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Publication Date

1994-06-01

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Working Paper
June 1994

Proceedings of the National Conference on Intelligent Transportation Technologies & the Environment
Hubert Humphrey Institute of Public Affairs, University of Minnesota
June 6-7, 1994

UCTC No. 297

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CARBON MONOXIDE IMPACTS OF AUTOMATIC VEHICLE IDENTIFICATION APPLIED TO ELECTRONIC VEHICLE TOLLING

by

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INTRODUCTION

Intelligent transportation technologies (ITT's) are being promoted as a means of reducing congestion delay, improving transportation safety, 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 and capacity of the existing highway and roadway systems to reduce congestion (Saxton and Bridges, 1991; Conroy, 1990; Shladover, 1991; Shladover, 1989). We are not confident, however, that vehicular emissions will be reduced by the full range of proposed ITT's.

The transportation-air quality community has lacked the appropriate tools in which to predict the effects of microscopic changes to vehicular activity induced by ITT's. The currently used emissions models, EMFAC in California, and MOBILE in the remainder of the US, are unable to provide the resolution needed to quantify the effects of these changes. Research at UC Davis is focusing on estimation of a statistical 'modal' model capable of simulating the emissions impacts from individual vehicles under various operating scenarios. The emissions model, currently a significantly modified version of the mathematical algorithms employed in the CALINE 4 Line Source Dispersion Model developed by Paul Benson and others at Caltrans (Benson, 1989), predicts carbon monoxide (CO) emissions based upon individual vehicle speed-time profiles and laboratory measured emission rates. The model, therefore, can be used to quantify vehicular carbon monoxide emissions under various ITT scenarios.

This paper examines the carbon monoxide (CO) emission impacts of one such applied ITT, namely Automatic Vehicle Identification (AVI) used to implement electronic tolling. AVI used in place of conventional toll booths has previously been identified as an ITT that is likely to offer air quality benefits (Washington, Guensler, & Sperling, 1993a). By allowing vehicles to be tolled either through a windshield displayed debit card, or by some other mechanism, vehicles could forgo the deceleration, stop-delay, and ensuing acceleration that results from an encounter with a conventional toll plaza. The results presented here represent the beginning stages of an ongoing emissions modeling effort. Future work will incorporate an improved model for CO, and models for hydro-carbons and oxides of nitrogen.

BACKGROUND

The five basic ITT "technology bundles" (Jack Faucett Associates, 1993) include: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), Commercial Vehicle Operations (CVO), and Advanced Public and Transportation Systems (APTS). Each of these technology bundles is designed to achieve the same general goal; improve the efficiency of the transportation system through the application of communications and computational technologies. 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 (Washington, Guensler, Sperling, 1993a).

Previous research has concluded that one of the most likely technology bundles to improve air quality are Advanced Traffic Management Systems (Washington, Guensler, Sperling, 1993b). As the name implies, ATMS employ computer control technologies to 'optimize' or smooth traffic flows on a transportation network. Examples of ATMS technologies are real-time traffic signal network optimization, real-time ramp metering, and electronic vehicle tolling via automatic vehicle identification technologies (AVI). These computer controlled systems are designed to reduce congestion levels; minimize system-wide delay levels, and generally smooth vehicular flows.

ATMS technology bundles also include various signal actuation bundles, incident detection, rapid accident response, and integrated traffic management.

Electronic toll collection, the topic of this paper, aims to smooth traffic flows by implementing advanced communications technologies between roadways and vehicles. If conventional tolling operations performed on bridges or tolled turnpikes were replaced with automatic and transparent vehicle identification and debiting, for example, then toll plaza induced delays experienced by motorists could be eliminated. The elimination of these activities would further result in fewer decelerations, idling, and acceleration events prevalent under conventional tolling operations. These ‘modal’ activities, representing high load and power conditions, have been shown to contribute significantly to the production of emissions from motor vehicles (LeBlanc, et al., 1994; CARB, 1991; Benson, 1989; Groblicki, 1990; Calspan Corp., 1973a; Calspan Corp., 1973b; Kunselman, et al., 1974). In fact, one sharp acceleration may cause as much pollution as does the entire remaining trip (Carlock, 1992). This suggests that a small percentage of a vehicle’s activity may account for a large share of it’s emissions (LeBlanc, et al., 1994). In addition, longer enrichment events are more highly correlated with large emission excursions than are shorter events (LeBlanc, et. al., 1994), and furthermore, deceleration events are 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 a few seconds.

Using a preliminary ‘modal’ model that accounts for relative contributions of CO emissions from acceleration, deceleration, cruise, and idle events, we assess the impacts of electronic tolling using AVI. The goal is to quantify the expected CO emission differences between a toll-plaza and the no toll-plaza, or AVI scenario. In addition, the expected variation in these benefits is approximated given current limitations of the vehicle emissions data.

DESCRIPTION OF THE MODAL MODEL

The preliminary ‘modal’ model employed in these analyses is a derivative of the emission algorithms employed in the CALINE Line Source Dispersion Model that has been developed over many years by the California Department of Transportation (Benson, 1989). The model is different from the CALINE algorithms in two very important respects. First, individual vehicle ‘FTP BAG 2’ (Washington, Guensler, and Sperling 1994) emission rates are used in the model, rather than ‘approximated’ average values derived from the vehicle fleet. Second, individual idle emission rates are used in the model, rather than ‘approximated’ average values derived from the vehicle fleet. These differences result in a statistical model that can explain approximately 70% of the variation in emissions for individual vehicles tested on 14 different emission testing cycles. This is in comparison to both the current EMFAC and CALINE models, while employing fleet average FTP Bag 2 and idle emission rate values, explain about 10% of the variation in emissions from individual vehicles (Washington, Guensler, and Sperling, 1994).

The modified CALINE model can be written as:

$$TE_{ik} = EI_{ik} + EA_{ik} + EC_{ik} + ED_{ik} \text{ where;}$$

- TE_{ik} = Total CO emission estimate for vehicle i on cycle k in grams,
- EI_{ik} = CO emissions from idle events for vehicle i on cycle k in grams,
- EA_{ik} = CO emissions from acceleration events for vehicle i on cycle k in grams,
- EC_{ik} = CO emissions from cruise events for vehicle i on cycle k in grams,
- ED_{ik} = CO emissions from deceleration events for vehicle i on cycle k in grams.

The carbon monoxide emission contributions from modal events are defined as:

$$EI_{ik} = (IR_{[grams/sec]}) * (t_{i[secs]}), \text{ where;}$$

- IR is the measured individual vehicle idle emission rate,
- t_i is time in the idle operating mode.

$$EA_{ik} = [(FTP2_{[grams/min]}) * (C1) * EXP (C2 * AS_{[mph^2/sec^2]})] * t_a_{[secs]} * I_{[min]}/60_{[sec]}, \text{ where};$$

FTP2 is measured emission rate on FTP Bag2 for individual vehicles,
 Coefficients C1 = 0.75 and C2 = 0.0454 for acceleration condition 1,
 Coefficients C1 = 0.027 and C2 = 0.098 for acceleration condition 2,
 AS is the acceleration speed product based upon average speed and average acceleration rate of the acceleration mode,
 Acceleration condition 1 is for vehicles starting at rest and accelerating up to 45 mph,
 Acceleration condition 2 is for vehicles starting at 15 mph or greater and accelerating up to 60 mph,
 t_a is the time in the acceleration mode.

$$EC_{ik} = (FTP2_{[grams/min]}) * [(0.494 + 0.000227 * S_{[mph]}^2)] * (t_c_{[secs]} * I_{[min]}/60_{[sec]}), \text{ where};$$

FTP2 is measured emission rate on FTP Bag2 for individual vehicles,
 S is the average speed of the cruise event,
 t_c is the time in the cruise event.

$$ED_{ik} = (IR_{[grams/sec]}) * (t_d_{[secs]})(1.5), \text{ where},$$

IR is the measured individual vehicle idle emission rate,
 t_i is time in the deceleration operating mode,
 1.5 is a constant derived from empirical data (not estimated by least squares).

The modified CALINE algorithms are used in conjunction with summed emissions from steady-state modal events for a vehicle on any cycle. For example, a given speed-time trace is parsed into discrete model events of idle, cruise, acceleration, and deceleration. The emissions from these events are then summed over the cycle to obtain the total emission estimate.

EXPERIMENTAL DESIGN

The modified CALINE algorithms are employed to estimate the difference in CO emissions between a vehicle encountering a conventional toll plaza, and uninterrupted flow experienced when automatic vehicle identification tolling operations are used. To perform these comparisons, a toll plaza is first simulated on a typical transportation link. The link could be a typical tolled bridge entrance, or an entrance to a tolled highway or freeway. The toll plaza design follows that described by Lin (1994), representing a Gate type 'C' operating at level of service A. Under these conditions, the average vehicle experiences about 6 to 8 seconds of delay waiting for previously queued vehicles (Lin, 1994). Since the emissions estimates from vehicles encountering toll plazas are done on a per-vehicle basis, and because level of service A is assumed in the analyses, demand greater than capacity induced congestion delay is considered here.

To simulate vehicular activity under the two different scenarios, speed-time profiles were developed for four different vehicle trajectories. Table 1 displays some characteristics of the four speed-time profiles. Two speed-time profiles were developed for both the toll plaza and no toll plaza (AVI) scenarios, one for drivers exhibiting 'aggressive' driving behavior and one for drivers exhibiting 'normal' driving behavior. For the no toll plaza scenario (AVI), aggressive drivers 'floated' around their 60 mph target speed by 3 mph with 1 mph/sec maximum acceleration and deceleration rates, while 'normal' drivers were assumed to 'float' around their 60 mph target speed by 1 mph with 0.5 mph/sec maximum acceleration and deceleration rates. Aggressive driving behavior for the toll-plaza scenario included acceleration and deceleration rates of about 4.5 mph/sec, while normal driving behavior includes acceleration and deceleration rates of 2 mph/sec. These rates agree with current car following and instrumented vehicle research that has substantiated acceleration and deceleration rates as high as 6 mph/sec (Cicero-Fernandez, et. al., 1993). All vehicles were assumed to begin and end their speed-time trajectory at a constant speed, either 40 mph, 50 mph, or 60 mph.

A BASIC computer program was used to ‘parse’ cycles into discrete modes of acceleration, deceleration, cruise, and idle (see Washington, Guensler, and Sperling, 1994). The program is also used to apply the modified CALINE algorithms and estimate CO emissions from the generated speed-time profiles.

Table 1. Characteristics of Assumed Vehicle Speed-Time Profiles for Toll-Plaza and AVI Scenarios

Cycle Description	Maximum Acceleration and Deceleration Rates (mph/sec)	Speed-Time Profile Distance in (Miles)	Speed-Time Profile Length (Seconds)	Speed-Time Profile Average Speed (mph)
Toll Plaza, ‘Aggressive’ Driving	4.5	40 mph - 0.328 50 mph - 0.481 60 mph - 0.518	40 mph - 46 50 mph - 55 60 mph - 53	40 mph - 25.7 50 mph - 31.5 60 mph - 35.2
Toll Plaza, ‘Normal’ Driving	2.0	40 mph - 0.322 50 mph - 0.486 60 mph - 0.517	40 mph - 56 50 mph - 67 60 mph - 66	40 mph - 20.7 50 mph - 26.1 60 mph - 28.2
AVI, ‘Aggressive’ Driving	1.0	40 mph - 0.320 50 mph - 0.486 60 mph - 0.514	40 mph - 29 50 mph - 35 60 mph - 31	40 mph - 39.7 50 mph - 50.0 60 mph - 59.7
AVI, ‘Normal’ Driving	0.5	40 mph - 0.322 50 mph - 0.486 60 mph - 0.517	40 mph - 29 50 mph - 35 60 mph - 31	40 mph - 40.0 50 mph - 50.0 60 mph - 60.0

All of the vehicles contained in the current Speed Correction Factor Data Base (see Guensler, 1994) were used to estimate CO emissions from a ‘fleet’ of vehicles passing through the toll plaza and AVI scenarios. After several outlying test results were discarded, 460 remaining vehicles were used to approximate the vehicle fleet.

Since the modal model can predict CO emission contributions from acceleration and deceleration events, the resulting emissions predictions reflect the effect of microscopic traffic flow adjustments under the two different scenarios. The results of the modeling runs can be seen in Table 2. The model predicts that ‘aggressively’ driven

Table 2. Carbon Monoxide Differences Between Toll Plaza and AVI Scenarios.

Driving Behavior with Toll-Plaza	Driving Behavior with AVI	Mean Carbon Monoxide Difference (grams / vehicle)	Median Carbon Monoxide Difference (grams / vehicle)	Standard Deviation in Carbon Monoxide Difference (grams)
Aggressive	Normal	40 mph - 19.26	40 mph - 3.36	40 mph - 54.26
		50 mph - 658.36	50 mph - 100.24	50 mph - 1912.19
		60 mph - 159.37	60 mph - 24.18	60 mph - 461.34
Aggressive	Aggressive	40 mph - 18.63	40 mph - 2.93	40 mph - 53.51
		50 mph - 655.88	50 mph - 99.96	50 mph - 1906.19
		60 mph - 153.72	60 mph - 23.37	60 mph - 446.06
Normal	Normal	40 mph - 5.29	40 mph - 1.03	40 mph - 13.86
		50 mph - 9.57	50 mph - 1.79	50 mph - 25.82
		60 mph - 15.29	60 mph - 2.81	60 mph - 42.09
Normal	Aggressive	40 mph - 4.66	40 mph - 0.86	40 mph - 12.88
		50 mph - 7.08	50 mph - 1.28	50 mph - 19.61
		60 mph - 9.64	60 mph - 1.75	60 mph - 26.70

vehicles entering the segments at 60 mph will emit about 154 more grams of CO with a mandatory stop toll-plaza than with AVI (on average). The median difference is about 23.37 grams of CO, which suggests that the distribution of CO emissions from this fleet of vehicles is non-normal and heavily skewed by influential ‘dirty’ vehicles. The standard deviation under the same scenario, about 446 grams, also illustrates the extreme influence of these high emitting vehicles.

The table also illustrates that ‘normal’ driving behavior, i.e. vehicle activity incorporating moderate acceleration and deceleration rates, results in much smaller CO emission rate differences. These findings agree with current literature that has identified high emission rates with extreme modal activity.

DISCUSSION

These findings suggest that reductions in CO emissions can be realized through the application of an Intelligent Transportation Technology (ITT). This ITT application, the replacement of conventional toll plazas with automatic vehicle identification technologies to debit passing vehicles, has been previously identified as an application of ITT’s with likely benefits to air quality. Influential factors include traffic volumes, emission characteristics of the vehicle fleet, and driving behavior of individuals under the different scenarios. For example, drivers may be inclined to drive aggressively under the toll plaza scenario, since it requires drivers to stop and queue, and then merge with traffic exiting adjacent toll plazas. These same drivers, however, may not be inclined to drive aggressively with the AVI scenario, since there is no stop-delay experienced.

Table 3 demonstrates the range of CO reduction estimates. The table shows the two extreme scenarios: normal toll-booth driving (mild acceleration and deceleration rates) replaced with aggressive AVI driving (unsteady throttle position during cruise); and aggressive toll-booth driving replaced with normal AVI driving. The table demonstrates that emission reduction estimates are extremely sensitive to assumptions about driving behavior. For example, assuming 50 mph entry and exit speeds, and 22,000 average daily traffic volume

Table 3. Expected CO Reductions (Metric Tons per Year) with Application of Electronic Toll Collection

Scenario 1: Normal Toll-Booth Driving and Aggressive AVI Driving			
Daily Traffic Volume Per Lane	60 mph	50 mph	40 mph
25,000	88	65	42
22,000	77	57	37
19,000	67	50	32
1,600	5.6	4.1	2.7
Scenario 2: Aggressive Toll-Booth Driving and Normal AVI Driving			
Daily Traffic Volume Per Lane	60 mph	50 mph	40 mph
25,000	1500	6000	180
22,000	1300	5300	150
19,000	1100	4600	130
1,600	93	380	11

per lane, we would expect anywhere from 57 to 5300 metric tons of CO reduction per year per lane from implementation of AVI. These estimates are not significantly different than those found in field studies performed in Massachusetts and New Jersey (Clean Air Act Corporation, 1993).

The results here indicate that application of electronic toll collection in lieu of traditional toll plaza’s can bring about significant reductions in carbon monoxide emissions from motor vehicles. The reductions however, are dependent upon driving behavior, approach speeds, traffic volumes, and the characterization of the vehicle fleet. In addition, modeling uncertainty will likely increase the range of uncertainty brought about by the previously mentioned factors. For instance, confidence interval analyses or Monte Carlo simulation techniques could capture the random error (and uncaptured systematic errors) associated with model predictions.

The dynamometer tested vehicles modeled in these analyses are likely not representative of the current vehicle fleet (Guensler, 1994). As the ‘typical’ vehicle fleet in one area is likely different than another, i.e. Los Angeles versus New York City, it is difficult to characterize any fleet with certainty. The most critical factor in vehicle fleet representation is the proportion of high-emitting vehicles. The effect of high-emitters in the modeled fleet can be seen in Table 2. The fleet mean response is much higher than the median response, which indicates that high emitters are extremely influential in the statistical estimates of model parameters. The effect of these high-emitters on statistical robustness is currently being investigated.

In the analyses presented here, congestion is assumed to not exist (outside of the toll-booth induced congestion), but practical experience shows that tolled links can operate in the congested flow regime, and we need to consider these congestion effects on emission estimates. This can be approached by expanding this analyses to include micro-simulations of traffic flow on a series of links.

Finally, we need to address the behavioral changes that might be induced by application of ITT's. For example, previous peak-period congestion induced by toll-plazas, now eliminated by application of electronic tolling using AVI, might make the travel route more attractive to motorists. If this short-term increase in peak period level of service attracts 'new' motorists to the facility, then the projected emissions reductions may be partially or fully offset by increased traffic and congestion. These questions can be partially addressed through field studies of electronic toll collection pilot projects, and perhaps through the use of advanced network simulation modeling.

BIBLIOGRAPHY

Benson, Paul (1989). "CALINE 4 - A Dispersion Model For Predicting Air Pollutant Concentrations Near Roadways". State of California Department of Transportation, Division of New Technology and Research. Revised June 1989.

Calspan Corporation (1973a). "A Study of Emissions from Light-Duty Vehicles in Six Cities; Buffalo, NY"; Prepared for the Environmental Protection Agency (Document #APTD-1497), Office of Mobile Source Air Pollution Control; Ann Arbor, MI; March 1973.

Calspan Corporation (1973b). "Automobile Exhaust Emission Surveillance (PB-220 775); Buffalo, NY"; Prepared for the Environmental Protection Agency (Document #APTD-1544), Office of Mobile Source Air Pollution Control; Ann Arbor, MI; May 1973.

CARB (1991), California Air Resources Board; Modal Acceleration Testing; Mailout No. 91-12; Mobile Source Division; El Monte, CA; March 20, 1991.

Carlock, Mark (1992). "Overview of Exhaust Emission Factor Models". In: Proceedings, Transportation Modeling: Tips and Trip Ups; Air and Waste Management Association; Pittsburgh, PA; March 1992.

Cicero-Fernandez, Pablo, Jeffrey Long (1993). "Modal Acceleration Testing on Current Technology Vehicles". Presented at the specialty conference: The Emission Inventory, Perception and Reality. Pasadena, CA. October 1993.

Clean Air Act Corporation (1993). "Proposed General Protocol for Determination of Emission Reduction Credits Created By Implementing An Electronic "Pike Pass" System On a Tollway". Prepared for NorthEast States for Coordinated Air Use Management, December 9, 1993.

Conroy, Patrick J; Transportation's Technology Future: Prospects for Energy and Air Quality Benefits; TR News; Transportation Research Board; Washington, D.C.; May June 1990.

Darlington, Thomas L., Patricia E Korsog, and Robert Strassburger; Real World and Engine Operation: Results of the MVMA/AIAM Instrumented Vehicle Pilot Study; Proceedings of the 85th Annual Meeting of the Air and Waste Management Association; AWMA; Pittsburgh, PA; June 1992.

Guensler, Randall (1994). "Vehicle Emission Rates and Average Operating Speeds". Dissertation, Department of Civil & Environmental Engineering, University of California at Davis, Davis, CA. 95616

Groblicki, Peter J.; Presentation at the California Air Resources Board Public Meeting on the Emission Inventory Process; General Motors Research Laboratories; Warren, MI; November 5, 1990.

Jack Faucett Associates; Information Package Prepared for the Video-Conference on the Effect of IVHS Technologies on Air Quality; Bethesda, MD; March 8, 1993. The specific IVHS technologies listed in the Faucett report are presented for each technology bundle in this paper, with a few minor additions.

Kunselman, P., H.T. McAdams, C.J. Domke, and M.E. Williams; Automobile Exhaust Emission Modal Analysis Model; Calspan Corporation; Buffalo, NY; Prepared for the Environmental Protection Agency (Document 460/3-74-005), Office of Mobile Source Air Pollution Control; Ann Arbor, MI; January 1974.

LeBlanc, David C., Michael D. Meyer, F. Michael Saunders, James A. Mulholland (1994). "Carbon Monoxide Emissions From Road Driving: Evidence of Emissions Due to Power Enrichment". Presented at the 73rd Transportation Research Board Annual Meeting, January 9 - 13, 1994, Washington D.C.

Lin, Feng-Bor (1994). "Level of Service Analysis of Toll-Plazas on Freeway Main Lines". Journal of Transportation Engineering, Vol. 120, No. 2. Mar./Apr. 1994.

Saxton, Lyle G., and G. Sadler Bridges; Intelligent Vehicle-Highway Systems; A Vision and A Plan (1991). TR News; 152, January-February 1991.

Shladover, Steven E.; Potential Contributions of IVHS to Reducing Transportation's Greenhouse Gas Production (PATH Technical Memorandum 91-4); Institute of Transportation Studies, University of California, Berkeley; Berkeley, CA; August, 1991.

Shladover, Steven E.; Roadway Automation Technology - Research Needs; Paper 880208, Presented at the 68th Annual Meeting of the Transportation Research Board; Washington, D.C.; January 1989.

U.S. Department of Transportation; National Transportation Strategic Planning Study (1990). Washington, D.C.; March 1990.

Washington, Simon, Randall Guensler, and Daniel Sperling (1993a). "Air-Quality Impacts of Intelligent Vehicle Highway Systems". *Transportation Planning and Air Quality II*. Paul Benson, ed. American Society of Civil Engineers. Forthcoming.

Washington, Simon, Randall Guensler, and Daniel Sperling (1993b). "Assessing the Emission Impacts of IVHS in an Uncertain Future". Proceedings of the World Car 2001 Conference, Riverside CA. The Center for Environmental Research & Technology, University of California Riverside.

Washington, Simon, Randall Guensler, and Daniel Sperling (1994). "Modeling IVHS Emission Impacts, Volume I: Assessment of the CALINE 4 Line Source Dispersion Model". Interim Draft Report, Feb. 2, 1994. Institute of Transportation Studies, University of California at Davis. Davis, CA 95616.