevated emission rates are not currently modeled, and may contribute to emission inventory underestimation.

3.2 Activity Specific Emission Rates (Guensler, 1993b)

The motor vehicle emission rates associated with each of the emission-producing vehicle activities (i.e. grams of emissions per unit of emission-producing vehicle activity) are functions of vehicle parameters, fuel parameters, vehicle operating conditions, and the vehicle operating environment. Table **3** illustrates some of the important variables that can be taken into consideration in developing emission rate estimates.

Table **3:** Vehicle Parameters, Fuel Parameters, Vehicle Operating Conditions, and Environmental Conditions Known to Affect Motor Vehicle Emission Rates

Vehicle Parameters:
- Vehicle class [weight, engine **size,** HP, etc.]*
- Model year
- Accrued vehicle mileage
- Fuel delivery (e.g. carbureted or fuel injected)
- Emission control system
- Onboard computer control system
- Control system tampering
- Inspection and maintenance history

Fuel Parameters:
- Fuel type
- Oxygen content
- Fuel volatility
- **Sulfur** content (SOx precursor)
- Benzene content
- Olefin and aromatic content
- Lead and metals content
- Trace sulfur (catalyst effects)*

Vehicle Operating Conditions:
- Cold **or** hot start mode (unless treated separately)
- Average vehicle speed
- Modal activities causing enrichment*
- **Load** (e.g. **A/C,** heavy loads, towing)
- Trip length **and** trips/day*
- Influence of driver behavior*

Vehicle Operating Environment:
- Altitude
- Humidity
- Ambient temperature
- Diurnal temperature sweep
- Roadgrade*

* These components *are* not explicitly included in the **USEPA** or CARB emission rate models.
Source: Guensler, 1**993**b

3.3 The Emission Inventory Process

An emission inventory is a quantitative assessment of the sources and magnitudes of total emission contributions. Emissions estimates from individual mobile source activities are summed to determine the total mobile source emission inventory that is used in air quality planning (CARB, 1992a; CARB, 1991a; Guensler and Geraghty, 1991). Emission inventory results also serve a second critical purpose; evaluating the emission impacts of new development or modification of local transportation facilities through micro-simulation.

The on-road motor vehicle emission modeling process consists of 1) quantifying emission-producing vehicle activities through a travel demand model or other means of estimation, 2) providing data on vehicle, fuel, operating, and environmental characteristics to the computer model, 3) running the emission rate model to predict activity-specific emission rates for the given vehicle, fuel, operating, and environmental characteristics, **4)** multiplying each activity estimate by its appropriate activity-specific emission rate, and 5) summing the estimated emissions for all activities. Ideally, these emissions estimates must be temporally and spatially resolved for the purposes of air quality modeling. Developing an accurate emission inventory for motor vehicles is tremendously complex. **As** with most modeling approaches, various modeling assumptions and data aggregation techniques have been developed to simplify the emission inventory preparation and minimize labor and data requirements (although simplifications often tend to yield uncertain estimates).

The first item to keep in mind, from an emission inventory standpoint, is that estimation of vehicle activity must necessarily be a secondary process. That is, emission-producing vehicle activities must first be identified, and emission rates associated with those activities must be quantified. Only then should vehicle activity be quantified. Without the knowledge of the emission cause-effect relationships at work, analysts are likely to quantify the wrong activities. Currently, four-step transportation planning models (UTPS-type models), often with post-processing, are used to estimate vehicle activity for emission inventories (Quint, et al., 1993; Bruckman, et al., 1992; Guensler and Geraghty, 1991). However, whether the outputs from these activity models provide reliable estimates of the factors that actually impact emission rates is an issue that will be discussed in the next chapter.

3.4 Assessment of IVHS Impacts

The procedure for evaluating the potential air quality impacts of any proposed transportation strategy involves three basic steps:

1) Develop a *Baseline Emission Inventory* -- The first step is to establish the quantity and the temporal and spatial location of emission from motor vehicles that exist today. This is the baseline condition, which is expected to change naturally over time as cities grow, as vehicle miles traveled (VMT) and trip generation continue to grow, and also as older vehicles are naturally retired from the fleet. **As** discussed previously, the emission inventory is prepared by quantifying the vehicle activity, identifying the conditions that affect the emission rated from these activities, applying the appropriate emission rates, and summing the total emissions impact.

2) Establish the ***Future*** *Baseline Emission Inventory* -- Before changes that any transportation strategy will cause can be assessed, planners must first evaluate the "no action" alternative. That is, we assess the emission inventory that would occur in a future year of concern is examined using the assumptions that nothing is done to change the status quo. For

air quality planning, we might choose to examine the year **20**10, as this year is the attainment deadline under the Clean Air Act (CAA) for the most seriously polluted urban areas. The city would continue to grow, the transportation infrastructure would grow in accordance with development plans already on the books, previously adopted air quality strategies would be phased-in, etc. This emissions evaluation gives analysts a future scenario to which they can compare the emissions that would result if proposed IVHS systems (or any other transportation strategies for that matter) are developed. In order to assess the future baseline emission inventory, analysts must be able to project changes in vehicle activity as well as changes in the conditions that affect emission rates for each of these activities.

3) Establish the *Scenario Future Emission Inventory* -- The emission inventory is developed for the future year of concern under the controlled conditions that we would like to examine. To assess the emissions impacts, we compare the controlled future emission inventory to the future baseline emission inventory. From an air quality planning perspective, emission reductions can only be claimed from emission control strategies that provide surplus emission reductions (Guensler, 1992b) above and beyond those emission changes that would have occurred anyway (i.e. were already included in the analyses used to prepare the local air quality management plan). The net difference in the emission inventories will be due to the changes in vehicle activity and changes in the conditions that affect emission rates for each activity caused by the implementation of the proposed emission control strategy (in this case an IVHS scenario).

Many of the **IVHS** technology bundles have the potential to change the amount of vehicle activity that will occur. All of the IVHS technology bundles also have the potential to affect both the vehicle and environmental characteristics that impact the magnitude of activity-specific emission rates. For example, if only newer vehicles use the IVHS infrastructure, the emission control technologies employed in the automated fleet will differ dramatically from the technologies of the current average fleet vehicle. In addition, the vehicle operating conditions of the trips, such as average vehicle speed or acceleration/deceleration patterns, will differ from existing average trip characteristics. The environmental characteristics of the trip may also increase or decrease emission rates, and will be dependent upon the specific impacts that the IVHS has on individual vehicle operations. For example, significant shifts in travel **by** time-of-day may change the ambient temperature characteristics of the affected trips. To assess the potential impacts of **IVHS** technology bundles on the future emission inventory, we must first establish what these technology bundles are, and then discuss the potential impacts that these bundles may have upon vehicle activity and the conditions that affect emission rates from each activity.

The emissions analyst prepares input files that describe all of the appropriate parameters and model outputs provide an emission rate for each emission-producing vehicle activity, given the conditions described. The vehicle fleet characteristics are prescribed, including such parameters as: composition of the fleet by model year, fuel system and emission control technology, and vehicle class; mileage accrual rates (miles/year) by vehicle class; inspection and maintenance/anti-tampering program effectiveness. The basic control files also contain fuel parameters as well as environmental parameters applicable to the modeling run, such as: altitude, ambient temperature, and daily minimum and maximum temperature. Finally, the operator specifies the specific vehicle operating conditions applicable to the scenario by providing information on average vehicle speed, percent of vehicles in cold/hot **start** mode, and percent of vehicles under heavy load (towing and air conditioning percentages, for example). Hence, the emission rates that are provided by the model outputs take into consideration all of the important parameters prescribed above.

Assessment of **IVHS** technology bundle impacts will hinge upon accurate assessment of changes in vehicle activity estimates. The most detailed vehicle activity data currently used in emission inventory and modeling work are outputs from transportation demand models, such as the Urban Transportation Planning System (UTPS) generation of models. UTPS-type models are generally described by a four step process: 1) estimating trip production and attraction within small geographic zones, based upon land use and socioeconomic data; **2)** assigning the generated trips from zone to zone, based upon gravity-type models; 3) assigning zone-zone trips to specific travel modes, based upon discrete choice analysis using socioeconomic and transport characteristic data (e.g. regression, logit, or probit analysis); and **4)** assigning the vehicle trips to specific links on a network model, using flow and capacity characteristics and an iterative delay minimization process. Thus, trips generated, vehicle miles traveled (VMT), and vehicle speeds can be estimated. The current accuracy of existing travel demand models, assessment of the state of the practice for these models, and development of methods to improve these models are currently being debated **today** (Purvis, 1992; Ismart, 1991; TRB, 1992), and state of the practice guidelines have been developed for implementation (Harvey, 1993b).

The evaluation of **IVHS** scenarios is also completely dependent upon the adequacy of the emissions algorithms contained in the models. These emission rates must be germane to the changes that **IVHS** is expected to bring. The models must adequately reflect the emissions producing activities and must **be** sensitive to changes in relationships that result from **a** policy initiative.

4.0 SOURCES OF EMISSION MODELING UNCERTAINTY

Modeling results are highly uncertain because the models were only designed to roughly estimate a "bulk" emission inventory, and were never designed to evaluate policy issues in the manner that they are often employed. Discussions of specific emission modeling problems, including such aspects as off-cycle and modal emissions, characterization of the vehicle fleet, cold- and hot-start emissions, evaporative emissions, potential interaction between emission model correction factors, and specific quantification and spatial allocation of vehicle activity, can be found in many sources (Guensler 1993a; Harvey 1993b; Bruckman and Dickson 1993; Pollack et al. 1992; Austin et al. 1992; Ashbaugh et al. 1992; TRB 1992; Bruckman and Dickson 1992; Purvis 1992; Benson 1992; Guensler and Geraghty 1991; Gertler and Pierson 1991; SAI 1991; Guensler et al. 1991; **Ismart** 1991; Lawson et al. 1990; **FHWA** 1990). The bottom line is that the current modeling methodologies, both for vehicle activity and emission rate estimates, are fraught with uncertainty.

Uncertainty is pervasive in all three emission modeling components: vehicle activity, activity-specific emission rates, and emission rate correction factors. Uncertainty is compounded in the methodologies used to develop the emission inventory. That is, vehicle activity uncertainty is combined with emission rate uncertainty that has already been combined with correction factor uncertainty. In examining the potential impacts of **IVHS** implementation scenarios on vehicle emissions, these uncertainty issues should be kept in mind.

5.0 POTENTIAL, IVHS IMPACTS ON ACTIVITY AND EMISSION RATES

This chapter describes the qualitative impacts that the various IVHS technology bundles could have on the vehicle activities and emission rate parameters that are used in emission models.

5.1 Potential IVHS Impacts on Emission-Producing Activities

According to national statistics (Hu and Young, 1992), the average household in 1990 traveled 7827 km (4,853 miles) going from home to work, 2,811 km (1,743 miles) shopping, 4,861 km (3,014 miles) for other family or personal business, and 6,548 km (4,060 miles) for social or recreational purposes; a total average annual of 24,355 kilometers (15,100 miles). The average American also choose their personal auto, van, or truck over public transit at an average ratio of **43:**1 (Hu and Young, 1992). Also in 1990, Americans paid an average of about 30 cents per liter ($1.15 per gallon) including tax for regular unleaded fuel, paid an average price for a domestic and import vehicle of $15,641 and $17,010 respectively, and paid an average prorate cost of about 25 cents per km (41 cents per mile) (Davis and **Morris,** 1992).

Vehicle activity can be characterized by trip type, trip purpose, trip length, time-of-day, etc. Travel behavior determines the demand for the transportation system. The demand for the transportation system is a function of transportation costs (e.g. time, fuel, parking, etc.) and transportation supply (e.g. land use configuration, mode availability, routes, congestion levels, etc.). As more and longer trips are made by individuals, vehicle miles of travel increase, as do vehicle emissions.

If vehicle activities activity is affected through the use of technology, policies, or transportation demand management, then the drivers could behave much differently in the future. This behavior could even affect location decisions made by households and businesses, ultimately affecting land uses. Ultimately, changes in driver behavior would also bring about changes in emissions, the direction and magnitude of the change determined by many factors.

Congestion is also a good indicator of driving behavior. By 1987, almost 70% of all urban interstate roads were congested during peak periods (Gordon, 1991). The amount of congestion experienced by drivers provides an indicator of the value of their trip in accordance with the value of their time. Presently, the cost of sitting in traffic appears to be fairly low compared to the value or utility of completing a specified trip -- especially during peak times when trip makers may have little flexibility. As drivers tolerate increasing levels of congestion, emissions increase geometrically.'

If driver behavior is affected through the use of technology, policies, or transportation demand management, then the drivers may behave much differently in an **IVHS** future. This behavior

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[3] Congestion should level off to a theoretical maximum as an iterative function **of** travel demand, local roadway capacity, local speed-flow relationships, local traffic volumes, and willingness to endure congestion at the individual level.

could even affect location decisions made by households and businesses, ultimately affecting land uses.

In our previous work, we discussed potential changes in trip making activity in terms of the land use and travel demand modeling framework (Sperling, et al., 1992). That is, we discussed potential changes in land use configuration, trip generation, mode choice, trip distribution, and route selection that could potentially result from the implementation of IVHS scenarios. In this section, we discuss the potential IVHS impacts within a different framework; potential changes in emission-producing vehicle activity.

5.1.1 VehicleMiles Traveled

The implementation of some information-related IVHS technologies will be designed to reduce vehicle miles of travel, by providing better information about route selection and helping motorists from becoming lost. Alternatively, some **IVHS** technologies that provide better information may increase vehicle miles of travel, as motorists attempt to reduce total travel time through selection of longer uncongested routes. Also, improved access to parking and cost information may reduce cruising activity (Ullberg, 1991).

Route selection in most travel demand models **is** based upon numerical algorithms that minimize total system travel time, thereby playing a large role in the modeled VMT estimates. The inherent assumption in the system-minimization model is that an individual will select a route that slightly increases their individual travel time whenever this choice results in a net system travel time savings (i.e. individuals will accept longer travel times if they reduce travel times for others by an equal or greater amount). This assumption is unrealistic. Because current route selection algorithms do not employ individual route choice models that would minimize individual travel times rather than system travel time, current predictions of vehicle activity are likely to be artificially low. Furthermore, the evaluation of IVHS technologies that affect individual travel times (especially those that may increase total system travel times) is impossible to undertake without making numerous assumptions and model modifications. In addition, as choice models evolve, the decisionmaking process will still be based upon assumptions relating to information availability that may be changing as **IVHS** technologies are deployed.

If the effective speed on new **AVCS** systems were twice the speed on the existing congested system, people might choose to live up to twice as far from their workplaces without having to spend more time traveling (Varaiya and Shladover, 1991). If travel speeds increase and congestion and travel times decrease, it is likely that average trip lengths will increase as attractive destinations, once inconvenient, become viable (Stafford, 1990). That **is,** consumers may opt to explore comparable services in new areas, increasing travel distances, as travel time costs are reduced. Better access to parking availability and cost information may change shopping and other destinations. Plus, potential diversion from higher-occupancy modes, such as buses and carpools, to single-occupant vehicles, may yield an increase in VMT. On the other hand, with ***APTS,*** the diversions could be from single occupant vehicles to alternative modes of transportation, reducing vehicles miles traveled.

Historically, the construction of the limited-access highway system and implementation of federal, state, and local planning/fiscal policies have tended to favor the development of rural lands for suburban uses. These policies have resulted in sprawling growth patterns surrounding urban areas. Similarly, development of a new high-efficiency, high-speed, limited access **IVHS** infrastructure may continue to promote sprawling development patterns, decreasing the efficiency of other services and increasing externalities associated with urban sprawl. However, closer analysis is likely to reveal that actual impacts will be a function of the infrastructure that is developed. In fact, it may be possible (although politically challenging) to use **IVHS** systems to direct population growth and changes in land use. Rational comprehensive planning initiatives may increase infill in desired locations and reduce sprawl associated with unstructured growth in outlying areas by targeting IVHS system access. The **IVHS** system, however, must be designed and implemented from the top down with this goal in mind for such structured growth to result.

5.1.2 Trip Ends - Cold, Hot, or Warm Engine Starts, and Engine "Hot Soaks"

As discussed earlier, each engine start results in elevated emissions rates that are often modeled as an emissions puff, either in the warm or hot start mode. The shut down of an engine also results in hot soak emissions; continued evaporation of hydrocarbons from the engine and fuel system. Hence, if IVHS technology bundles increase or decrease the number of trips made, the emissions associated with the trip ends will increase or decrease accordingly. Because the emissions associated with cold **starts** are much greater than the emissions associated with hot starts, if **IVHS** technology bundles increase or decrease the fraction of cold engine starts, emissions associated with the trip ends will increase or decrease accordingly.

If capacity and travel speeds increase and congestion and travel times decrease, it is likely that additional vehicle trips will be undertaken (Stafford, 1990). **As** discussed in the last section, people may opt to live further from work, or perhaps businesses will become more willing to move to remote locations that are readily accessible through **IVHS** congestion relief. In either case, if daily travel time is reduced through **IVHS** implementation, some may substitute non-travel activities while others may undertake new travel activities to replace the time was previously consumed in driving. "How much change" is the question. Fully automated traffic lanes are anticipated to increase freeway flow capacities from today's 2000-2200 vehicles per lane per hour to as much as 3600-7200 vehicles per lane per hour, with the possibility of vehicles operating at speeds of 97 kph (60 mph) or more. The impacts upon trip generation are by no means certain. The relationships between travel time budgets, disposable income, and travel behavior must be refined.

Another non-trivial possibility is that **IVHS** technology will increase the efficiency of trip making (and reduce emissions) if increased access to information yields increased trip chaining.[4] Preliminary studies have indicted that the emission rates currently employed for hot

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[4] **On the more obscure side, onboard advertising may play a major role in the marketing and profitability of advanced traveler information services. Advertising may prompt drivers to undertake additional trips.**

starts in California may be significantly overestimated (Guensler, et al., **1994).** If proven true for the fleet, this means that any strategy designed to increase trip chaining is likely to have a significantly larger emission reduction impact than previously presumed.

Unless mitigated by design, urban and suburban land use densities are likely to continue to decrease, much in the same manner that we have experienced after the development of the Interstate Highway System, if the proposed **IVHS** system provides numerous access points similar to the current highway system. Motor vehicle trip generation rates tend to increase as density decreases. The relationships between land use and transportation demand are complicated, and only recently has research begun in earnest (Parker, 1994). Note also, the physical location of the infrastructure and location of access points will spatially change vehicle activity patterns, and therefore the locations at which emissions are created

5.1.3 Engine Idling

IVHS technologies are very likely to decrease the amount of idling time likely to be experienced by motor vehicles in the future baseline scenario. Advanced traffic management systems are likely to reduce vehicle wait times at intersections, a major cause of idle emissions. Access to more and better information will likely result in less time caught in queues and motoring in search of parking spots. Finally, advanced vehicle control systems have the potential to significantly reduce the amount of congestion currently experienced by vehicles, thereby reducing time spent at idle.

5.1.4 Exposure to Diurnal and Multi-Day Diurnal Temperature Fluctuation

Diurnal evaporative emissions result from the expansion of fuel and increased vapor pressure in the fuel tank caused by ambient warming. Diurnal emissions are controlled to a great extent (when evaporative control canisters are functioning properly), but some diurnal emissions still occur. The existence of the vehicle and its fuel tank is the activity that causes the emissions. Emissions associated with diurnal temperature variation are not likely to be significantly impacted by **IVHS** technologies, unless there is a major change in the number or fuel characteristics of vehicles in the fleet. Hence, if **IVHS** vehicles become niche vehicles and are purchased as additional household vehicles, diurnal emissions might increase.

Multi-day diurnal emissions are important because if a vehicle sits idle for more than one or two days, the evaporative control canister becomes saturated, and emission control efficiency drops significantly. Hence, if **IVHS** technology bundles cause vehicles to remain unused for multiple days, multiday diurnal emissions from the non-IVHS fleet may increase.

5.1.5 Vehicle Refueling

Emissions from vehicle refueling will be a function of the number of additional fleet vehicles associated with the **IVHS** system, the type of fuel they employ, their fuel efficiency, the ***size*** of the fuel tanks, and any additional refueling emission control systems used with the new-technology vehicles. In comparing a future case scenario, one would want to examine the number of non-IVHS vehicles that the **IVHS** vehicles would replace; hence, while there are emission increases associated with new **IVHS** vehicles, there are also emission reductions associated with displaced vehicles in the future fleet. Vehicle efficiency is often considered "the forgotten emission control strategy." Improvements in fleet fuel efficiency generally lead to reductions in emissions because fuel tanks are downsized, fueling is less frequent, and smaller fuel-efficient vehicles generally emit less per mile than their larger counterparts (DeLuchi, et al., 1992). Changes in vehicle efficiency expected to result from **IVHS** will clearly be reflected in reductions in refueling emissions.

5.1.6 Modal Activity (e.g. High Power Demand, Heavy Engine Loads, or Engine Motoring)

All of the **IVHS** technologies discussed in this paper are designed to reduce congestion. Congestion relief is likely to reduce the number of significant acceleration and deceleration events that cause elevated emission rates. Hence the likelihood that modal emission-producing activities will be undertaken is significantly reduced, especially when the computerized vehicle technologies can be readily programmed to avoid undertaking enrichment activities. For example, intelligent vehicles can be pre-programmed for onramp acceleration rates that do not yield excess emissions.

Better tools are needed to assess the impacts of changes in modal operations, because traffic flow tradeoffs resulting from **IVHS** and other transportation improvement strategies are complex. Consider for example the effect on driving conditions of "improving" one part of the highway system: doing so may push congestion elsewhere, and in a complex non-linear manner. For example, ramp metering reduces congestion on the freeway upstream of the onramp but also causes congestion on the freeway onramp itself; congestion that can spill over onto other roadways. In an ongoing study at UC Davis using travel demand models for the Sacramento region, Johnston and Page found that on a systemwide level, automation of freeways appear to result in significantly reduced vehicle-hours of delay on the freeways, but these reductions are coupled with large congestion increases on the onramps, arterials, and collectors that feed into the freeway system (Johnston and Page, 1991). Changes in the modal components of emission contributions are very likely to be significant.

Unfortunately, modal emission rates and relationships for both the current and future vehicle fleet are relatively unknown at this time, and potential emission tradeoffs associated with changing vehicle flow parameters cannot be evaluated without further analysis of existing and future data. As additional second-by-second emission profiles become available for modern vehicles that are likely candidates for **IVHS** incorporation, these tradeoffs will become more clear (at least for those vehicles for which data become available). However, it is likely that the projected emission effects that result from specific modal operations will play a very important role in determining which vehicles will ultimately be selected for **IVHS** incorporation. Individual vehicle emission behavior and final **IVHS** vehicle fleet profiles are inextricably linked.

5.2 Potential IVHS Impacts on Vehicle and Fuel Parameters:

(Vehicle Class, Model Year, Fuel Type and Fuel Characteristics, Fuel Delivery Systems, Emission Control Systems, and Onboard Computer Control Systems)

One of the real challenges with modeling future **IVHS** scenarios will be predicting if there will be a significant change in composition of the future vehicle fleet. Fleet average emission rates are dependent upon the composition of the vehicle fleet. Vehicle characteristics such as weight, engine size, horsepower, model year, accrued vehicle mileage, fuel delivery system (e.g. carbureted or fuel injected), emission control system, onboard computer control system, control system tampering, inspection and maintenance history, etc., are all important emission-related parameters (Guensler, 1993b) and are all directly dependent upon the composition of the vehicle fleet. Plus, fuel characteristics such as oxygen content, volatility, sulfur content, aromatic content, metals content, all affect the magnitude of various emissions associated with vehicle activity (Guensler, 1993b).

The implementation of **IVHS** technology bundles **is** likely to change the character of the vehicle fleet, as not all of the fleet will be able to take advantage **of** the **IVHS** infrastructure that is developed. These five parameters may change as a function of the **IVHS** technology bundles that are adopted. However, in assessing the composition of the uncertain future vehicle fleet, existing regulatory programs must be considered. For example, the California Low Emissions Vehicle and Clean Fuels Program requires significantly cleaner new vehicles and mandated percentages of electric vehicles. Plus, new and innovative regulatory approaches are being considered that will clearly affect the composition of the vehicle fleet, such as: parking cash-out programs, congestion pricing, increased gasoline taxes, emission feebate programs, pay-at-the-pump insurance, etc. Even with years of previous experience, modelers have extreme difficulty in forecasting future fuel prices, let alone predicting which innovative strategies will be adopted/implemented and what the impacts will be.

Fleet turnover rates may also be affected by **IVHS** technologies. If newer vehicles, complete with **IVHS** instrumentation are purchased, a larger supply of used vehicles may enter the market for a time and encourage fleet turnover. On the other hand, a significant increase in average new vehicle prices may play a mitigating role by encouraging the retention of older non-IVHS vehicles in the fleet for longer periods of time. Given these two competing factors, the ultimate effect **is** currently unknown.

Emission rates for given activities are affected by the extent to which vehicle emission controls have degraded over time; generally a function of accrued vehicle mileage, maintenance history, and whether the control systems have been tampered with. The first issue of concern is whether the **IVHS** vehicle fleet will exhibit the same emission control system degradation as the future projected fleet (i.e. will the same vehicle and control technologies exist as discussed previously, and will the emission control systems behave differently over time due to the change in operating modes experienced by the vehicles). Vehicle control requirements (allowed degradation rates) continue to evolve over time. Plus, with the current applications of onboard computer technologies, even in the absence of **IVHS,** there is no reason to believe that tampering rates will change significantly. The second issue of concern is the effects that **IVHS** technology bundles will have upon accrual of vehicle mileage, whether vehicles will be properly maintained, and whether emission control systems will be tampered with. On the other hand, a shift to an electric vehicle **IVHS** infrastructure would have significant implications.

Advanced traffic management systems will provide information to drivers that will have the potential to affect mode choice. Better access to parking availability and cost information may shift trips to shared modes for those destinations with high time and cost penalties. Yet, better access to information and parking availability may shift trips to single occupant **IVHS** modes for those destinations with high time and cost penalties. Better information about ridesharing possibilities, e.g. instantaneous carpool matching or automated calls for jitneys, may increase the use of shared **IVHS** modes. As the relative number of trips by mode changes, the vehicle fleet composition also changes. One potential problem in this area is the relative uncertainty associated with emission rates from heavy-duty vehicles including buses under their variety of duty-cycles.

The demonstrated preference of the traveler for single occupant mode will likely be encouraged under **IVHS** scenarios that reduce the time cost of travel. Advanced vehicle control systems will likely increase the utility of single occupant vehicles. The decision to take alternative modes appears to be based in part on out-of-pocket costs and comparative time costs. In fact, on-vehicle productivity probably plays a role in selecting certain modes of transit. In making the decision to switch back from an alternative mode to the single occupancy vehicle **(SOV)** mode, the traveler would in effect relinquish productive on-vehicle time as a passenger in exchange for a shorter non-productive trip as a driver.

As with the other technologies, advanced public transportation systems have the potential to increase the use of shared modes. Changes in mode choice may result from the implementation of transit oriented **IVHS** systems, which can yield potentially significant changes in vehicle and fuel characteristics. Overall, trips may shift to single occupant IVHS vehicles as faster travel times reduce out-of-pocket costs and **an** increase in the utility of the single occupant vehicle. However, trips may shift to transit and paratransit if advanced information and traffic management technology is applied to and favors those modes (Woodworth, et al., 1993; Hammond, 1989a and 1989b).

Given the tremendous uncertainty in the emission impacts of **IVHS** technology bundles, it seems crucial that any comprehensive **IVHS** implementation plan include provisions for emissions monitoring. Arguments in favor of onboard and remote monitoring systems have been made in the motor vehicle emissions literature. Some individuals contend that a vehicle capable of monitoring its own emission rates on an ongoing basis constitutes an intelligent vehicle system. While the argument over whether such monitoring systems are truly **IVHS** is **an** issue of semantics, the need for developing such systems is apparent. Although **IVHS** development and implementation will occur over a much loner timeframe than the estimated turnover of the vehicle fleet (around 12 years) it is important to begin monitoring research now both from the standpoint of better understanding the causal factors at work in emissions processes as well as ensuring that **IVHS** will be able to achieve substantial emissions reductions benefits.

5.3 Potential IVHS Impacts on Vehicle Operating Conditions

In the case of information technologies, the temporal distribution of trip making may change as a function of access to information indicating substantial time savings during off-peak periods; more peak spreading may occur. Changes in number of trips, by time of day, and the physical conditions (i.e. vehicle flow conditions) under which the vehicle is operated may change as a result of **IVHS.**

5.3.1 Cold and Hot Start Modes

Discussed earlier, as a discrete emission-producing activity. See sections 3.1 and 5.1.2.

5.3.2 Average Speed and Modal Contributions

Average speeds as well as speed-acceleration profiles are expected to change as a result of **IVHS** implementation. For example, advanced traffic management systems are designed to increase average vehicle speeds through the reduction in stop delays; a benefit that is likely to reduce vehicle emissions. Advanced traveler information systems also increase average operating speeds, usually by routing flows to uncongested routes. However, because individuals make route decisions designed to minimize their own travel time, the provision of perfect information may lead to higher overall congestion levels when individual decisions are made at the expense of overall system efficiency; nevertheless, it may be possible to reduce total travel times by designing efficient information systems that provide information selectively (dePalma, 1992).

A comprehensive advanced vehicle control system infrastructure will likely relieve congestion along existing freeways and expressways, as a result of computer control over separation distances and from a reduction in number of accidents. Thus, AVCS systems will likely reduce the magnitude of emissions allocated to these spatial locations. Reduced congestion levels will result in improved vehicle flow and better levels of service on automated segments. However, if the infrastructure creates additional traffic congestion along ramps and arterials surrounding access points as indicated by Johnston and Page (Johnston and Page, 1991), congested traffic conditions on local roads are likely to increase emissions allocated to these spatial locations.

Carbon monoxide and hydrocarbon emissions from motor vehicles are modeled as functions of average vehicle speed. There is a high degree of uncertainty associated with the VOC and CO speed-emission relationships (Guensler, 1993b), especially for modem fuel-injected vehicles operating at low average speeds (important for establishing future emission baselines under congested scenarios) and at high average speeds (important for estimating emissions under **IVHS** scenarios). The problems associated with using the average speed modeling regime for the evaluation of **IVHS** impacts are explored later in Chapters 9 and 10.

5.3.3 Vehicle Load

The typical vehicle load factors that are currently modeled (air conditioning and towing) are not likely be significantly altered by the implementation of IVHS systems, unless perhaps the system cannot accommodate towing or these types of emission effects are not exhibited by the new **IVHS** fleet. However, as noted for modal emission-producing activities, all **IVHS** technologies have the potential to impact vehicle load characteristics by reducing congestion. Additional research into the effects of vehicle loads under specific operating conditions is necessary.

5.3.4 Driver Behavior

Laboratory emission test result differences between trained and untrained drivers have been noted (Ripberger, 1991), but the findings are still preliminary in nature. Experienced laboratory drivers may perform smoother accelerations and decelerations on the testing cycles than would typically be exhibited by onroad drivers. Thus, laboratory drivers with different "gas pedal behavior" may achieve significantly lower emission rates for the modern low-emission vehicles operating dynamometer cycles than would untrained drivers. If continued laboratory research supports the preliminary findings, IVHS systems would appear to have an additional emissions benefit; the capability of using computerized controls to mimic the smoother acceleration and deceleration behaviors noted in the laboratory.

5.4 Potential IVHS Impacts on Environmental Conditions

The number of trips by time of day are likely to change as a function of operating conditions. Trip distribution may change as a function of reduced travel time during peak periods, so that more trips can be made during peak periods. Information technologies may change, the temporal distribution of trip making as a function of access to information, and peak spreading may occur. The resulting change in ambient environmental conditions, based upon time-of-day, may affect vehicle emission rates.

5.4.1 Altitude, Humidity, and Diurnal Temperature Sweep

None of the five technology bundles should have any relative impact upon altitude, humidity, or diurnal temperature sweep. These environmental conditions for the future baseline emission inventory scenario should also exist for the future controlled emission inventory scenario.

5.4.2 Ambient Temperature

To the extent that an IVHS technology bundle changes the time of day of a vehicle's operation, the ambient temperature under which the trips are made will change. The change in time-of-day for trips will likely be related to the time and out-of-pocket costs of a trip as a function of times.

Traffic control systems do not seem likely to significantly alter the time-ofday characteristics of trip making. **As** congestion is relieved, the times of trips may shift to some extent, but shifts of less than one hour are unlikely to be perceptible in the emission modeling process, compared to the relatively large amounts of error already associated with trip aggregation.

If AVCS yields significantly different travel characteristics, in terms of time and dollar costs, there may be a significant shift in time of day for travel. For the commute mode, if seems unlikely that there will be a significant shift (i.e. more than an hour or so) in time of departure, so the temperature change is probably minor. However, if AVCS significantly reduces congestion during the afternoon peaks, other trip purposes, such as shopping and recreation may be undertaken under higher temperature if these trips are normally made during the evening period.

To the extent that commercial vehicle operations technology bundles will provide goods movers instantaneous access to traffic conditions and are likely to provide valuable route and labor optimization, the systems may significantly alter the time of day for heavy-duty vehicle traffic. If detailed studies indicate that off-peak operations are significantly more efficient than peak operations, the ambient temperature of the operating environment will change significantly. Although the temperature differences are not very significant for diesel vehicles, the medium and heavy-duty gasoline truck fleet emission rates may be significantly impacted.

If public transportation can obtain a greater market share, through **APTS** technologies, the time of personal commute trips may change. However, it seems unlikely that the time of trips will change by more than one hour, and the impacts may be minor or imperceptible given the models employed.

5.4.3 Road Grade

The only IVHS technology bundle that seems likely to change road grade conditions is Advanced Vehicle Control Systems (AVCS), which requires a new infrastructure. If such an infrastructure were developed, the emission rate models might be adapted based upon new data to account for emission reductions associated with gently-sloped, grade-separated right-of-way. However, potential impacts cannot be evaluated with current models.

6.0 DISCUSSION OF POTENTIAL IMPACTS BY TECHNOLOGY BUNDLE

The following section summarizes the potential impacts of **IVHS** on emission producing activities and activity-specific emission rates for three of the basic technology bundles: advanced traffic management systems, advanced traveler information systems, and automated vehicle control systems. This section reiterates the major cause-effect relationships discussed previously and attempts to put these changes into real world context in a manner that describes potential interaction effects.

6.1 Advanced Traffic Management Systems

Advanced traffic management systems (ATMS) are technologies designed to optimize vehicle flow on the transportation network, typically utilizing real-time traffic information. Examples of ATMS include signal timing optimization, ramp metering, electronic toll collection, incident detection, rapid accident response, and integrated traffic management. Generally speaking, ATMS can be broken into two categories, those that aim to improve recurrent congestion problems such as ramp metering, and those that aim to improve non-recurrent congestion such as rapid accident response.

A strategy designed to combat recurrent congestion is signal timing optimization is the Fuel Efficient Traffic Signal Management (FETSIM) program, which is expected to improve fuel efficiency by minimizing stop delay and inertial losses (CEC, 1983; LADOT, **1987;** Deakin, et al., 1984). Similarly, ramp metering is designed to regulate flow onto congested freeways, as to prevent the freeways from deteriorating to level of service of D, E, or **F,** smooth ramp flows, and reduce weaving at the freeway merge (TRB, 1985)

Rapid accident response systems and incident detection, however, can be used to reduce non-recurrent events. Information about accidents, incidents, and construction work events are relayed to a central traffic management center, who then optimizes signals, ramp meters, etc., to minimize delays and maximize throughput. Roving and real-time dispatched service vehicles are also used to clear accidents and incidents quickly.

Our previous paper iterated the likely air quality impacts of such systems, emphasizing the importance between off-peak and peak travel, and recurrent and non-recurrent congestion events (Washington, et al., 1993a). We found that although ATMS strategies designed to combat recurrent congestion are likely to offer air quality benefits, they will likely be less effective and less certain than those strategies aimed at non-recurrent congestion. Recurrent congestion, caused when travel demand exceeds roadway capacity, accounts for approximately 40% of all congestion. On the other hand, non-recurrent congestion, resulting from incidents and accidents, accounts for the remaining 60% of congestion delay occurring during both the peak and off-peak periods (Cambridge Systematics, 1990b; FHWA, 1986). These characteristics describe two important differences in terms of potential air quality improvements. First, by simple accounting of vehicle hours of delay, the potential benefits for non-recurrent congestion appear greater than the potential benefits of relieving recurrent congestion. But the more important difference is characterized in the difference between transportation system operation during peak compared to off-peak periods. During peak travel periods, a large percentage of the core transportation system is operating under conditions where demand exceeds capacity, which means that there is significantly less excess capacity for re-routing of traffic. Thus, potential air quality benefits for recurrent congestion are less significant than for non-recurrent congestion.

These findings, however, were presented in light of one assumed future transportation paradigm. Suppose we were to consider simultaneous application of technologies, resulting in a significantly different future transportation system. For example, suppose that vehicle manufacturers were to discover the many benefits of "supercars. (Lovins, et al., 1993) and auto manufacturing plants were retooled to meet the new demand and market. Considering that near-term design vehicles could attain fuel economy of approximately **242** km per gallon (150 miles per gallon) (Lovins, et al., 1993), the emissions reductions could be substantial. Widespread adoption of this technology could, over the long term, essentially cut current motor vehicle emissions by around ***60%*** to 75%. In addition, high acceleration or high speed activities, of great concern today, may become increasingly less important with advanced vehicle combustion technologies or alternative fuels. *Also,* peak versus off-peak travel concerns would also become less critical, since 'supercars' incorporate engine off at idle, and emissions associated with congestion may diminish considerably.

Hence, in this revised supercar scenario, the emission benefits associated with non-recurrent congestion relief and the minor emission benefits associated with recurrent congestion relief in previous analyses would already have been allocated to 'supercar' implementation before ATMS was even implemented. **Of** course, introduction of 'supercars' could not occur overnight, ***so*** the projected emission changes associated with ATMS would likely diminish over time. With motor vehicle emissions reduced significantly under the alternative scenario described, the marginal emission impacts of ATMS (and all other **IVHS** technologies) would essentially become a minor consideration. Under a 'supercar' scenario, the major consideration of ATMS would be minimized travel times on a transportation network, improved mobility and reduce vehicle delays, and improved traffic safety.

6.2 Advanced Traveler Information Systems

Advanced traveler information systems (ATIS) are designed to provide information to individuals about routes and system conditions ***so*** that travel times can be minimized. These technologies include onboard electronic maps, electronic route guidance and planning, changeable message signs, externally linked route guidance systems, vehicle condition warning systems, emergency mayday beacons, and ride share information availability.

Again, with the current vehicle fleet, the importance of off-peak and peak travel periods and recurrent versus non-recurrent congestion events is important when considering the air quality impacts of these technologies. Consider, however, that future vehicles may be capable of monitoring information about emission control performance through the use of onboard diagnostic systems. Furthermore, as the cost and size of remote and onboard sensing devices is reduced through technology advances, future vehicles may be capable of monitoring and recording instantaneous emission rates, as well as cumulative emissions. The cumulative emissions could be used in assessing annual registration fees that incorporate a pollution fee component. Thus, drivers who pollute more would pay more, while more conservative drivers or drivers that own low emission vehicles would pay less.

With emission information available to drivers and regulatory agencies and with an emission fee system in place, driving behavior may change significantly (depending **of** course, on the fee per gram of emissions and the demand elasticity). High emission activities associated with speed and acceleration, for example, might be reduced significantly. Also, people would be less inclined to tamper with vehicles and more inclined to keep vehicles 'tuned up' under such a pricing scheme. Finally, drivers may drive less, or trip-chain more frequently, when a traditionally fixed driving cost (registration fee) is converted into a variable cost.

If the emission fee transportation control measure described above were in place, the amount of high emission activity will probably decrease, and overall congestion levels might also decrease as drivers seek out less expensive travel times. Of course, the magnitude of these impacts is highly speculative. Clearly, ATIS systems provide operational benefits, in terms of congestion relief and improved safety. However, the impacts of ATIS systems applied in an emission fee future could be even more beneficial to air quality. Emission fee systems provide additional incentive for the use of those ATIS systems that are implemented. Plus, ATIS systems can be programmed to evaluate alternative routes in terms of time and emissions, ***so*** that route decisions are made on a more informed basis.

6.3 Advanced Vehicle Control Systems

Advanced Vehicle Control Systems (AVCS) encompass technologies designed to provide lateral and or longitudinal control of vehicles, and may be designed to route and control vehicles throughout the entire trip. The main thrust of AVCS technologies is to improve highway capacity by both reducing headway at all speeds and by reducing lateral space requirements between vehicles. In addition, congestion events and accidents caused by driver behavior such as rubbernecking, response to bottlenecks, etc., can be mitigated. In theory, roadway capacity can be doubled or even quadrupled with AVCS. **As** iterated in our earlier papers, however, AVCS may not necessarily lead to improvements in air quality (Washington, et al., 1993a and 1993b).

In **summary,** the potential adverse air quality impacts assuming an unchanging vehicle fleet include (Washington, et al., 1993a and 1993b):

- Vehicles may experience significantly higher operating speeds when AVCS is implemented, potentially yielding significant emission rate increases (especially for NOx).
- Determining the appropriate extent of automation is problematic, and severe congestion may result at automation endpoints and on nearby local arterials and connectors (Johnston and Page, 1991), yielding increased emission rates.

- Increased capacity and travel speeds on automated segments may provide capacity for latent demand over the long term, increasing vehicle activity and further exacerbating congestion effects at automation endpoints.
- The possible suburbanization effects of significantly reduced travel times could create many additional trips and could encourage additional urban sprawl.

On the other hand, if automation were applied simultaneously with electric vehicle technologies, the air quality outlook may be very different. For example, a grade-separated and automated infrastructure for half-width electric vehicles could be developed to provide access to and from core business districts from outlying suburbs (Washington and Guensler, 1993). The infrastructure could be designed specifically for commuters, but could be used also for non-work trips. The limited range of the network (and electric vehicles), the focus on peak period travel, and the provision of single occupant vehicles to appease consumer demand might provide a system with the potential to significantly reduce emissions. Commuters diverted to the automated electric vehicle infrastructure would create additional capacity on the existing transportation system, thereby decreasing congestion for conventional vehicles (Washington and Guensler, 1993). The message should be clear: linking automation with other technologies might provide an air quality outlook that is significantly enhanced compared to the independent implementation of the technologies, and may be the only way in which to feasibly implement the AVCS technology ***so*** that an air quality benefit **is** realized.

7.0 THE AVERAGE SPEED MODELING REGIME

As mentioned earlier, one of the most significant issues that will need to be addressed in the emission modeling regime if **IVHS** implementation scenarios are to be evaluated is the change in vehicle operating modes and average speeds. This chapter summarizes the average speed modeling regime (from Guensler 1993a) and discusses the fundamental flaws associated with using the average speed regime for **IVHS** evaluation.

The baseline exhaust emission rates used in the USEPA's MOBILE and CARB's EMFAC models (CARB, 1992a; USEPA, 1992), are derived through the testing of thousands of new and in-use motor vehicles upon a certification testing cycle, **known** as the federal test procedure (FTP). Vehicles are tested dynamically on computerized treadmills (dynamometers). The FTP consists of a defined set of modal patterns **(start,** stop, acceleration, deceleration, idling, and constant-speed cruise operations), and is composed of three sub-cycles, known as the Bag 1, Bag 2, and Bag **3** cycles (emissions are collected in separate sample bags for each sub-cycle). Bag 1 contains emissions from a cold engine **start** and running exhaust, Bag 2 contains only running exhaust emissions and is collected after the engine is hot and combustion is stabilized, and Bag **3** contains emissions from a hot engine **start** and running exhaust. The bag samples are analyzed to determine the average emission rates for the vehicles operating under the test parameters. In EMFAC7F, the baseline exhaust emission rate (often referred to as the basic emission rate, or BER) is the average emission result for the vehicle class operating under Bag 2 of the FTP (the hot-stabilized test cycle component with an average operating speed of 25.8 kph (16 mph)).

Because the certification cycle is used to test new vehicles, for compliance with federal emissions requirements, as well as in-use vehicles, for ongoing compliance with certification requirements and for evaluation of inspection and maintenance program effectiveness, numerous data are available for vehicles operating under the FTP Bag 2 cycle conditions. However, emission rates noted under the Bag 2 testing conditions often differ significantly from the emission rates for the same vehicle when tested under other hot-stabilized testing cycles. Because thousands of vehicles have been tested under the FTP to develop the baseline exhaust emission rates, the desire on the part of regulatory agencies to define a relationship between baseline emission rates and emission rates at other average speeds seems logical. In this way, ongoing testing of vehicles can be conducted on the single certification cycle, rather than upon numerous cycles. Given the fact that these emission tests cost roughly $1,000.00 each, developing a relationship between average operating speed and emission rates would save a substantial amount of emission testing resources.

7.1 Correction Factors

It is important that the basic operating premise of the emission rate models and the concept of correction factors be clearly defined before proceeding to the analysis of the existing speed correction algorithms. The basic approach taken in existing emission rate models is to establish the baseline exhaust emission rate (or basic emission rate) and then to adjust that rate when an external variable is known to affect the magnitudes of these rates.

When onroad operations differ from the conditions of the Federal Test Procedure (FTP), the baseline emission rates are "corrected" to take into account those differences. The emission factors for vehicles on the FTP are compared to the emission factors for the same vehicles under the alternative conditions. The ratio of emissions under the alternative conditions to the emissions on the standard conditions is used to correct the noted average baseline emission rate. For example, if a number of vehicles are tested on the FTP at 75F and on the FTP at 105F and the hydrocarbon emissions at 75F are half the average emissions noted under the same test cycle but at 105F, the emission ratio for this temperature condition is **2.** To estimate emission rates at 105F, the average baseline exhaust emission rate for a subgroup of the fleet (for a model year and vehicle classification) would be multiplied by the correction factor of 2.

All of the individual correction factors are assumed to be independent and are employed in a simple linear form to correct the basic emission rates of each model year and vehicle classification for the variety of conditions believed to impact emission rates:

$$ER_{myr} = (BEER_{myr})(TCF)(SCF)(FCF)$$

where the ER is the onroad emission rate for the specific model year, BEER is the baseline exhaust emission rate for the model year, TCF is the temperature correction factor for the existing onroad temperature, the SCF is the speed correction factor for the existing onroad average speed, and the FCF is the fuel correction factor for the existing onroad fuel composition (this example is illustrative, and does not include all of the correction factors employed in the models). The onroad emission rates for each model year are then weighted by the travel fraction for that model year and an average emission rate for the vehicle class is calculated.

7.2 Speed Correction Factors

Because the certification cycle is used to test new vehicles, for compliance with federal emissions requirements, as well as in-use vehicles, for evaluation of inspection and maintenance program effectiveness, numerous data are available for vehicles operating under the FTP Bag 2 cycle. However, emission rates noted under the Bag 2 testing conditions can differ significantly from the emission rates for the same vehicle when tested under other hot-stabilized testing cycles. Because thousands of vehicles have been tested under the FTP to develop the baseline exhaust emission rates, the desire on the part of regulatory agencies to define a relationship between baseline emission rates and emission rates at other average speeds seems logical. In this way, ongoing testing of vehicles can be conducted on the single certification cycle, rather than upon numerous cycles (saving substantial agency resources).

To model emission rates at speeds other than 25.8 kph (16 mph), the US Environmental Protection Agency (USEPA) and the California Air Resources Board (CARB) developed speed correction factors, or statistically derived emission ratios (Guensler 1993a; Guensler, et al., 1993b; USEPA, 1992; CARB, 1992a; CARB, 1992b; EEA, 1991; USEPA, 1988). This emission ratio can be thought of as the average emission rate at the speed in question divided by the average emission rate for the same vehicle group under Bag 2 of the FTP. To approximate vehicle emissions at speeds other than 25.8 kph (16 mph), the baseline exhaust emission rate is multiplied by the statisticallyderived emission ratio.

In current emission inventory methodologies, gram/mile vehicle emission rates are modeled as non-linear functions of average operating speed (CARB, 1992b; EEA, 1991). In MOBILE4.1 (the United States Environmental Protection Agency's emission rate model) and EMFAC7F (the California Air Resources Board's emission rate model), exhaust emissions of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) from lightduty vehicles, on a gram/mile basis, are modeled as decreasing as average vehicle speeds increase between 0 kph and roughly 72.6 kph (45 mph), and modeled as increasing with average vehicle speed above 72.6 kph . Both MOBILE4.1 and EMFAC7F predict significant emission rate increases with speed for all pollutants at speeds above 88.7 kph (55 mph).

USEPA and CARB staff developed speed correction factors (SCFs) by testing more than 500 lightduty vehicles on laboratory dynamometers under a variety of chassis dynamometer cycles, including the certification cycle (federal test procedure). Each of the emission testing cycles are characterized by a unique set of acceleration, deceleration, constant speed cruise, and idle activities in a fixed procedural pattern. Bag samples were collected from vehicle tailpipes under the test cycles, using EPAs constant volume sampling and analytical procedures outlined in the Code of Federal Regulations. The total emissions for each vehicle test were quantified, and the average emissions per mile traveled were tabulated in the emissions database.

For each pollutant and motor vehicle technology group, CARB staff statistically correlated emission results to the average speeds of the test cycles used to generate the emissions data. Regression analyses were used to determine the relationships and develop the SCFs. CARB and USEPA staff used different data preparation, model specifications, and analytical techniques to develop SCFs for their models. The methodologies are similar in some respects, e.g. averaging of emission test results prior to analysis, but are significantly different in many other respects, e.g. the data employed in the analyses, the functional form of the relationships, and the specific averaging techniques employed (CARB, 1992b; EEA, 1991).

8.0 SPEED CORRECTION FACTOR DATA

Each of the test cycles used by the USEPA and CARB to gather emission rate data are composed of a unique profile of stops, **starts,** constant speed cruises, acceleration, and deceleration. Each cycle has a different overall average speed. Speed correction factors currently used in emission models were derived statistically from the relationship between cycle emission rate and average cycle speed. Specifically, the ratio of the baseline emission rate at an average speed **of** 25.8 kph (16 mph) and the emission rate at other average speeds is employed as the correction factor.

In the USEPA model, the denominator of the emission ratio is the emission rate for 31.6 kph (19.6 mph), the average test speed of the entire Federal Test Procedure (FTP). However, it should be noted that the 31.6 kph FTP test result also includes weighted emission contributions from hot and cold **start** operations, which none of the other cycles include. As discussed in section 7.0, this approach leads to distinct problems in the use of speed correction factors in the federal emissions model. Thus, all analyses employed the emission results of the FTP Bag 2 analysis, a 25.8 kph (16 mph) baseline speed (Guensler, 1993a).

8.1 Emission Testing Cycles

The laboratory test cycles employed by the USEPA and CARB for collecting speed correction factor data included: three low speed cycles, the New York City cycle, speed cycle 12, the three sub-cycles of the FTP, speed cycle 36, highway fuel economy test, and four high-speed cycles developed by CARB staff. In addition, data were collected for two idle tests, one with vehicles in neutral and one with vehicles in drive. The applicable test cycles are listed in table 4, and second-by-second speed profiles for each testing cycle is provided in Appendix A.

As noted in table 4, the Federal Test Procedure actually employs three component test cycles: a 41.4 kph (25.6 mph) average speed cold **start** running exhaust test cycle (FTP Bag 1); a 25.8 kph (16 mph) average speed hot stabilized running exhaust cycle (FTP Bag **2);** and a 41.4 kph (25.6 mph) average speed hot **start** exhaust emission test cycle (FTP Bag **3)** that is identical to the cold **start** cycle. By the time the engine has completed the FTP Bag 1 cycle, the engine and catalytic converter are hot, meaning that combustion has stabilized and emission control systems are functioning efficiently. Hence, the incomplete combustion characteristics associated with internal combustion engine **starts** are theoretically not exhibited by vehicles during the FTP Bag 2 portion of the dynamometer test.

With the exception of the FTP Bag 1 and Bag 3 cycles, all of the other testing cycles listed in table 4 are conducted with the vehicles already in a hot stabilized mode (like the FTP Bag 2 cycle), and test results do not include a contribution from the engine **start.** Because the Bag 1 and Bag 3 cycle tests contain incremental emission components directly linked to incomplete

Table 4: SCF Emission Testing Cycles Employed by the *CARB* and USEPA

Cycle	ID Code	Cycle Duration (Seconds)	Average Speed (kph)
Idle in Neutral	IDLE1	n/a	0.0
Idle in Drive	IDLE2	n/a	0.0
Low Speed 1	LS1	616	4.0
LAW Speed 2	LS2	637	***5.8***
Low Speed 3	LS3	624	5.6
New York City Cycle	NYCC	598	11.5
Speed Cycle 12	sc12	349	19.5
Federal Test Procedure	**FTP**	1371[a]	31.6[a]
FTP Bag 1, Cold-Start	**(BAG 1)**	505	41.3
FTP Bag 2, Hot-Stabilized	(BAG 2)	866	25.8
FIT Bag 3, Hot-Start	**(BAG 3)**	505	41.3
Speed Cycle 36	SC36	996	57.9
Highway Fuel Economy Test	HFET	765	77.9
High-speed 1	HS1	474	72.7
High-speed 2	HS2	480	82.3
High-speed 3	HS3	486	93.2
High-speed 4	HS4	492	103.9

[a] The total duration of the FTP is 1876 seconds (the sum of Bags 1,2, and 3). However, the duration and average speed in this table are based upon the weighted percent contribution of Bags 1,2 and 3 to the final test result, per the FIT averaging method (see Code of Federal Regulations, Title 40, **Part** 86).

combustion at engine **start,** these data are not used in developing the CARB speed correction factors. This is a logical step in the CARE3 modeling methods because engine **start** emissions are calculated separately from speed-related running exhaust emissions. As mentioned earlier, the denominator of the emission ratios employed in developing EPAs Mobile model include emission contributions from hot and cold **start** operations **...** but only under the specific baseline test cycle conditions (against which all other emissions behavior is compared). If differences in cold and hot **start** emissions behavior exist across cycles (which is likely) uncertainty in the USEPA SCF analyses is exacerbated and transferability **of** results across test conditions is sacrificed.

Because the idle test cycles are non-loaded cycles, the data were not used in developing the SCFs. Exclusion of the idle data is consistent with the CARB and USEPA approaches. In a cursory examination of idle data, a great deal of variability between the behavior **of** vehicles under the two idle tests can be seen (Washington, 1993). Additional studies related to the behavior of vehicles at idle are recommended.

The basic characteristics of each test cycle are tabulated and compared in table ***5.*** The table shows the mean speed, maximum speed, standard deviation, and standard deviation divided by the mean speed for all speed cycles. Probably the most revealing descriptive statistics are standard deviation and coefficient of variation (standard deviation of speed divided by mean speed). Each test cycle can also be characterized by a number of basic modal characteristics, including such aspects as maximum speed, and percentage of the cycle operated in idle, cruise, acceleration and deceleration modes. Table *6* contains a summary of these modal characteristics.

Table 5: Descriptive Statistics for the USEPA and CARB Emission Testing Cycles

Cycle Name	Mean Speed	Maximum Speed	Standard Deviation of Speed	Coefficient of Variation of Speed (SD/Mean)
Low Speed 1	2.45	10.00	3.07	1.25
Low Speed 2	3.64	14.00	4.15	1.14
Low Speed 3	4.02	16.00	4.38	1.09
New York City Cycle	7.10	27.70	8.00	1.13
Speed Cycle 12	12.07	29.10	10.23	0.85
FTP Bag 1[a]	25.58	56.67	18.23	0.71
FTP Bag 2	16.04	34.30	10.72	0.67
FTP Bag 3[a]	25.58	56.67	18.23	0.71
Speed Cycle 36	35.85	57.00	18.88	0.53
Highway Fuel Economy Test	48.27	59.90	10.09	0.21
Highway 1	45.07	53.30	9.67	0.21
Highway 2	51.03	59.90	11.22	0.22
Highway 3	57.77	67.40	13.03	0.23
Highway 4	64.44	74.90	14.95	0.23

[a] The data collected under the Bag 1 and Bag 3 cycles of the Federal Test Procedure are not used to develop SCFs because they contain cold and hot engine start emission contributions. However, because these cycles are components of the FTP, they presumed to represent driving conditions encountered by the vehicle fleet.

Table 6: Test Cycle Characteristics

CYCLE NAME	ID #	TIME (sec)	DIST. (miles)	AVG. SPEED (mph)	MAX SPEED (mph)	STD. DEV. SPEED	Ye CYCLE IDLE	% CYCLE ACCEL.	% CYCLE DECEL.	Ye CYCLE CRUISE
LS1	3	616	0.42	2.45	10.00	3.07	47.7	16.2	17.9	18.2
LS2	4	637	0.64	3.64	14.00	4.15	38.8	23.4	24.3	13.5
LS3	5	624	0.70	4.02	16.00	4.38	36.5	24.2	25.6	13.7
NYCC	6	598	1.18	7.10	27.70	8.00	34.9	23.9	24.2	17.0
sc12	7	349	1.17	12.07	29.10	10.23	27.2	26.1	24.1	22.6
BAG 1	9	505	3.59	25.58	56.67	18.23	19.6	21.0	20.4	39.0
BAG 2	10	866	3.86	16.04	34.30	10.72	18.6	25.3	19.3	36.8
BAG 3	11	505	3.59	25.58	56.67	18.23	19.6	21.0	20.4	39.0
SC36	12	996	9.92	35.85	57.00	18.88	6.5	19.0	16.0	58.5
HFET	13	765	10.26	48.27	59.90	10.09	0.7	14.1	11.8	73.4
HS1	14	474	5.93	45.07	53.30	9.67	1.1	13.3	9.9	75.7
HS2	15	480	6.80	51.03	59.90	11.22	1.0	13.8	10.4	74.8
HS3	16	486	7.80	57.77	67.40	13.03	1.0	14.2	10.9	73.9
HS4	17	492	8.81	64.44	74.90	14.95	1.0	15.3	11.4	72.3

8.2 Technology Groups

In the USEPA MOBILE4.1 emission rate model (EEA, 1991), separate SCF regression coefficients were calculated for thirteen different technology groups, based upon model year, fuel delivery technology (carbureted, fuel injected, throttle body injected), computer control system (open or closed loop), and catalyst system (oxidation only, 3-way, or 3-way plus oxidation). Separate models are derived for "normal" emitters and "high emitters" in each of the 13 technology groups, where the definition of emitter class is based upon standard deviation cutpoints for vehicle performance under the FTP. Hence, 26 separate SCF algorithms are employed in USEPA's MOBILE4.1 model (Guensler, 1993a).

According to the CARB technical support document (CARB, 1992b), the CARB model employs only four technology groups, based upon the premise that insufficient data are available to establish a strong relationship between emission rates and average vehicle speeds for many of the groups contained in the USEPA model. The variables used to define the four CARB vehicle technology groups (CARB, 1992b) were: model year and fuel injection type (port injection, carburetion, or throttle body injection). Emission control system configuration, i.e. catalytic converter type (none, oxidation catalyst only, 3-way catalyst, or oxidation catalyst plus 3-way catalyst), used in the USEPA analyses were not used to specifically separate technology groups. The and open/closed loop emission control system classification (pre-circa 1980 system, closed loop system, and open loop system) was not used to differentiate between technology groups. However, all vehicles that employed pre-1980 control systems and open loop control systems fell only into technology group 1, **and** none of the closed loop system vehicles fell into that category. Hence, a natural division in terms of this vehicle characteristic resulted. Because the four technology groups used to develop the latest version of the CARB SCFs in EMFAC7F are based upon fewer vehicle characteristics than those used by the USEPA, the number of test vehicles in each technology group is subsequently larger. Table 7 contains a summary of the technology group characteristics employed, as outlined in the CARB technical support document (CARB, 1992b).

Table 7: CARB Vehicle Technology Group Characteristics (with the value of each variable that meets the stated condition)

CARB Technology Group	Model Year	Fuel Delivery Technology
1	Pic-1986	Carbureted and Throttle Body Injected Vehicles
2	Pic-1986	Fuel Injected Vehicles
3	1986+	Carbureted and Throttle Body Injected Vehicles
4	1986+	Fuel Injected Vehicles

If two vehicle groups (or technology groups) exhibit significantly different behavior with respect to average cycle speed, separate models are needed *to* account for these differences (or an additional explanatory variable should be included in the model *to* account for the noted difference). **A** statistically justifiable development of separate models for separate technology groups requires that mutually exclusive data sets be employed in developing each model. **If** mutually exclusive data sets are not employed, the statistical differences in emission behavior become obscured, and the original justification for model separation is no longer supported.

8.3 Vehicle Test Data

The **USEPA** tested 464 in-use vehicles *to* develop the **SCFs** currently used in Mobile 4.1 for 1981 and later model years. Vehicles were tested during two separate analytical samplings (**EPA5** and **EPA8**) under as many as eight different dynamometer test cycles (plus one or two idle tests). The ***CARB*** tested another 69 lightduty automobiles during four separate test samplings between 1987 and 1990 (**2R8709, 2R8906, 2S89C2, 2S90C1**) under a number of different test cycles, including 4 high speed cycles.

Table **8** contains a description of the vehicles tested during each of the six test samplings, with information on the fuel injection technologies and under what cycles these vehicles were tested. Table 9 contains vehicle information in another format, indicating the model years of the vehicles tested by fuel injection group.

Table 8: Test Matrix by Project, Mean Cycle Speeds and Technology, Data Provided by the CARB and USEPA (Consistent with USEPA Data Summaries)

		2R8709		2R8906		2S89C2		2S90C1		EPA5		EPA8		
Speed mph	**kph**	**CB TBI**	**FI**	**CB TBI**	**FI**	**CB TBI**	**FI**	**CB TBI**	**FI**	**CB TBI**	**FI**	**CB TBI**	**FI**	**Total**
2.5	4.0											148	**88**	236
3.6	5.8											148	**88**	236
4.0	6.5											148	**88**	236
7.1	11.3									203	25	148	**88**	464
12.0	19.4									203	25	148	**88**	464
16.0	25.8	4	1	**8**	12	17	26	1		203	25	148	**88**	533
36.0	58.1	4	1	**8**	12					203	25	148	**88**	489
45.4	73.2	4	1	**8**	12									25
48.0	77.4	4	1	**8**	12	17	26	1		203	25	148	**88**	533
51.0	82.3	4	1	**8**	12									25
57.6	92.9	4	1	**8**	12	17	26	1						69
64.3	103.7	4	1	**8**	12	17	26	1						69

CB = Carbureted; TBI = Throttle Body Injection; FI = Fuel Injected

The difference of 4 vehicle tests (17 in the above data set vs. 21 in the CARB data set), noted in column 6 (**2S89C2**), is attributable to the fact that the results for the 4 lightduty trucks (LDTs) were excluded **from** the analyses in this report. The LDTs were excluded because the CO and **NOx** certification **standards** for these vehicles were somewhat less stringent than for autos.

Table 9: Fleet Breakdown by Project, Model Year, and Fuel Delivery Technology, Data Provided by the CARB and USEPA (Consistent with USEPA Data Summaries)

	2R8709		2R8906		2S89C2		2S90C1		EPA5		EPA8		
Year	CB TBI	FI	CB TBI	FI	CB TBI	FI	CB TBI	FI	CB TBI	FI	CB TBI	FI	Total
1977									18				18
1978									32				32
1979													
1980									2				2
1981									125	5	19		149
1982									5		20		25
1983	1								18	15	24		58
1984	1								3	5	10	1	20
1985	1	1			3	5					35	14	59
1986	1				7	7	1				12	7	35
1987					3	3					20	34	60
1988			2	2	4	8					8	13	37
1989			6	9		3						19	37
1990				1									1
Total	4	1	8	12	17	26	1	0	203	25	148	88	533

CB = Carbureted; TBI = Throttle Body Injection; FI = Fuel Injected

A total of 533 vehicles were tested on a variety of testing cycles: 317 pre-1986 carbureted or throttle body injected vehicles, 46 pre-1986 fuel injected vehicles, 64 later-model carbureted or throttle body injected vehicles, and 106 later-model fuel injected vehicles. Every vehicle was tested on the FTP and highway fuel economy test cycles, but no vehicle was tested on every cycle. A limited number of vehicles were tested on the high and low speed cycles. Data were collected from only 69 vehicles on the high speed cycles: 6 pre-1986 carbureted or throttle body injected vehicles, 6 pre-1986 fuel injected vehicles, 24 later-model carbureted or throttle body injected vehicles, and 33 later-model fuel injected vehicles. Data were collected on the USEPA low speed cycles from 226 vehicles: 108 pre-1986 carbureted or throttle body injected vehicles, 15 pre-1986 fuel injected vehicles, 40 later-model carbureted or throttle body injected vehicles, and 63 later-model fuel injected vehicles (see table 10).

Table 10: Total Number of Vehicles Tested by the USEPA and CARB, by Model Year Group and Fuel Delivery Technology Group

	Fuel Delivery Technology Group	
Model Year	Carbureted and Throttle Body Injected	Fuel Injected
Pre-1986	317	46
1986+	64	106

8.4 Vehicle Emission Response to Average Test Cycle Speed in the SCF Database

(Guensler 1993a)

The SCF database contains the emission test results for more than 500 vehicles tested under a set of emission testing cycles (the standard test cycles have different average speeds). Figure **3** is a scatterplot of the difference between the baseline gram/hour carbon monoxide emission test results (FTP Bag **2** cycle) and the emission test result on the other standard testing cycles for each 1986 and later model year fuel-injected vehicles included in the **SCF** database. Notice that some vehicles become cleaner on low speed cycles while other vehicles become dirtier on low speed cycles (the same is noted for high speed cycles).

The $\log_{10}$ of the emission rate ratio (ratio of the baseline gram/hour carbon monoxide emission test result and the emission test result on the alternative cycles) for each 1986 and later model year fuel-injected vehicles is reported in Figure **4.** If a vehicle's emission rate on a low speed test cycle were 5 times the emission rate for the same vehicle on the FTP Bag **2** cycle, the emission ratio value of log(5) would be reported for that test at the average speed of the low speed cycle. The emission ratio at (16 mph) for every vehicle is 1 by definition (the emission rate on the FTP Bag **2** cycle divided by itself). Notice in figure **4** that some vehicles exhibit emissions increases of more than **3** orders of magnitude (1000 times) when operating a test cycle with lower average speed than the FTP, while other vehicles may exhibit emission decreases of more than 3 orders of magnitude while operating on lower speed cycles.

Figures **5** through 8 provide similar results for changes and ratios for **HC,** and NOx emission rates.

In reviewing these figures, it becomes clear that the emission response with respect to change in average test cycle speed is highly erratic for carbon monoxide, somewhat erratic for hydrocarbons, and more systematic for oxides of nitrogen. The erratic emission behavior across test cycles (noted for carbon monoxide and hydrocarbons) is an important reason why large standard errors are associated with models that predict emission rate changes as a function of average operating speed alone.

One might argue that extreme values should be treated as outliers. However, as is discussed by Guensler (Guensler, 1993a), these cases must still be shown to be non-representative of the vehicle fleet before they can be excluded. The extreme values noted for some vehicles in the emission testing database may simply represent a failure of the overall modeling approach where average vehicle speed is assumed to be the only causal variable. Many vehicles exhibited erratic emission response behavior across test cycles. It may be that the erratic vehicle behavior on a specific cycle is simply a signal that important independent variables or interaction terms have been omitted from the model.

Figure 3: Change in Baseline Exhaust Emission Rate (g/hr) vs. Average Test Cycle Speed SCF Database - Carbon Monoxide, 1986+, Fuel Injected Vehicles

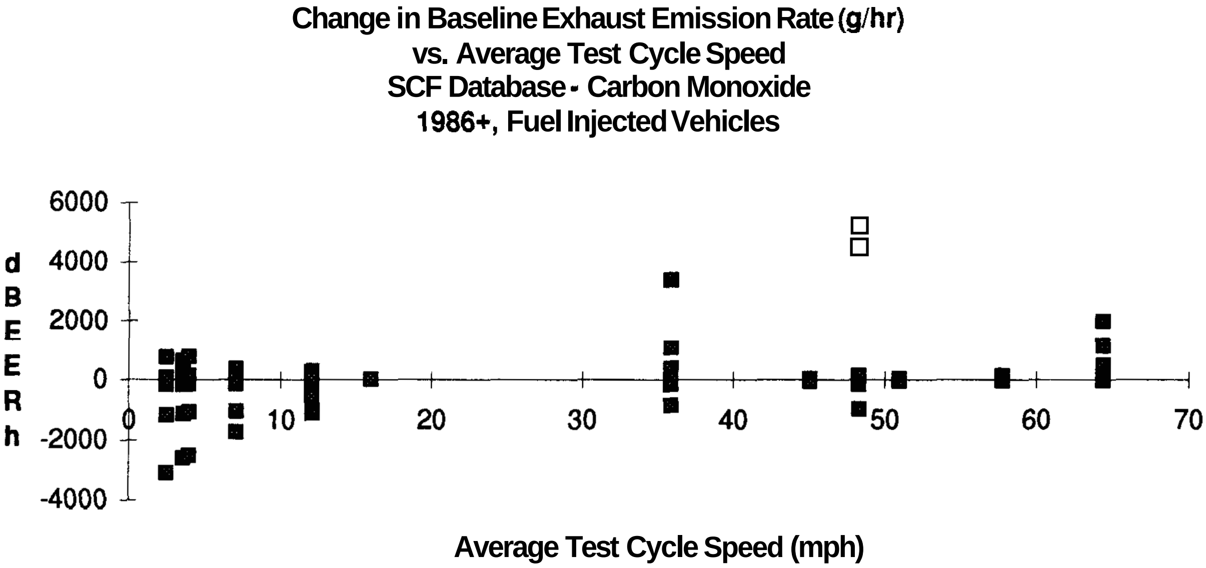


Figure 4: log (Emission Rate Ratio), log(SCF), log ((g/hr)/(g/hr)) vs. Average Test Cycle Speed SCF Database - Carbon Monoxide, 1986+, Fuel Injected Vehicles

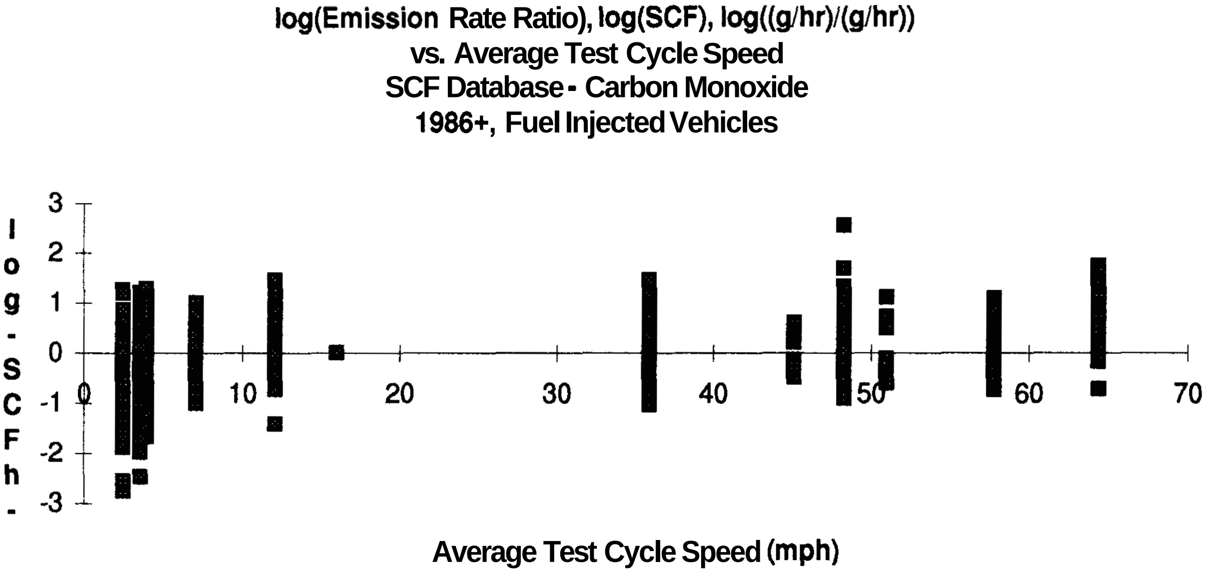


Figure 5: Change in Baseline Exhaust Emission Rate (g/hr) vs. Average Test Cycle Speed SCF Database - Hydrocarbons, 1986+, Fuel Injected Vehicles

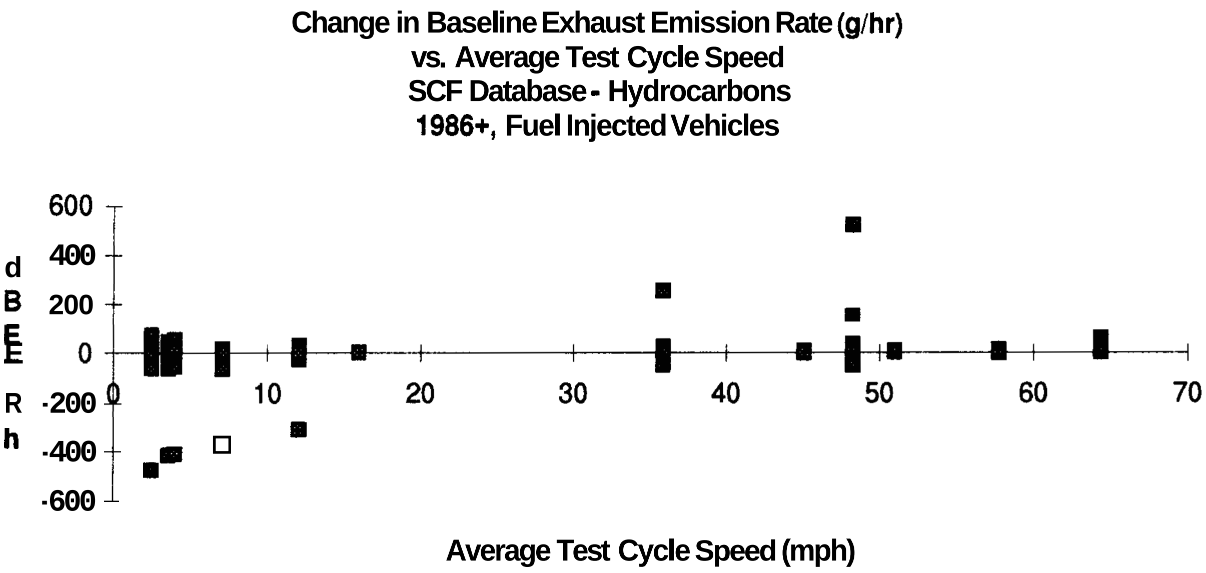


Figure 6: log (Emission Rate Ratio), log(SCF), log ((g/hr)/(g/hr)) vs. Average Test Cycle Speed SCF Database - Hydrocarbons, 1986+, Fuel Injected Vehicles

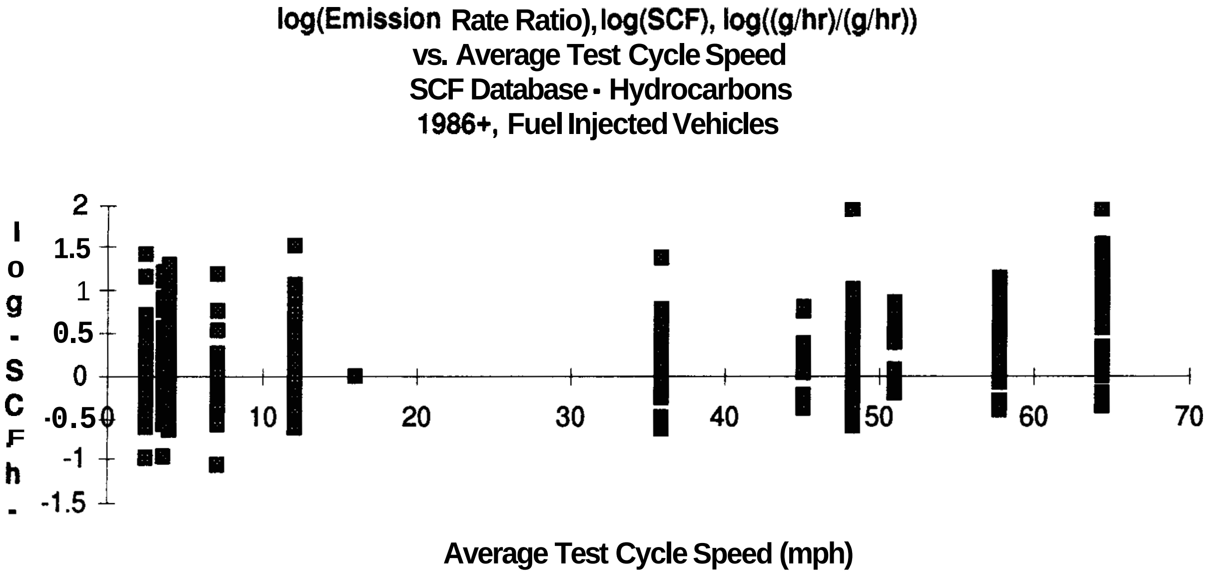


Figure 7: Change in Baseline Exhaust Emission Rate (g/hr) vs. Average Test Cycle Speed SCF Database - Oxides of Nitrogen, 1986+, Fuel Injected Vehicles

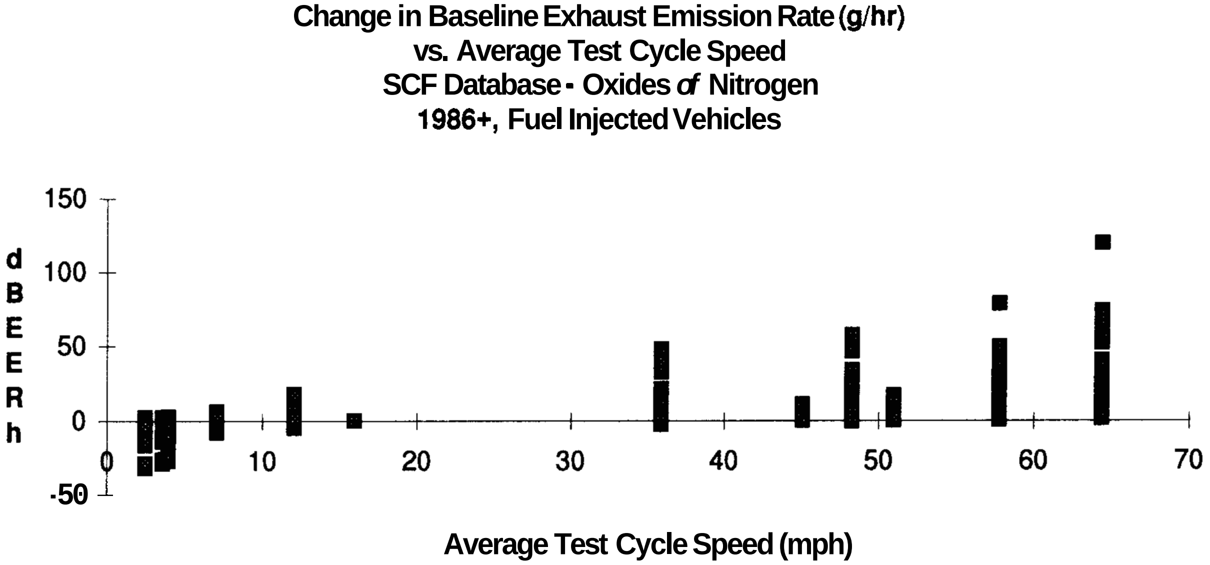
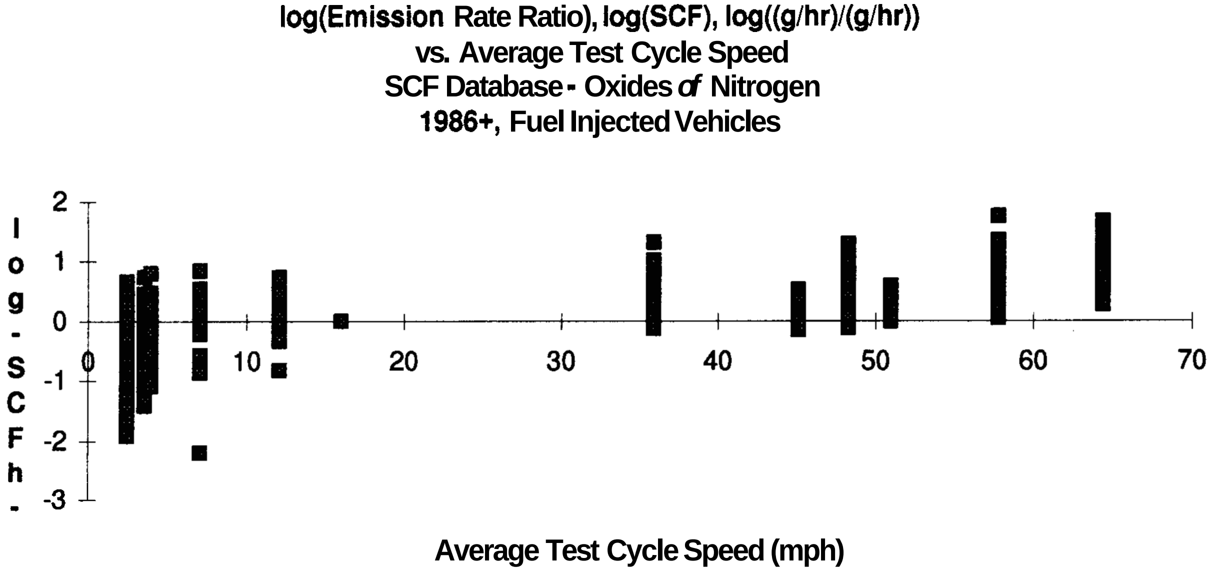


Figure 8: log (Emission Rate Ratio), log(SCF), log ((g/hr)/(g/hr)) vs. Average Test Cycle Speed SCF Database - Oxides of Nitrogen, 1986+, Fuel Injected Vehicles



9.0 THE IMPACTS OF HIGHLY VARIABLE EMISSIONS RESPONSES IN ASSESSING IVHS SCENARIOS

When any variety of **IVHS** implementation scenarios are examined, the changes in vehicle emissions associated with the IVHS strategies will result from changes in vehicle activity and changes in vehicle emission rates. The impacts associated with changes in vehicle activity are fairly straightforward. Increases or decreases in vehicle miles of travel or number of trips can be readily modeled, and although the emissions uncertainty associated with each trip or mile traveled is not explicitly estimated in the current modeling regime the concept of this type of error is readily understood and accepted. However, changes in emission rates associated with changes in traffic flow conditions are not as easily quantified. The error terms associated with these changes are not readily understood and should not be accepted without question.

In this preliminary analysis, the potential changes in emission rates associated with improved levels of service are examined for modern fuel-injected vehicles. Percent changes in emission rates are estimated for a variety of level of service improvement combinations. **A** range of emission impact estimates are provided, based upon confidence intervals associated with the existing modeled relationships between average vehicle speed and emissions. The high degree of uncertainty in emission estimates is evidenced by the large range of empirical results. The actual uncertainty in emission impact estimates is even greater than indicated by the ranges provided in this paper, due to the innumerable sources of emission calculation uncertainty that are discussed in recent emission inventory uncertainty literature.

The results of the impact assessment indicate that our ability to estimate the emission impacts of IVHS-related level of service using the conventional models available today are questionable at best. The analyses that follow are similar to those previously undertaken in the evaluation of congestion pricing scenarios (Guensler and Sperling, 1994) and the qualitative conclusions that we can reach based upon our knowledge of the cause effect relationships at work are identical: 1) where **IVHS** causes automobile vehicle trips and vehicle miles of travel to decline, emission benefits for all pollutants will accrue, to the extent that they are not offset by increased emissions from alternative modes; **2)** where **IVHS** reduces congestion and smoothes traffic flow, emission rates per mile of travel will likely decline for carbon monoxide and hydrocarbons, but will likely increase for oxides of nitrogen; **3)** if **IVHS** yields increased vehicle activity at high speeds, in excess of **88.7** kph ***(55*** mph), emission increases are likely for all pollutants; and **4)** where **IVHS** increases congestion and lowers average operating speeds on local roads, emission rates per kilometer will likely increase for all pollutants.

The large ranges surrounding the projected percent change in emission rates are based upon the confidence intervals associated with the use of speed correction factors as presented in a previous work (Guensler, Washington, and Sperling, 1993). The actual range in emission rate impact is even greater than presented here, because there are additional sources of uncertainty for which statistical inferences of confidence have yet to be developed, such as the relationship between operating environment and changes in cold and hot **start** emission rates (Guensler 1993b).

10.0 ANALYSIS OF EMISSION RATE IMPACTS OF IVHS SCENARIOS, BASED UPON CHANGES IN AVERAGE SPEEDS

If average speeds of travel on a freeway were improved by **IVHS** technologies from 48.4 kph (30 mph) to 80.6 kph (50 mph), the EMFAC7F emission model would predict a decrease in carbon monoxide emission rates by 6 percent, a decrease hydrocarbon emission rates by 3 percent, and an increase oxides of nitrogen emissions by 69 percent for 1986 and later model year fuel injected vehicles along these routes.[5] Modeled emissions changes associated with changes in average speeds when the average speed of the **IVHS** implementation scenario rises above 97.8 kph (60 mph) are predicted to be significant increases.

Given the predicted changes in emission rates, one could easily surmise that the increases in average vehicle operating speeds are likely to yield significant reductions in CO and HC emission rates, while concurrently increasing the emission rates of NOx. However, the point estimates don't tell the whole story. When the calculated emission rate changes include estimates of uncertainty, it becomes clear that the emission change estimates are questionable. When a bootstrap approach to estimating combined error (Efron, 1982) was employed to calculate the upper and lower confidence bounds for the prediction, we are 95 percent confident that the estimated 6 percent reduction in carbon monoxide emissions associated with increasing average vehicle speeds from 48.4 kph to 80.6 kph for 1986 and later model year fuel injected vehicles lies somewhere between a 59 percent decrease and a 89 percent increase in emission rates (see Guensler, 1993a for confidence interval derivation procedures). We are dealing with a huge range of uncertainty.

For the purposes of this analysis, a range of level of service improvements that could be provided by **IVHS** implementation will be examined. Table 11 contains the estimated average speed for various standard level of service conditions on a freeway (TRB, 1985). These average speeds were rounded to the nearest 8.1 kph (5 mph) increment so that prepared emission change tables could be readily employed. Tables 12 through 14 contain estimates of carbon monoxide, hydrocarbon, and oxides of nitrogen emission rate changes for modern-fuel-injected vehicles associated with the approximations of changes in average speeds associated with changes in levels of service. A bootstrap approach to estimating combined error (Efron, 1982) was employed to calculate the upper and lower bound estimates in tables 12 through 14 (Guensler, 1993a). The predicted error bands around the estimated percent change in emission rate account for the standard deviation of each SCF estimate as well as the covariance between the predicted SCF terms (Guensler, 1993a).

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[5] Different percentage changes would be predicted by the **MOBILE** model because the derivation of *speed* correction factors employed different methodologies than those employed in developing EMFAC (see Guensler, 1993b).

Table 11: Typical Average Speeds at Specified Levels of Service for Use in Comparing Potential Emissions Impacts from IVHS-Related Level of Service (LOS) Improvements

LOS	HCM[a] Average Speed (mph)	Approx? Average Speed (mph)	HCM[a] Average Speed (kph)	Approx.[b] Average Speed (kph)
A	60	65	97	105
B	57	60	92	97
C	54	55	87	89
D	46	45	74	73
E	30	30	48	48
F	<30	25	<48	40
F_{I}	n/a	20	n/a	32
F_{II}	n/a	10	n/a	16
F_{III}	n/a	5	n/a	8.1

[a] Highway Capacity Manual (TRB, 1985)

[b] Approximate average speeds for hypothetical comparison

Table 12: Change in Carbon Monoxide Emission Rates Associated with Potential IVHS-Related Changes in LOS-Based Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds

				Percent Emission Rate Change		
Initial LOS	Avg. Speed	IVHS LOS	Avg. Speed	Lower 95%	Model Predicted	Upper 95%
FIII	5	A	65	-64	-8	83
F_{III}	5	B	60	-67	-38	4
F_{III}	5	C	55	-77	-57	-33
F_{III}	5	D	45	-86	-69	-52
F_{III}	5	E	30	-78	-55	-20
F_{II}	10	A	65	-42	59	263
F_{II}	10	B	60	-44	5	95
F_{II}	10	C	55	-57	-28	15
F_{II}	10	D	45	-76	-48	-19
F_{II}	10	E	30	-66	-22	56
F_{I}	20	A	65	-12	68	152
F_{I}	20	B	60	-32	17	79
F_{I}	20	C	55	61	-15	55
F_{I}	20	D	45	-78	-38	22
F_{I}	20	E	30	-36	-17	0
F	25	A	65	-1	82	194
F	25	B	60	-30	28	120
F	25	C	55	-59	-6	89
F	25	D	45	-77	-31	47
F	25	E	30	-22	-10	0
E	30	A	65	5	105	234
E	30	B	60	22	43	136
E	30	C	55	-53	3	103
E	30	D	45	-72	-25	50
D	45	A	65	2	232	736
D	45	B	60	4	115	342
D	45	C	55	-1	43	118
C	55	A	65	-11	120	314
C	55	B	60	0	46	118
B	60	A	65	-9	46	95

Source: Derived from **tables in Guensler,** 1993a

Table 13: Change in Hydrocarbon Emission Rates Associated with Potential IVHS-Related Changes in LOS-Based Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds

Initial LOS	Avg. Speed	IVHS LOS	Avg. Speed	Percent Emission Rate Change: Lower 95%	Percent Emission Rate Change: Model Predicted	Percent Emission Rate Change: Upper 95%
F_{III}	5	A	65	-71	-34	25
FIII	5	B	60	-76	-51	-17
FIII	5	C	55	-81	-63	-43
F_{III}	5	D	45	-84	-72	-58
FIII	5	E	30	-84	-65	-47
F_{II}	10	A	65	-46	7	108
F_{II}	10	B	60	-53	-21	32
F_{II}	10	C	55	-59	-40	-15
F_{II}	10	D	45	-70	-55	-39
F_{II}	10	E	30	-73	-43	-10
F_{I}	20	A	65	-14	46	121
F_{I}	20	B	60	-30	9	61
F_{I}	20	C	55	-49	-16	31
F_{I}	20	D	45	-56	-36	-6
F_{I}	20	E	30	-44	-22	-10
F	25	A	65	-6	66	165
F	25	B	60	-28	25	98
F	25	C	55	-45	-3	70
F	25	D	45	-53	-27	17
F	25	E	30	-22	-12	-5
E	30	A	65	-1	90	220
E	30	B	60	-20	43	140
E	30	C	55	-38	11	98
E	30	D	45	-47	-17	41
D	45	A	65	21	140	345
D	45	B	60	11	76	192
D	45	C	55	-1	34	83
C	55	A	65	1	76	163
C	55	B	60	3	30	63
B	60	A	65	-2	33	63

Source: Derived from tables in Guensler, 1993a

Table 14: Change in Oxides of Nitrogen Emission Rates Associated with Potential IVHS-Related Changes in LOS-Based Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds

				Percent Emission Rate Change		
Initial LOS	**Avg. Speed**	**IVHS** LOS	**Avg. Speed**	**Lower 95%**	**Model Predicted**	**Upper 95%**
F_{III}	5	**A**	65	6	24	45
F_{III}	5	B	60	-11	2	1
FIII	5	C	55	-26	-17	-8
F_{III}	5	D	45	-51	-43	-37
F_{III}	5	E	30	-62	-54	-48
F_{II}	10	**A**	65	33	50	68
F_{II}	10	B	60	11	23	35
F_{II}	10	C	55	-8	0	1
F_{II}	10	D	45	-40	-31	-23
F_{II}	10	E	30	-55	-45	-36
F_{I}	20	**A**	65	82	119	160
F_{I}	20	B	60	54	79	107
F_{I}	20	C	55	30	46	63
F_{I}	20	D	45	-7	0	7
F_{I}	20	E	30	-28	-20	-13
F	25	**A**	65	100	153	213
F	25	B	60	71	107	149
F	25	C	55	46	69	96
F	25	D	45	8	15	22
F	25	E	30	-12	-8	-5
E	30	**A**	65	110	175	251
E	30	B	60	80	125	180
E	30	C	55	53	83	119
E	30	D	45	16	25	36
D	45	**A**	65	80	119	163
D	45	B	60	54	80	108
D	45	C	55	32	46	63
C	55	**A**	65	37	50	61
C	55	B	60	17	23	28
B	60	**A**	65	17	22	26

Source: Derived from tables in Guensler, 1993a

Based upon the analysis of percent emission rate change for combinations of initial and final average speed in 8.1 kph (5 mph) increments (see Appendix B), the following conclusions might be drawn (Guensler 1993a):

1. Changes in average vehicle speed appear to yield greater percentage changes in carbon monoxide and hydrocarbon emission rates for older carbureted vehicles than for newer fuel injected vehicles (except at speeds exceeding 80.6 kph where the emission change estimates for older carbureted vehicles are highly uncertain).

2. Changes in average vehicle speed yield appear to provide greater percentage changes in oxides of nitrogen emission rates for newer fuel injected vehicles than for older carbureted vehicles.

3. Percentage changes in emission rates appear more stable (i.e. the confidence band is narrower) for older carbureted vehicles than for newer fuel injected vehicles, making the percentage change estimates more certain for older carbureted vehicles than for newer fuel injected vehicles (except at speeds exceeding 80.6 kph where the emission change estimates for older carbureted vehicles are highly uncertain).

4. Predicted increases in emission rates are fairly certain for all pollutants when moving toward extremely low speeds (i.e. 8.1 kph) and predicted decreases are fairly certain for all pollutants when moving from extremely low speeds.

5. Increasing average vehicle speeds from low speeds (0 to 48.4 kph) to moderate speeds (between 48.4 and 72.6 kph) should provide carbon monoxide benefits for older vehicles, and hydrocarbon emission benefits for all vehicles. However, the carbon monoxide benefits for modern fuel injected vehicles associated with these speed changes are highly uncertain.

6. Increasing average vehicle speeds from very low speeds (below 24.2 kph) to low to moderate speeds (perhaps between 24.2 and 64.5 kph) should provide an emission benefit for oxides of nitrogen.

7. Model-predicted emission changes for carbon monoxide and hydrocarbons are extremely variable for increases from moderate to very high average travel speeds. However, based upon the presumed cause-effect relationship between engine load and vehicle enrichment, moving toward very high free flow travel speeds from moderate travel speeds is likely to significantly increase emission rates and prove detrimental to air quality. It is probably reasonable to expect increases in both hydrocarbon and carbon monoxide emission rates at high speeds even though the confidence bands are wide.

8. Changes in carbon monoxide and hydrocarbon emission rates associated with small relative average speed changes at high speeds (e.g. increasing average speed from 80.6 kph to 88.7 kph) are too uncertain to accurately assess. Given the highly variable response **of** vehicles to the changes in average test cycle speed, the limited number of vehicles tested, and the nature of the high speed cycles themselves (high initial acceleration rates), the high degree of uncertainty is to be expected for carbon monoxide and hydrocarbon emissions.

9. Decreasing average vehicle speeds from above 96.8 kph to below 88.7 kph (but remaining above 56.5 kph) is likely to provide large emission benefits for oxides of nitrogen,

moderate emission benefits for hydrocarbons, and may also provide carbon monoxide benefits (as indicated by bootstrap analysis).

10. The average speed modeling regime for oxides of nitrogen is probably not unreasonable. The range of confidence for changes in oxides of nitrogen emissions is narrow even for high speed operations, indicating that the oxides of nitrogen increases are likely to be significant and fairly certain at high speeds. Because emissions of oxides of nitrogen are important in terms of ozone formation than was previously realized by air quality management planning agencies (NRC 1991), evaluation of oxides of nitrogen emissions changes is paramount in **IVHS** impact assessments for many areas.

11. The application of speed correction factors and the average speed modeling regime to analysis of emissions along corridors will yield highly uncertain results.

11.0 EFFECTS OF MODAL ACTIVITY

Average speed does not cause emissions. Two trips with the same average speed can be made by a vehicle, but the emissions from each trip may differ significantly because emissions are a function of combustion parameters and emission control systems. The modal characteristics of the trip (acceleration, deceleration, cruise and idle patterns) appear to be much more likely to cause changes in the combustion parameters and control system efficiency than the average speed.

Second-by-second laboratory tests indicate that changes in operating mode (acceleration and deceleration) are capable of producing significant emissions, but are not currently modeled (Darlington et al. 1992; CARB 1991b; Benson 1989; Groblicki 1990; Calspan 1973a; Kunselman et al. 1974). Recent laboratory testing indicates that high acceleration rates are significant contributors to instantaneous emission rates, and that one sharp acceleration may cause as much carbon monoxide pollution as does the entire remaining trip (CARB, 1991b; Carlock, 1992b). Pollutant "emission puffs" do occur, typically when the vehicle goes into enrichment and not enough air is available to facilitate complete combustion, and these events may be associated with high rates of acceleration or deceleration. Surprisingly, even vehicle operations at a relatively stable high speed flow appear to show some variability in emission rates that may be associated with accelerations and decelerations, even though the rates of acceleration and deceleration at these speeds are low (Guensler 1993b). Modal effects are not directly addressed in 'average speed emissions analysis.

IVHS is likely to smooth vehicle flows and reduce the number of significant acceleration and deceleration events that cause elevated emission rates along the routes upon which IVHS is implemented. Depending upon how the systems are implemented, IVHS has the potential to increase traffic congestion along routes that feed onto or off of the **IVHS** system (Johnston and Page, 1991) causing traffic flow to become less smooth. But the impact of flow smoothing is not well represented in the average speed modeling regime based upon the limited number and variety of test cycles employed in developing the relationships (Guensler, Washington, and Sperling, 1993). Better tools are needed to assess both the actual changes in modal operations as well as the changes in emission rates associated with these changes in modal operations.

When examining the changes postulated for average vehicle operating speed, we can assert that when average speed increases and flows are smoothed, the change in emission rate should be toward the optimistic end of the confidence interval. The rationale behind this assertion is that many recent studies have clearly indicated that decreased modal activity leads to decreased emission rates and these effects not captured by the current speed correction factor modeling regime.

Some analysts (Decorla-Soma, 1994) have advocated switching travel demand models from a link-based modeling regime to a trip-based modeling regime, because the speed correction factors were originally derived from driving cycles that represented .trips.. The refined models would provide average speed of trips rather than average speeds on network links. This is an applicability issue (i.e. trip-based SCFs are applied to link-based activity) that is not addressed in this document but is discussed in Guensler, 1993a. The applicability issue surely plays a role in whether the speed correction factors applied to any given traffic flow pattern are likely to be biased high or biased low. Applying tripderived **SCFs** to link activity is very likely to bias some emission estimates high and other estimates low, depending upon the specific situation modeled. However, data are only now being collected (second-by-second emission test results from in-use vehicles) from which these potential effects can be evaluated. Nevertheless, as indicated in the uncertainty analyses reported here, the inherent uncertainty associated with the use of these .trip-based. speed correction factors is likely only to provide perceived benefits from a major shift toward trip-based modeling. The current application of speed correction factors to link-based activity may be providing better estimates of vehicle emissions than would result if the **SCFs** were applied to trip-based estimates of activity. The bottom line is that no evidence is yet available to support the assertions that any improvements would accrue from switching to a trip-based activity modeling regime. Noting that **IVHS** improvements are likely to be link-based (i.e. improvements in traffic flow are likely to be noted throughout the network along those links that are currently congested) switching to a trip-based modeling regime may even make the task of modeling benefits even more difficult.

12.0 CONCLUSIONS

Accurately quantifying emission reductions resulting from changes in mobile source operating conditions is extremely difficult. Changes in emission-producing vehicle activity must be estimated, and activity-specific emission rates for these changes must be known. Yet, if intelligent vehicle highway systems are to be seriously considered as an environmentally benign congestion management tool, the emission tradeoff between induced trips and increased VMT and reduced congestion-related vehicle emission rates need to be quantified.

Tables 15 through 17 summarize the potential influence that various **IVHS** implementation technology bundles may have upon emission-producing vehicle activities and factors affecting vehicle emission rates. In terms of emission producing vehicle activity and emission rate impacts, the important items to note: 1) the implementation of advanced public transportation systems is likely to provide significant emission-related benefits in all categories of vehicle activity and variables that affect emission rates, and pursuit of APTS technologies for air quality purposes appears beneficial; **2)** the impacts of **IVHS** on trip making and VMT are highly uncertain; and **3) IVHS** has the potential to significantly reduce emissions associated with modal activities but that these reductions cannot be quantified at this time.

The emissions impacts of changes in trip making and VMT are relatively straightforward if the operating environment of the vehicle remains unchanged. **A** percentage reduction in trip ends **(starts** and engine shutdowns) can be translated into percentage changes in trip-end emissions. Similarly, reductions in VMT can be translated into reductions in running emissions.

From an emissions standpoint, analysts have been advocating **IVHS** implementation primarily for the benefits in reducing traffic congestion, expecting that the changes in the vehicle operating environment (i.e. average speed) will produce significant emission reductions. Because the travel demand and emission rate models do not well represent the actual cause-effect relationships at work (especially for modal activities), it is impossible to determine in a definitive manner the overall emission impacts of **IVHS** implementation. Our analyses indicate that changes in average vehicle operating speed yield highly uncertain emission impact estimates. Given the emission rate relationships that we have available today, when **IVHS** technology bundles are implemented, they should be designed to : 1) increase average vehicle speeds from below **24.2** kph **to** above **24.2** kph (remaining below **64.5** kph) for emission benefits in all pollutants, **2)** increase average vehicle speeds from below **48.4** kph **to** above **48.4** kph (remaining below **64.5** kph) in areas where reductions in carbon monoxide and hydrocarbon emissions are desired, **3)** avoid allowing previously congested routes **to** exceed **64.5** kph average speed as a result of **IVHS** implementation, and **4)** avoid creating congestion on non-IVHS routes. In areas where ozone formation is NOx limited, the implementation of **IVHS** may yield significant increases in NOx emissions detrimental to air quality. However, it should be noted also that as causal relationships and interactions between vehicle characteristics and modes of operation are unveiled through new research, the findings may change. Indeed, research may reveal that flow smoothing benefits are much greater than currently projected by the emission models for all pollutants.

Table 15: Potential Impacts of Various IVHS Technology Bundles on Emission-Producing Vehicle Activities Increasing Activity (+), No Change (=), and Decreasing Activity (-)

	ATMS	ATIS	AVCS	APTS	CVO[a]
Vehicle Miles Traveled	?[b]	?[b]	?[b]	-	=
Cold Engine Starts	=	-	?	-	-
Warm or Hot Engine Starts	=	-	?	-	-
Engine "Hot Soaks"	=	-	?	-	-
Engine Idling	-	-	-	-	-
Diurnal Temp.	=	=	=	=	=
Multi-Day Diurnal Temp.	=	?	?	+	=
Vehicle Refueling	-	?	?	-	=
Modal Behavior	-	?	-	?	-

[a] Changes in the CVO category apply almost exclusively to the goods movement sector.

[b] Depends upon whether longer trips are made in order to save travel time and what modes are selected (reduced VMT for shared modes).

[c]

Table 16: Potential Impacts of Various IVHS Technology Bundles on Vehicle Parameters and the Expected Effect on Vehicle Emission Rates Increasing Emission Rates (+), No Change (=), and Decreasing Emission Rates (-)

	ATMS	ATIS	AVCS	APTS	CVO[a]
Vehicle class	?	+	?		-
Fleet Turnover[b]	-?	-?	-?	-?	-?
Accrued vehicle mileage	+-	+	+		-
Tampering and I&M	-				-

[a] Changes in the CVO category apply almost exclusively to the goods movement sector.

[b] Fleet turnover represents changes in the on-road vehicle fleet expected to arise from IVHS implementation. Benefits accrue when newer model year vehicles enter the fleet with fuel injection systems, advanced emission control systems, and onboard computer controls. The IVHS listed above will encourage fleet turnover; however, a significant increase in average vehicle price may play a mitigating role by encouraging the retention of older vehicles in the fleet for longer periods of time. Remember, emission reductions associated with fleet turnover only accrue when fleet turnover is beyond that expected for the future year.

Table 17: Potential Impacts of Various IVHS Technology Bundles on Vehicle Operating Conditions and the Expected Effect on Vehicle Emission Rates Increasing Emission Rates (+), No Change (=), and Decreasing Emission Rates (-)

	ATMS	ATIS	AVCS	AFTS	CVO[a]
Cold or hot start mode	=	?	+		
Average vehicle speed					-
Modal Activities			-		-
Vehicle Load			-		
Driver behavior	-		-	-	+

a Changes in the CVO category apply almost exclusively to the goods movement sector.

Table 18: Potential Impacts of Various IVHS Technology Bundles on Environmental Conditions and the Expected Effect on Vehicle Emission Rates Increasing Emission Rates (+), No Change (=), and Decreasing Emission Rates (-)

	ATMS	ATIS	AVCS	AFTS	CVO[a]
Altitude & Humidity	=	=	=	=	=
Ambient temperature	?[b]	=	?[b]	?[b]	=
Diurnal temperature sweep	=	=	=	=	=
Road grade	=	=	?[b]	=	=

a Changes in the CVO category apply almost exclusively to the goods movement sector.
b Depends upon changes in travel by time of day.

Note that none of the observations presented in this paper actually dealt with ***air quality,*** only with vehicle activity and emission rates that affect air quality. **A** whole new set of uncertainties arises with respect to pollutant dispersion. For example, will the presence of high-speed vehicle platoons change the pollutant dispersion characteristics, and will drivers potentially be exposed to higher in-vehicle pollutant concentrations (Benson, 1993)?. Furthermore, the formation of ozone occurs when hydrocarbons and oxides of nitrogen are combined in the presence of sunlight. Hence, whether the pollutants are emitted during the morning or evening periods can be of serious consequence to single day ozone formation. In general, morning emissions tend to form more smog. However, the photochemical reactions that occur during a daily cycle can often be exacerbated by poor airflow conditions that cause the trapping of pollutant in an airshed for multiple days. This means that under extremely stagnant conditions, the emission of the pollutant by time of day is of lesser consequence. We are dealing with a complex system, composed of tremendously complex interactions, and we must face the fact that our predictive capabilities today are still in their infancy.

The implementation of IVHS technologies has the potential to dramatically alter the transportation infrastructure; affecting land use patterns, trip generation, trip distribution, mode choice, and route selection. IVHS implementation will change vehicle characteristics and vehicle operating conditions and will have a mixed effect upon emissions (and energy use). Emission increases and decreases are likely to result from specific changes. Ideally, the magnitude of emission increases and decreases would be measured. Unfortunately, at this time, for most of the land use, trip making, and emission rate effects, insufficient theoretical and empirical evidence exist to make such a determination. Given the poor state of understanding with respect to the actual cause-effect relationships between vehicle activity and emission rates at work for motor vehicles, especially associated with modal vehicle activities, it is impossible to determine in a definitive manner the overall emission impact of IVHS.

To better evaluate the emission impacts of IVHS systems: 1) land use models need to be capable of incorporating the influence of new IVHS infrastructures; 2) travel demand models need to be upgraded to consider fundamentally different highway capacity (traffic flow) relationships, to be more sensitive to microscale traffic flow changes, and to incorporate additional feedback loops between the various travel demand model components; and 3) emissions models need to represent relationships between vehicle operating modes and emissions more accurately. As these analytical tools evolve, the impacts of IVHS implementation can be better evaluated.

The primary goal of IVHS-related emissions research should be to identify and quanti@ the important cause-effect relationships at work. To achieve this goal, the effect of modal vehicle operations on emissions must be further investigated. Future IVHS-emissions research should be designed to: 1) identify important emission related vehicle activities in the IVHS and non-IVHS vehicle fleets affected by IVHS implementation; 2) develop a modal emission modeling framework, applicable to IVHS and non-IVHS vehicle fleets; 3) improve existing transportation demand models or develop new activity modeling approaches that combine demand and simulation so that modal activity outputs can be estimated; 4) develop a new modal emissions model using second-by-second emission testing data now becoming available; and 5) analyze the implications of IVHS implementation, in terms of IVHS and non-IVHS vehicle performance profiles, based upon the emission rate model outputs.

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Appendix A - Second-by-Second Speed vs. Time Profiles of the Emission Testing Cycles Employed in Developing USEPA and CARB Speed Correction Factors (Guensler, 1993a)

Figure A-l

Low Speed 1
Emission Testing Cycle
Speed vs. Time Trace

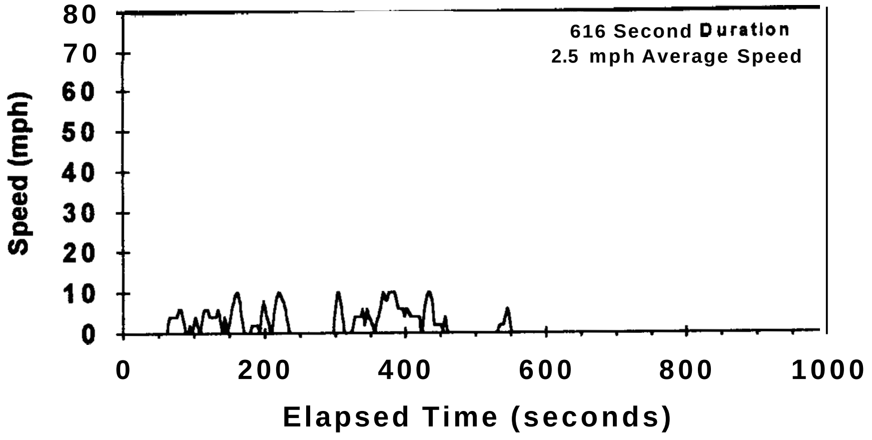


Figure A-2

Low Speed 2
Emission Testing Cycle
Speed vs. Time Trace

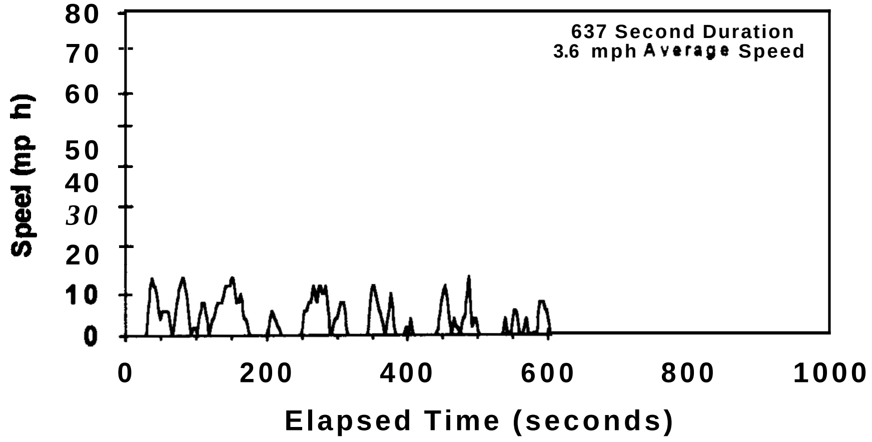


Figure A-3

Low Speed 3
Emission Testing Cycle
Speed vs. Time Trace

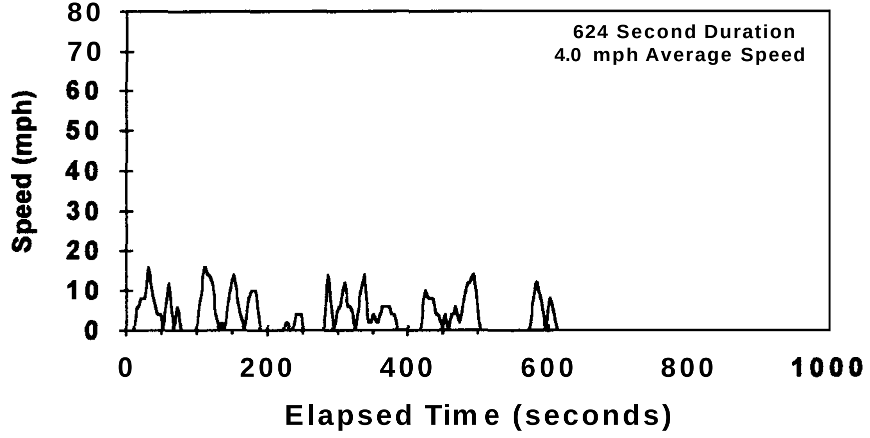


Figure A-4

New York City Cycle
Emission Testing Cycle
Speed vs. Time Trace

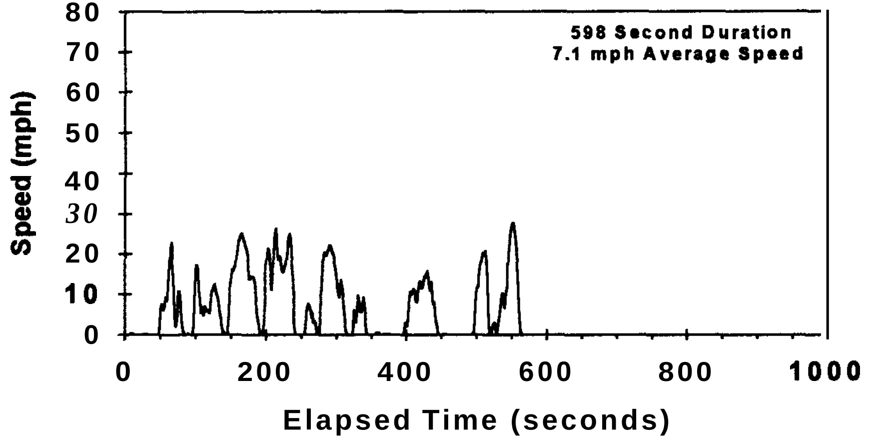


Figure A-5

Speed Cycle 12
Emission Testing Cycle
Speed vs. Time Trace

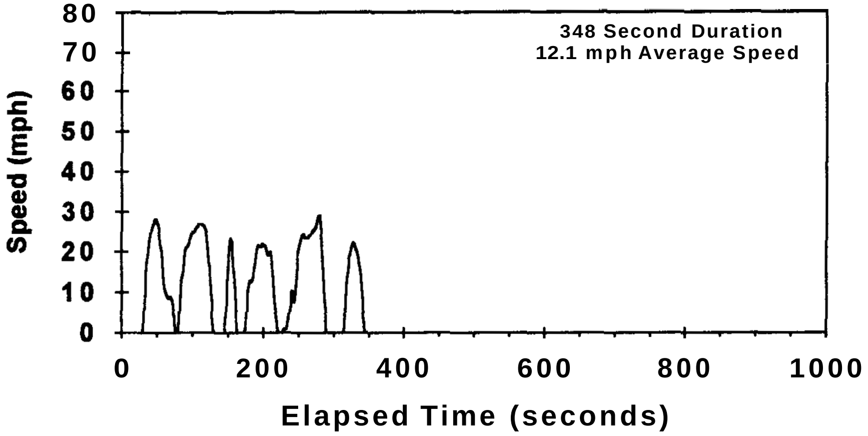


Figure A-6

Federal Test Procedure - Bag 1
Emission Testing Cycle
Speed vs. Time Trace

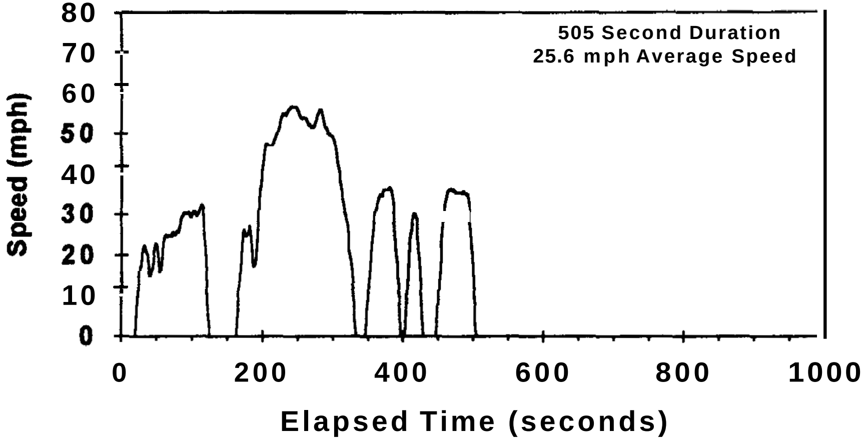


Figure A-7

Federal Test Procedure - Bag 2
Emission Testing Cycle
Speed vs. Time Trace

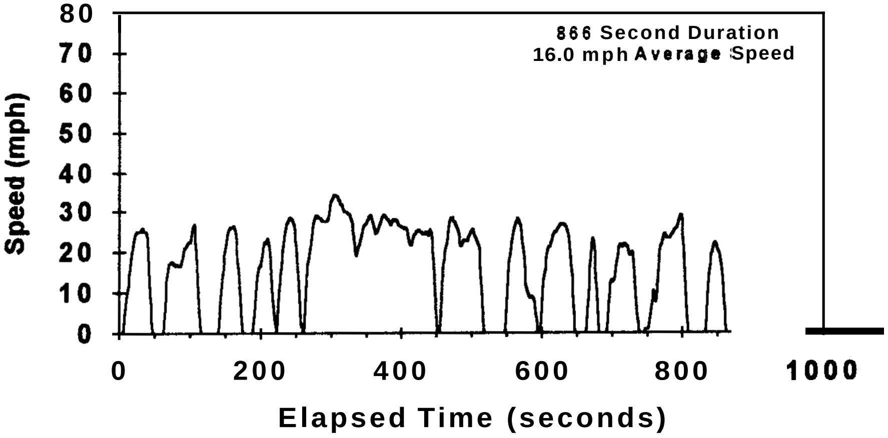


Figure A-8

Federal Test Procedure - Bag 3
Emission Testing Cycle
Speed vs. Time Trace

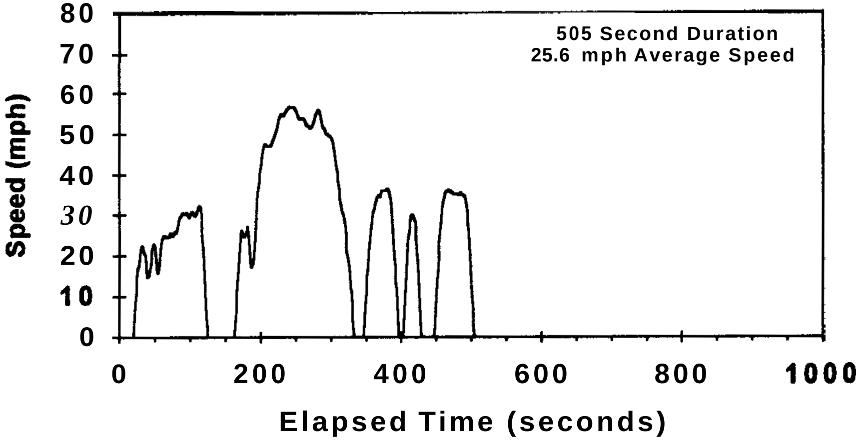


Figure A-9

Speed Cycle 36
Emission Testing Cycle
Speed vs. Time Trace

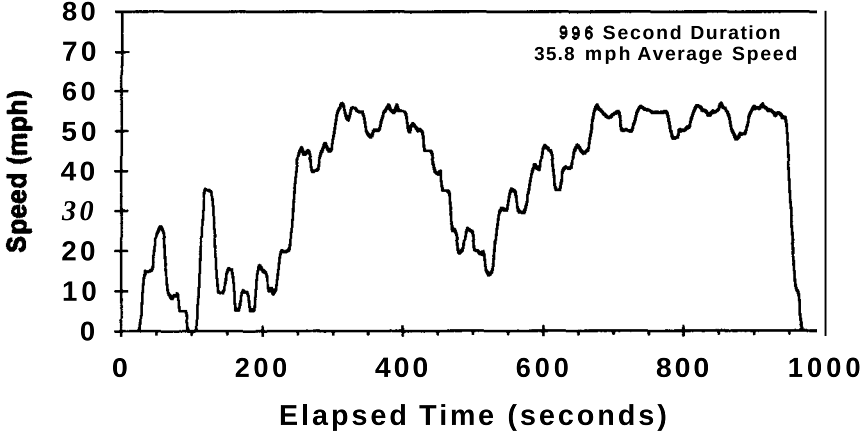

996 Second Duration
35.8 mph Average Speed

Figure A-10

High Speed 1
Emission Testing Cycle
Speed vs. Time Trace


474 Second Duration
45.1 mph Average Speed

Figure A-11

Highway Fuel Economy Test
Emission Testing Cycle
Speed vs. Time Trace

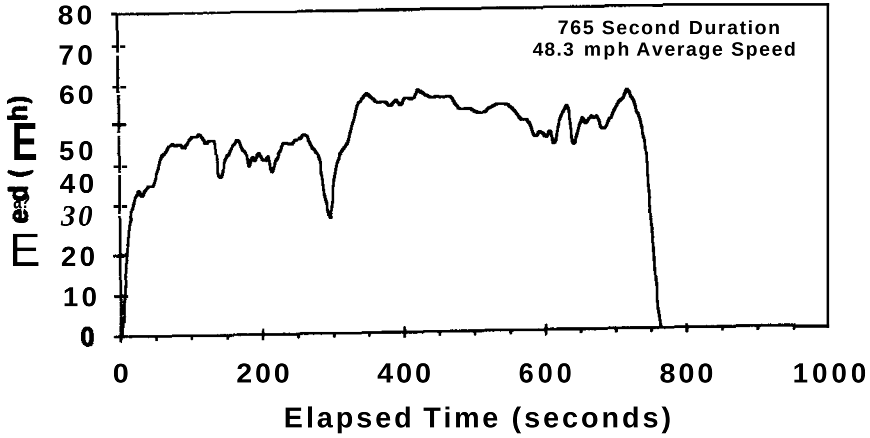


Figure A-12

High Speed 2
Emission Testing Cycle
Speed vs. Time Trace

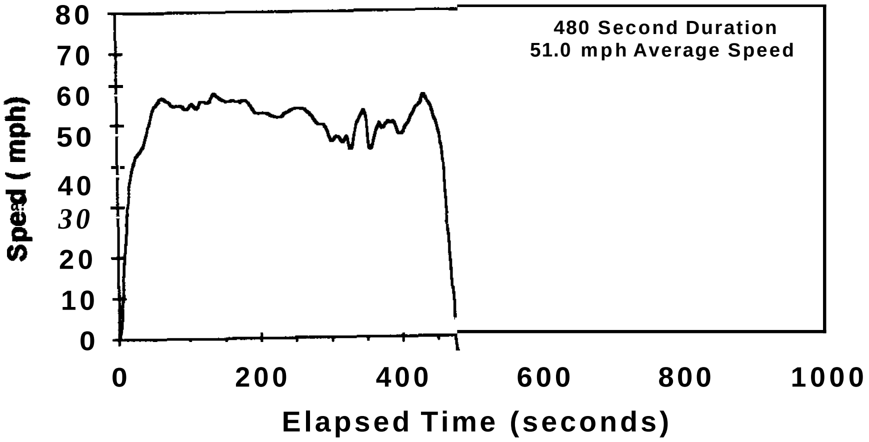


Figure A-13

High Speed 3
Emission Testing Cycle
Speed vs. Time Trace

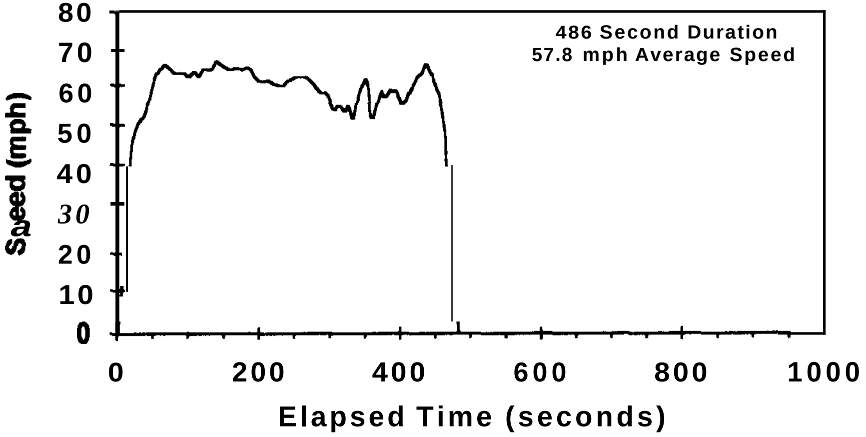
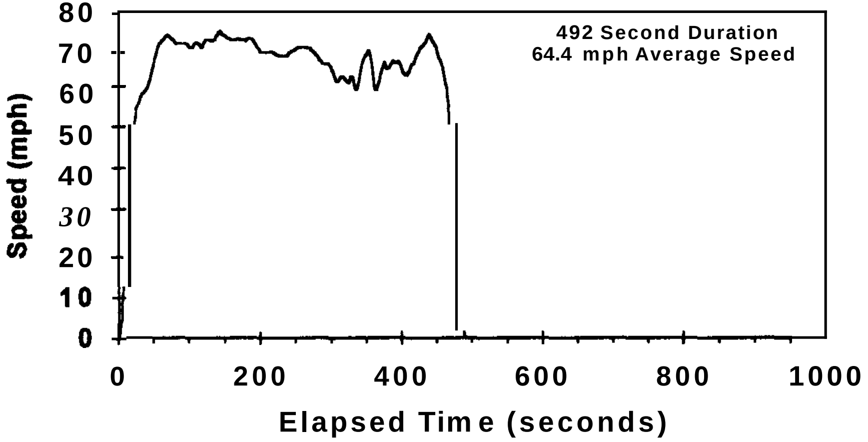


Figure A-14

High Speed 4
Emission Testing Cycle
Speed vs. Time Trace



Appendix BI - Percent Change in Carbon Monoxide Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	CO, 1986+ FI Vehicles % Change in g/km Emission Rate Bootstrap Analysis		
		Low	Pred	High
5	5	0	0	0
5	10	-57	-40	-29
5	15	-61	-44	-26
5	20	-71	-46	-11
5	25	-77	-49	-11
5	30	-78	-55	-20
5	35	-78	-61	-36
5	40	-82	-66	-48
5	45	-86	-69	-52
5	50	-85	-67	-47
5	55	-77	-57	-33
5	60	-67	-38	4
5	65	-64	-8	83
10	5	40	70	129
10	10	0	0	0
10	15	-31	-6	40
10	20	-51	-7	72
10	25	-61	-12	78
10	30	-66	-22	56
10	35	-68	-33	23
10	40	-72	-43	-6
10	45	-76	-48	-19
10	50	-74	-44	-14
10	55	-57	-28	15
10	60	-44	5	95
10	65	-42	59	263
15	5	34	85	152
15	10	-29	10	45
15	15	0	0	0
15	20	-28	-4	26
15	25	-45	-10	29
15	30	-51	-20	15
15	35	-57	-30	-4
15	40	-67	-39	-11
15	45	-77	-43	-2
15	50	-75	-38	8
15	55	-57	-22	22
15	60	-32	11	65
15	65	-25	63	171
20	5	11	98	229
20	10	-42	19	97
20	15	-20	6	38
20	20	0	0	0
20	25	-21	-7	4

Appendix BI (Cont.) - Percent Change in Carbon Monoxide Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	CO, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis		
		Low	Pred	High
20	30	-36	-17	0
20	35	-52	-27	-4
20	40	-66	-35	8
20	45	-78	-38	22
20	50	-78	-32	41
20	55	61	-15	55
20	60	-32	17	79
20	65	-12	68	152
25	5	11	119	313
25	10	-47	32	154
25	15	-23	16	81
25	20	-4	9	26
25	25	0	0	0
25	30	-22	-10	0
25	35	-42	-21	7
25	40	-62	-29	24
25	45	-77	-31	47
25	50	-76	-25	67
25	55	-59	-6	89
25	60	-30	28	120
25	65	-1	82	194
30	5	24	143	342
30	10	-41	47	183
30	15	-14	30	103
30	20	0	22	55
30	25	0	12	28
30	30	0	0	0
30	35	-29	-12	10
30	40	-54	-22	28
30	45	-72	-25	50
30	50	-72	-18	75
30	55	-53	3	103
30	60	22	43	136
30	65	5	105	234
35	5	52	176	361
35	10	-20	66	208
35	15	2	49	127
35	20	3	41	104
35	25	-9	30	73
35	30	-9	16	40
35	35	0	0	0
35	40	-37	-13	16
35	45	-62	-17	38
35	50	-63	-10	63

Appendix BI (Cont.) - Percent Change in Carbon Monoxide Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	CO, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis Low	Pred	High
35	55	-41	15	91
35	60	-8	63	163
35	65	6	139	332
40	5	89	219	452
40	10	4	90	244
40	15	12	74	201
40	20	-7	68	189
40	25	-19	56	161
40	30	-22	37	118
40	35	-14	17	58
40	40	0	0	0
40	45	-40	-8	19
40	50	-46	0	42
40	55	-20	31	96
40	60	3	91	246
40	65	5	187	454
45	5	108	256	602
45	10	21	110	322
45	15	0	98	322
45	20	-18	94	345
45	25	-32	81	313
45	30	-34	59	256
45	35	-28	34	155
45	40	-16	11	68
45	45	0	0	0
45	50	-16	8	32
45	55	-1	43	118
45	60	4	115	342
45	65	2	232	736
50	5	88	233	586
50	10	15	96	281
50	15	-7	85	298
50	20	-29	83	354
50	25	-41	72	320
50	30	-43	52	253
50	35	-39	27	170
50	40	-30	5	84
50	45	-25	-6	19
50	50	0	0	0
50	55	2	32	100
50	60	2	99	335
50	65	-2	209	701
55	5	48	151	301
55	10	-13	48	133

Appendix BI (Cont.) - Percent Change in Carbon Monoxide Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	CO, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis		
		Low	Pred	High
55	15	-20	38	131
55	20	37	34	154
55	25	-48	26	137
55	30	-52	12	111
55	35	-48	-5	68
55	40	-51	-19	23
55	45	-55	-27	1
55	50	-51	-22	-2
55	55	0	0	0
55	60	0	46	118
55	65	-11	120	314
60	5	-5	77	205
60	10	-50	6	77
60	15	-40	-4	46
60	20	-44	-8	46
60	25	-54	-15	41
60	**30**	58	-24	27
60	35	-62	-34	8
60	40	-71	-43	-6
60	45	-78	-47	-6
60	50	-77	-43	-2
60	55	-55	-29	0
60	60	0	0	0
60	65	-9	46	95
65	5	-45	30	169
65	10	-73	-21	71
65	15	-63	-31	30
65	20	-61	-36	9
65	25	-66	-41	1
65	30	-70	-47	-7
65	35	-77	-53	-6
65	40	-82	-57	-6
65	45	-88	-59	-2
65	50	-88	-56	2
65	55	-76	-46	4
65	60	-49	-28	7
65	65	0	0	0

Appendix BII - Percent Change in Hydrocarbon Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

		HC, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis		
Initial Average speed	**Final Average speed**	**Low**	**Pred**	**High**
5	5	0	0	0
5	10	-57	-38	-26
5	15	-71	-49	-33
5	20	-76	-55	-37
5	25	-80	-60	-41
5	30	-84	-65	-47
5	35	-85	-69	-54
5	40	-85	-71	-58
5	45	-84	-72	-58
5	50	-82	-69	-55
5	55	-81	-63	-43
5	60	-76	-51	-17
5	65	-71	-34	25
10	5	34	65	132
10	10	0	0	0
10	15	-34	-18	2
10	20	-54	-27	6
10	25	-67	-35	0
10	30	-73	-43	-10
10	35	-75	-49	-23
10	40	-73	-54	-34
10	45	-70	-55	-39
10	50	-66	-51	-34
10	55	-59	-40	-15
10	60	-53	-21	32
10	65	-46	7	108
15	5	48	102	236
15	10	-2	23	52
15	15	0	0	0
15	20	-32	-12	4
15	25	-51	-23	-1
15	30	-61	-32	-8
15	35	-64	-39	-20
15	40	-62	-44	-28
15	45	-60	-45	-26
15	50	-59	-40	-20
15	55	-49	-27	-1
15	60	-35	-5	38
15	65	-26	28	114
20	5	58	135	312
20	10	-6	43	116
20	15	-5	15	46
20	20	0	0	0
20	25	-28	-12	-2

Appendix BII (Cont.) - Percent Change in Hydrocarbon Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	HC, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis		
		Low	Pred	High
20	30	-44	-22	-10
20	35	-49	-31	-15
20	40	-52	-36	-17
20	45	-56	-36	-6
20	50	-57	-30	6
20	55	-49	-16	31
20	60	-30	9	61
20	65	-14	46	121
25	5	70	171	411
25	10	-6	65	200
25	15	-1	33	101
25	20	2	14	39
25	25	0	0	0
25	30	-22	-12	-5
25	35	-33	-21	-7
25	40	-46	-27	2
25	45	-53	-27	17
25	50	-55	-20	44
25	55	-45	-3	70
25	60	-28	25	98
25	65	-6	66	165
30	5	85	210	508
30	10	9	89	268
30	15	8	52	152
30	20	11	30	76
30	25	5	14	27
30	30	0	0	0
30	35	-20	-11	1
30	40	-37	-17	14
30	45	-47	-17	41
30	50	-48	-8	68
30	55	-38	11	98
30	60	-20	43	140
30	65	-1	90	220
35	5	114	245	553
35	10	28	111	302
35	15	23	70	178
35	20	18	46	94
35	25	6	28	50
35	30	-3	12	25
35	35	0	0	0
35	40	-21	-7	15
35	45	-36	-8	38
35	50	-38	2	65

Appendix BII (Cont.) - Percent Change in Hydrocarbon Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	HC, 1986+ FI Vehicles % Change in g/km Emission Rate Bootstrap Analysis		
		Low	Pred	High
35	55	-28	24	100
35	60	-6	60	171
35	65	13	115	273
40	5	140	271	549
40	10	51	126	276
40	15	38	83	160
40	20	19	59	110
40	25	-4	40	87
40	30	-12	23	56
40	35	-13	9	26
40	40	0	0	0
40	45	-19	-1	20
40	50	-22	9	48
40	55	-13	33	100
40	60	1	74	181
40	65	17	135	337
45	5	139	276	534
45	10	61	127	229
45	15	33	86	152
45	20	5	63	127
45	25	-20	44	113
45	30	-29	26	87
45	35	-28	12	56
45	40	-17	2	23
45	45	0	0	0
45	50	-7	9	27
45	55	-1	34	83
45	60	11	76	192
45	65	21	140	345
50	5	121	245	462
50	10	51	108	187
50	15	22	70	144
50	20	-8	50	130
50	25	-32	33	117
50	30	-41	17	91
50	35	-39	3	57
50	40	-33	-6	27
50	45	-22	-8	7
50	50	0	0	0
50	55	2	21	48
50	60	11	60	141
50	65	9	118	286
55	5	73	186	413
55	10	16	73	147

Appendix BII (Cont.) - Percent Change in Hydrocarbon Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	HC, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis		
		Low	Pred	High
55	15	1	41	97
55	20	-24	24	92
55	25	-42	10	82
55	30	-50	-3	60
55	35	-50	-14	35
55	40	-50	-22	13
55	45	-46	-23	0
55	50	-33	-17	-2
55	55	0	0	0
55	60	3	30	63
55	65	1	76	163
60	5	19	124	311
60	10	-25	35	110
60	15	-28	10	52
60	20	-38	-4	40
60	25	-50	-15	38
60	30	-58	-25	22
60	35	-63	-33	6
60	40	-65	-39	-3
60	45	-66	-40	-10
60	50	-59	-35	-10
60	55	-39	-22	-4
60	60	0	0	0
60	65	-2	33	63
65	5	21	73	244
65	10	-52	5	84
65	15	-53	-15	35
65	20	-56	-27	15
65	25	-62	-36	7
65	30	-69	-43	-2
65	35	-74	-49	-13
65	40	-78	-53	-18
65	45	-78	-53	-17
65	50	-74	-49	-14
65	55	-63	-40	-1
65	60	-39	-24	-1
65	65	0	0	0

Appendix BIII - Percent Change in Oxides of Nitrogen Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	NOx, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis		
		Low	Pred	High
5	5	0	0	0
5	10	-22	-17	-12
5	15	-37	-32	-27
5	20	-48	-43	-38
5	25	-57	-51	-45
5	30	-62	-54	-48
5	35	-63	-54	-47
5	40	-58	-51	-44
5	45	-51	-43	-37
5	50	-39	-32	-25
5	55	-26	-17	-8
5	60	-11	2	1
5	65	6	24	45
10	5	14	21	29
10	10	0	0	0
10	15	-21	-18	-15
10	20	-37	-31	-26
10	25	-48	-40	-33
10	30	-55	-45	-36
10	35	-55	-45	-35
10	40	-50	-40	-31
10	45	-40	-31	-23
10	50	-25	-18	-10
10	55	-8	0	1
10	60	11	23	35
10	65	33	50	68
15	5	38	47	58
15	10	18	22	26
15	15	0	0	0
15	20	-21	-16	-13
15	25	-35	-27	-20
15	30	-43	-33	-24
15	35	-43	-33	-23
15	40	-37	-27	-19
15	45	-24	-17	-9
15	50	-7	0	1
15	55	11	22	33
15	60	32	50	66
15	65	57	83	108
20	5	62	76	93
20	10	35	45	58
20	15	14	20	26
20	20	0	0	0
20	25	-18	-13	-9

Appendix BIII (Cont.) - Percent Change in Oxides of Nitrogen Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	NOx, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis		
		Low	Pred	High
20	30	-28	-20	-13
20	35	-28	-20	-13
20	40	-21	-13	-7
20	45	-7	0	7
20	50	10	20	30
20	55	30	46	63
20	60	54	79	107
20	65	82	119	160
25	5	81	103	134
25	10	48	68	93
25	15	25	38	54
25	20	10	15	22
25	25	0	0	0
25	30	-12	-8	-5
25	35	-13	-8	-3
25	40	-5	0	5
25	45	8	15	22
25	50	24	38	54
25	55	46	69	96
25	60	71	107	149
25	65	100	153	213
30	5	91	120	165
30	10	55	82	120
30	15	31	50	75
30	20	15	25	39
30	25	5	8	13
30	30	0	0	0
30	35	-2	0	1
30	40	4	8	12
30	45	16	25	36
30	50	32	50	71
30	55	53	83	119
30	60	80	125	180
30	65	110	175	251
35	5	89	121	166
35	10	54	82	121
35	15	30	50	75
35	20	14	25	39
35	25	4	9	15
35	30	-2	0	1
35	35	0	0	0
35	40	5	8	12
35	45	16	25	36
35	50	32	50	72

Appendix BIII (Cont.) - Percent Change in Oxides of Nitrogen Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

Initial Average Speed	Final Average Speed	NOx, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis		
		Low	Pred	High
35	55	53	83	120
35	60	78	125	181
35	65	109	175	254
40	5	78	104	140
40	10	**45**	68	97
40	15	23	38	58
40	20	7	16	26
40	25	-5	0	5
40	30	-11	-7	-4
40	35	-11	-8	-5
40	40	0	0	0
40	45	10	15	21
40	50	25	38	54
40	55	45	69	97
40	60	69	107	152
40	65	99	154	219
45	5	57	77	101
45	10	30	46	66
45	15	10	20	32
45	20	-7	0	7
45	25	-18	-13	-7
45	30	-26	-20	-14
45	35	-27	-20	-14
45	40	-18	-13	-9
45	45	0	0	0
45	50	13	20	27
45	55	32	46	63
45	60	54	80	108
45	65	80	119	163
50	5	32	47	62
50	10	12	22	32
50	15	-7	0	1
50	20	-23	-16	-9
50	25	-35	-27	-20
50	30	-42	-33	-25
50	35	-42	-33	-24
50	40	-35	-27	-20
50	**45**	-21	-16	-12
50	**50**	0	0	0
50	55	16	22	28
50	60	35	50	***64***
50	65	59	83	107
55	5	8	21	35
55	10	-9	0	1

Appendix BIII (Cont.) - Percent Change in Oxides of Nitrogen Emission Rates Associated with Changes in Average Vehicle Speeds (1986 and Later Model Year Fuel Injected Vehicles) with 95% Confidence Bounds (Guensler, 1993a)

		NOx, 1986+ FI Vehicles %Change in g/km Emission Rate Bootstrap Analysis		
Initial Average Speed	Final Average Speed	Low	Pred	High
55	15	-25	-18	-10
55	20	-39	-31	-23
55	25	-49	-40	-31
55	30	-55	-45	-35
55	35	-55	-45	-35
55	40	-49	-40	-31
55	45	-39	-31	-24
55	50	-22	-18	-14
55	55	0	0	0
55	60	17	23	28
55	65	37	50	61
60	5	-15	-1	1
60	10	-26	-19	-10
60	15	-40	-33	-25
60	20	-52	-44	-35
60	25	-60	-51	-41
60	30	-65	-55	-44
60	35	-64	-55	-44
60	40	-60	-51	-41
60	45	-52	-44	-35
60	50	-39	-33	-26
60	55	-22	-18	-15
60	60	0	0	0
60	65	17	22	26
65	5	-31	-19	-6
65	10	-41	-33	-25
65	15	-52	-45	-37
65	20	-62	-54	-45
65	25	-69	-60	-50
65	30	-72	-63	-53
65	35	-72	-63	-53
65	40	-69	-60	-50
65	45	-62	-54	-45
65	50	-52	-45	-37
65	55	-38	-33	-27
65	60	-21	-18	-15
65	65	0	0	0