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Effect of Arterial Signalization and Level of Service on Measured Vehicle Emissions

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ABSTRACT

The purpose of this research is to study the effect of arterial traffic signal timing and coordination on vehicle emissions. Traffic signal timing improvement is one of the most common congestion management practices in the United States. Although the benefits of improved signal timing for reduced fuel consumption are well documented, its effectiveness as an emission Transportation Control Measure has not been clearly investigated. In this work, an empirical approach based on real-world, on-road vehicle emission measurements was used.

A total of 824 one-way runs representing 100 hours and 2,020 vehicle miles of travel were conducted involving four drivers and eight gasoline fueled light-duty vehicles on two signalized arterials in Cary, North Carolina: Walnut Street and Chapel Hill Road. Modal analyses of the data indicated that emission rates are highest during acceleration and tend to decrease, in descending order, for cruise, deceleration, and idle. A modal approach is utilized to quantify the effect of arterial traffic signal timing and coordination on emissions.

A key result from this study is that signal coordination on Walnut Street yielded measurable improvements in arterial level of service and reduction in emissions. For Chapel Hill Road, substantial reductions in emissions were observed for uncongested (LOS A/B) versus congested traffic flow (LOS D/E) when comparing travel in the same direction at different times of day. The findings confirm the utility of signal coordination and congestion management as effective tools for emission control.

KEYWORDS: Vehicle Emissions, Signalized Arterials, Level of Service, On-board Vehicle Emissions Measurement, Real-World Vehicle Data, Effect of Traffic Signalization on Emissions, Modal Analysis

INTRODUCTION AND RESEARCH OBJECTIVES

Highway vehicles contribute substantially to national and local emissions of carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_X), and particulate matter (PM) [1, 2, 3]. Transportation and air quality managers at the state level have the task of developing and evaluating Transportation Control Measurements (TCMs) and other types of Transportation Improvement Plans (TIPs). One of the objectives of TCMs and TIPs is to improve air quality. The benefits of many TCMs and TIPs accrue at the "micro" level, such as individual signalized intersections, traffic control devices, roadway facility improvements (e.g., ramps, roundabouts), improved incident response and management, and others.

Traffic signal timing improvement is the most widespread congestion management practice in the United States [4, 5]. Signal timing improvements can include simple changes in timing plans or can include complex computer-controlled signal coordination along an entire corridor. When effective, signal improvement benefits can include: reduced congestion; increased safety; and improved response times for emergency vehicles. Although the benefits of improved signal timing for reduced fuel consumption are well documented, the effectiveness of signal timing as a TCM has not been empirically investigated. Hallmark *et al.* [4] have conducted a study in Atlanta where MEASURE model was utilized to study the effect of signal timing on CO emissions where on-road activity data were collected using handheld laser range-finding (LRF) devices. Significant reductions in CO emissions were estimated when traffic signals were coordinated [4], however, model findings were not compared with on-road emissions measurements.

The main objectives of this paper are to: (1) assess the feasibility of current methods for estimating traffic signal impacts on emissions; (2) describe an on-board emission measurement system; (3) discuss key considerations in on-road data collection; (4) present an example of the type of data obtained from one on-road trip with an instrumented vehicle; and (5) evaluate the effect of traffic signal timing and coordination with respect to vehicle emissions on selected corridors based upon field data collection.

ASSESSMENT OF CURRENT METHODS

The data required to accurately assess the air quality benefits of signal timing improvements must be of sufficient temporal and spatial resolution to enable identification and evaluation of hotspots, and measurement of the change in emissions as a result of traffic signal coordination and timing. Existing regulatory highway vehicle emission factor models, such as EMFAC in California and MOBILE in the rest of the U.S., are based upon assumed standardized driving cycles tested on dynamometers. A driving cycle is composed of a unique profile of stops, starts, constant speed cruises, accelerations and decelerations and is typically characterized by an overall time-weighted average speed [2, 3]. Different driving cycles are used to represent driving under different conditions. Dynamometer tests typically suffer from well-known shortcomings associated with non-representativeness of actual driving conditions [2, 6]. For example, many tests under-represent short-term events that cause high emissions even for a properly functioning vehicle, such as high accelerations.

The development of the new version of the MOBILE emission factor model, MOBILE6, is a substantial improvement over the previous MOBILE5b model [2, 7, 8]. For the first time, it is possible to develop regional emission estimates based upon a weighted averaging of different facility-specific, link-based driving cycles, some of which represent different levels of service. While the MOBILE6 model is likely to enable more accurate area-wide average emissions estimation than its predecessor, the use of standardized driving cycles make the MOBILE6 model inapplicable for evaluation of the "micro" scale impact of signal improvements. MOBILE6 is designed to evaluate emissions impacts on a regional level not a finer level, and therefore is poorly suited to estimate the emissions-reduction benefits of TCMs [2,4].

In addition to MOBILE6 there are several traffic operations software packages that provide vehicle emissions. CORSIM, for example predicts vehicle emissions from look-up tables on a second-by-second basis as a function of vehicle type, speed, and acceleration [9]. The program determines the total emissions on each link by applying the default emission rates (based on speed and acceleration) to each vehicle for each second the vehicle travels on the given link. INTEGRATION on the other hand computes the fuel consumption for each vehicle on a second-by-second basis as a function of speed and acceleration. It then estimates vehicle emissions on a second-by-second basis as a function of fuel consumption, ambient air temperature, and the extent to which a particular vehicle's catalytic converter has already been warmed up during an earlier portion of the trip [10].

SYNCHRO, a traffic signal simulation and optimization model, first predicts fuel consumption (calculated as a function of vehicle-miles, total delay in veh-hr/hr, and total stops in stops per hour). Fuel consumption is then multiplied by an adjustment factor (differs depending on the type of emissions) to estimate vehicle emissions [11].

Other traffic signal models, such as Transyt-7F [12], Passer II-90 [13], HCS [14], and SIGNAL97 [15], do not include emission predictors. Recently, a mesoscopic emission model was developed based on on-board measurements of average speed and number of stops [16], and dynamometer vehicle emissions measurement. The dynamometer data were separated into deceleration, acceleration, and cruise driving modes. The model uses a generalized speed trace to predict emissions associated with each stop. It should be noted that in all these models emission estimates are based upon dynamometer testing of vehicles rather than real-world measurements.

A NEW EMPIRICAL APPROACH

In this work, an empirical approach based on real-world, on-road vehicle emission measurements is utilized. On-board vehicle activity and emissions measurement is widely recognized as a desirable approach for quantifying emissions from vehicles since data are collected under real-world conditions at any location traveled by the vehicle [17-23]. Variability in vehicle emissions as a result of variation in vehicle operation, signal control and other factors can be represented and analyzed more reliably than with the other methods such as dynamometer tests and Remote Sensing Devices (RSD) measurements. This is because such measurements eliminate the concern about non-representativeness that is often an issue with dynamometer testing. On-board emissions measurement has not been widely used because in the past it has been prohibitively expensive. This is now changing, however, as EPA and others have developed a variety of portable instruments [24-28]. Details of measurement methods are outside the scope of this paper and more information is given elsewhere [21, 22].

The specific method employed in this research, based upon instrumentation of individual vehicles and measurement of tailpipe emissions, offers the benefit of providing representative on-road second-by-second vehicle activity and emissions data, which enables characterization of emissions at any time or location during a trip. With on-road data of high temporal and spatial resolution, it is then possible to evaluate the local effect of signal control.

DESCRIPTION OF ON-BOARD SYSTEM

A portable, on-road vehicle data measurement device (OEM-2100^{TM}) was deployed to collect vehicle emissions and engine data as the vehicle is driven under real-world conditions

[21]. The system is comprised of a five-gas analyzer, an engine diagnostic scanner, and an on-board computer. The five-gas analyzer measures the volume percentage of CO, CO_2, HC, NO_x, and O_2 in the vehicle exhaust. The engine scanner downloads second-by-second engine and vehicle data from the On-Board Diagnostics (OBD) link of the vehicle.

The OEM-2100™ can be installed in approximately 15 minutes in a light duty vehicle. It has three connections with the vehicle: a power cable typically connected to the cigarette lighter or power port, an engine data link connected to the OBD link, and an emissions sampling probe inserted into the tailpipe. The connections are fully reversible and do not require any modification to the vehicle. Figure 1 illustrates the placement of the OEM-2100™ instrument on a seat inside a vehicle. Figure 2 illustrates the emission sampling probe and hose, which are routed into the vehicle and to the instrument.

The precision and accuracy of the OEM-2100™ was tested by the New York Department of Environmental Conservation (DEC) and at the U.S. EPA's National Fuels and Vehicle Emissions Laboratory in Ann Arbor, Michigan [29]. Three light-duty gasoline vehicles (1997 Oldsmobile sedan, 1998 Plymouth Breeze and 1997 Chevy Blazer) were tested by NYDEC using the I/M 240 and NYCC driving cycles. Two light-duty vehicles, a Mercury Grand Marquis and a Dodge full size pickup truck, were tested by EPA using the FTP, US06, NYCC, and FWY-HI driving cycles at Ann Arbor. The emissions were measured simultaneously by the dynamometer equipment and by the OEM-2100™. The OEM-2100™ has good precision, as reflected in R^2 values compared to the dynamometer ranging from 0.90 to 0.99, depending on the pollutant. Details regarding the instrumentation can be found elsewhere [21].

FIGURE 1. OEM-2100^{TM} installed in a 1998 Toyota Camry

FIGURE 2. Sampling probe routed from vehicle tailpipe into vehicle, secured by clamps.

Field Data Collection

Vehicle emissions and activity data collected with the OEM-2100^{TM} were supplemented by additional measurements. Road grade was measured with a digital level on the study corridors at one-tenth mile increments. The data were encoded into a database and synchronized with the engine and emissions data. Key characteristics of the study corridors, such as roadway geometry (e.g., number of lanes), speed limits, and traffic control device locations (e.g., traffic signals) were recorded. A laptop computer was used to record: (1) temperature and humidity measured using a portable weather gauge; (2) vehicle information such as model year, make, model, VIN, engine size, odometer reading, and curb weight; and (3) events, including the time at which the vehicle crossed the centerline of key intersections or entered queues.

Study Design

The primary objective of the experiment was to study the effect of signal coordination on vehicle emissions by comparing vehicle activity and emissions data collected before and after signal coordination plans were implemented. The experiment type chosen was a before-and-after study without control groups with approximately the same number of runs performed before and after the coordination plans were implemented. The focus was on measurement of hot stabilized emissions on arterials. Cold-start emissions, although important [30], were not included in the study but could be addressed in the future.

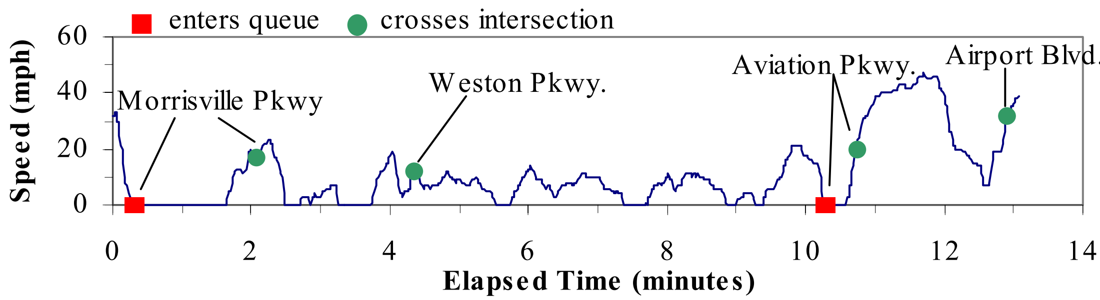
A variety of potential "threats to validity" of this type of study design were identified and evaluated. Some factors could be controlled in the before and after studies, such as selection of the same vehicle, driver, travel direction, and peak travel period. Other factors are not controllable, such as ambient weather conditions or systematic changes in traffic volumes. Changes in traffic volume were judged to be sufficiently small over the course of the study as to be negligible. In contrast, weather conditions, although not controllable, are observable and data were collected for these factors.

Data were collected on two signalized arterials in Cary, North Carolina between September and December 2000. Table 1 depicts the traffic characteristics of the two arterials. A total of 824 one-way runs representing 100 hours and 2,020 vehicle miles of travel were conducted involving four drivers and eight gasoline fueled light-duty vehicles. These vehicles were: two 1999 Ford Taurus sedans; two 1996 Oldsmobile Cutlass sedans; a 1998 Chevrolet Venture Minivan; a 1997 Jeep Cherokee; a 1998 Toyota Camry; and a 1997 Dodge Caravan. Repeated runs were made in order to characterize inter-run variability and to develop stable estimation of mean emissions. Details of the experimental design can be found elsewhere [21].

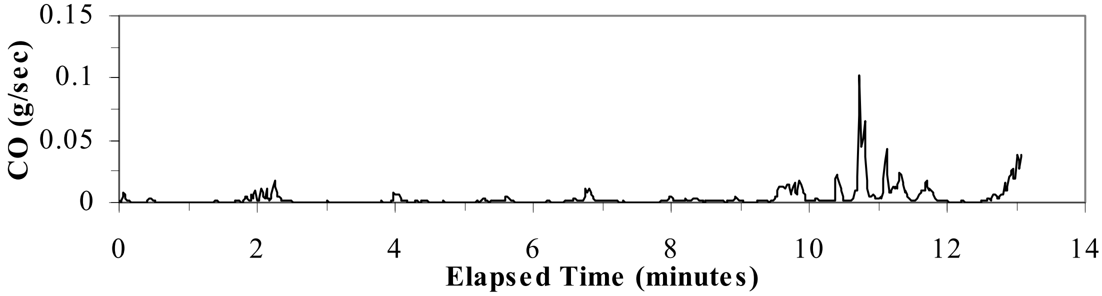
TABLE 1 Traffic Characteristics of Test Signalized Arterials

Characteristic	Chapel Hill Rd. (Morrisville Pkwy. to Airport Blvd.)	Walnut Street (Dillard Dr. to Cary Towne Blvd.)
Corridor Length (mi.)	2.6	2.3
Speed Limit (mph)	45	35, 45
Through Lanes	2	4
Center Turn Lane?	No	Yes
Traffic Signals	Morrisville Pkwy., Weston Pkwy., Aviation Pkwy., Airport Blvd.	Cary Towne Blvd., Maynard Rd., Cary Towne Cntr., Sturdivant Dr., Nottingham Dr., Buck Jones Rd., US 1/64 E, Meeting St., Dillard Dr.,
Signal Density (signals/mi.)	1.5	3.9
Free Flow Speed (mph)[a]	45	40, 45
Arterial Level of Service[b]	F – AM North C - AM South C – PM North E – PM South	C – AM North C - AM South D – PM North C – PM South

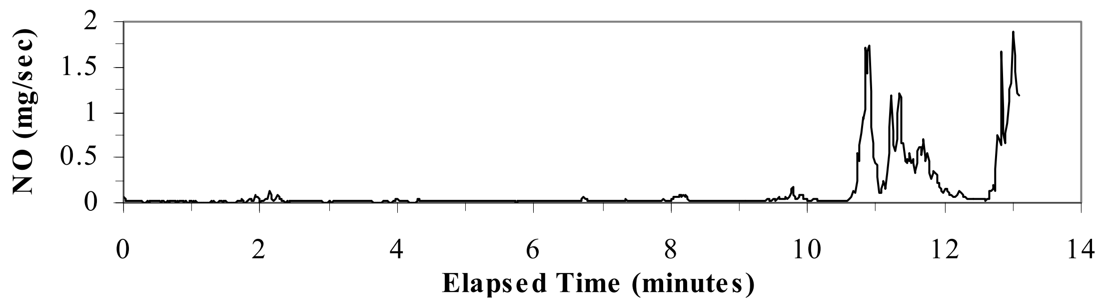
a. Frey *et al.*, 2001 [21]
b. Based on HCM Exhibit 15-2 [31]



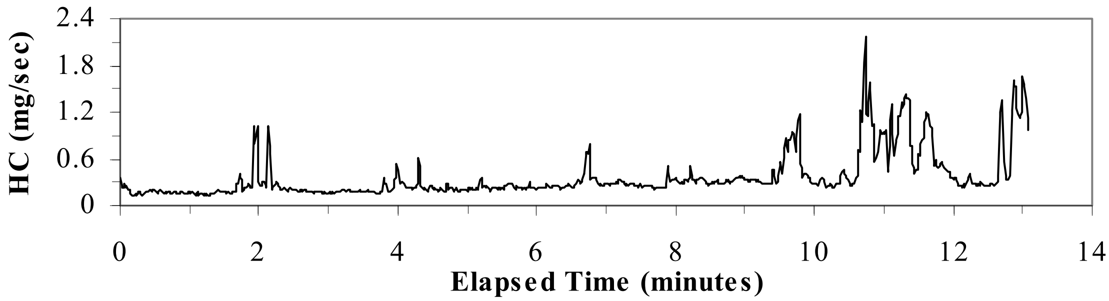
a. Example of Speed versus Time Trace



b. Example of CO Emissions versus Time Trace



c. Example of NO Emissions versus Time Trace



d. Example of HC Emissions versus Time Trace

FIGURE 3 Example Speed and Vehicle Emissions Profile for a 1999 Ford Taurus Driven on Chapel Hill Road on August 30, 2000.

SAMPLE RAW DATA AND MODAL EMISSIONS

To illustrate the type of data that were collected, Figure 3 depicts an individual one-way vehicle trip for a 1999 Ford Taurus. Figure 3a shows second-by-second speed versus elapsed trip time. The trip took place on Chapel Hill Road starting south of Morrisville Parkway and ending a short distance north of Airport Boulevard. Instantaneous speed ranged from zero to approximately 50 mph, and the average speed was 11 mph. There is stop-and-go traffic between Weston Parkway and Aviation Parkway, indicating that the signal at Aviation Parkway caused long delays in the corridor.

Emission traces for the measured pollutants are shown in Figures 3b to 3d for CO, NO, and HC respectively. For all three pollutants, it is clear that the highest emission rates, on a mass per time basis, occur during small episodes of the trip. The largest peak in the emission rate occurs at the same time as the acceleration from zero to approximately 40 mph as the vehicle clears the intersection with Aviation Parkway. These data suggest that the CO emission rates during idling or crawling are comparatively low compared to the CO emissions during an acceleration such as the one at Aviation Parkway. Similar patterns are observed in Figure 3c and Figure 3d for other two pollutants.

The time traces in Figure 3 also suggest that emission rates differ during different modes of driving [19, 21-23, 32]. In particular, the largest emission rates appear to be associated with acceleration events. Therefore, the data were divided into four modes: (a) acceleration; (b) cruise; (c) deceleration; and (d) idle [21-23].

A modal analysis for the 1999 Ford Taurus (on Walnut Street) is depicted in Figure 4. The average emission rates shown were based upon measurements obtained during 94 runs in the before (no signal coordination) case and 84 runs in the after (with signal coordination) case.

Average emissions during the acceleration mode are significantly higher than for any other driving mode, for all three of the pollutants measured. For each of the three pollutants, the four average modal emission rates are significantly different from each other at the 0.05 significance level, except for cruising and acceleration emissions of NO in the before case. The average acceleration emission rates for CO and NO are more than a factor of 10 higher than the average idling emission rates, and the average acceleration emission rates for HC are approximately a factor of five higher than the average idling emission rates.

Figure 4 also gives insight regarding the differences in modal emission rates between the before and after conditions. The average modal emission rates for a given pollutant were not statistically significantly different in half of the cases. For example, HC idle and deceleration, NO idle and acceleration, and CO idle and acceleration modal emission rates were similar in both the before and after cases. Although the average HC acceleration and cruise emission rates in the before and after cases are statistically significantly different from each other, they are not substantially different and are within 20 percent of each other. When modal emissions were evaluated at a more disaggregated level, such as by time of day and direction of travel, more frequent pronounced differences in emission rates were observed when comparing the before and after cases. The larger differences are in part because of the smaller sample sizes involved and the inherent variability in the data. In addition, there could be some influence of changes in ambient conditions or in the condition of the vehicle, even though the before and after studies were performed as close together in time as possible.

It is hypothesized that modal emission rates should be similar in the before and after studies, and that differences between the two may arise because of factors not under the direct control of the investigators, such as temperature, humidity, and vehicle maintenance. To control

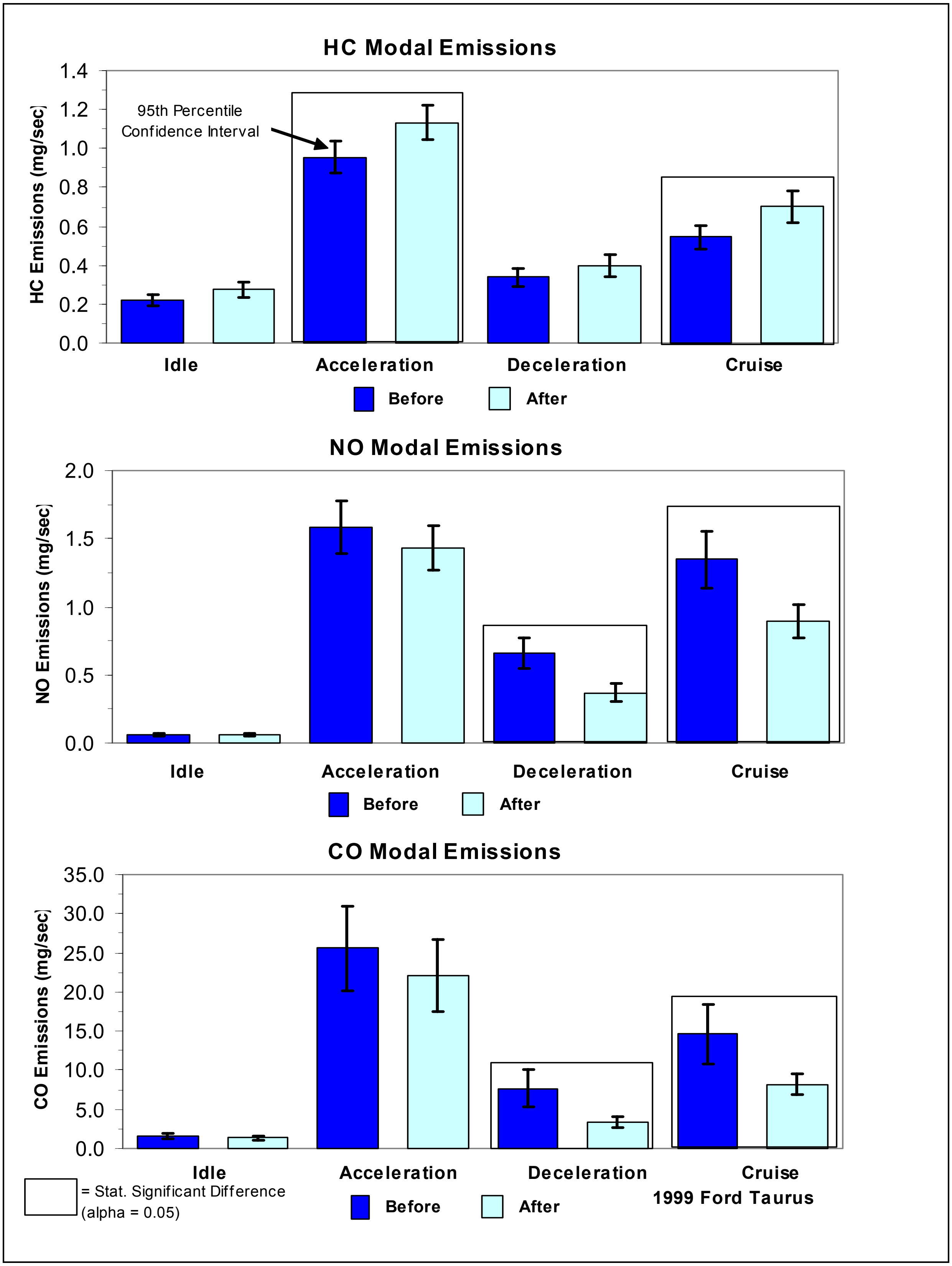


FIGURE 4 Walnut Street Modal Emission Rate for 1999 Ford Taurus Before and After Signal Coordination.

for the variability, the before and after conditions were based upon the same modal emission rates. The total emissions were estimated as product of the trip duration and a weighted average emission factor by mode as indicated in Equation 1:

$$TE = TD\left[\left(EF_{idle} \times PT_{idle}\right) + \left(EF_{accel} \times PT_{accel}\right) + \left(EF_{decel} \times PT_{decel}\right) + \left(EF_{cruise} \times PT_{cruise}\right)\right] \qquad (1)$$

Where,

TE = Total emissions (mg or g)

TD = Average trip duration for peak time/direction combination (seconds)

EF_{idle} = Emission factor for individual driving mode (e.g., idle) in units of mg/sec or g/sec

PT_{idle} = Fraction of total time spent in a particular mode (fraction)

Details of this methodology are described elsewhere [21].

EFFECT OF SIGNAL IMPROVEMENTS ON EMISSIONS

A summary of the measured impact of signal coordination on emissions is presented in this section for the two sites. The NC Department of Transportation developed the revised signal timing and coordination plans for the two sites using the SYNCHRO/ SIM TRAFFIC simulation packages. These plans were subsequently adjusted with a bandwith-type and further refined in the field based on actual operation.

Walnut Street

For the Walnut Street corridor, between Dillard Drive and Cary Towne Boulevard, the North Carolina Department of Transportation (NCDOT) implemented a new signal timing improvement and coordination plan in mid-November 2000. Therefore, field data collection occurred before the change during the period between October 31st and November 10th and after the change during the period between November 30th and December 13th.

Changes in traffic parameters and vehicle emissions on the corridor-level were examined for two primary vehicles, the Ford Taurus and Oldsmobile Cutlass. Tables 2 and 3 summarize the key findings for Walnut Street in the before and after cases. Total emissions estimated using modal rates that were averaged from the before and after values were utilized in the comparison. Absolute values for traffic variables and emissions are given in Tables 2 and 3, along with percent differences between the before and after cases.

As shown in Tables 2 and 3, there was a statistically significant improvement in traffic flow in both travel directions in the morning, and in the northbound direction in the afternoon, observed with both primary vehicles. Emissions decreased for some or all of the three pollutants in each case where traffic flow improved significantly. In cases where there was no significant change in traffic flow, there was also no significant change in emissions. Traffic flow, as quantified by travel time, average speed, delay rate, and stops per mile, improved approximately 15 to 60 percent, while emissions decreased by approximately 10 to 20 percent in most cases. Improvements in level of service were also observed.

The observed relation between NO_X emissions and average speed might be counterintuitive when contrasted against traditional emission models results. Emission factor models are based upon average emissions for a set of specific driving cycles [2, 33]. The use of average speed as a descriptor of a driving cycle is inadequate, since driving cycles with different profiles of acceleration, cruise, deceleration, and idle can have the same average speed. Thus, the use of average speed as a means to extrapolate between driving cycles can produce misleading results. On the other hand, the data in this study are based upon real world microscale vehicle activity representative of the visited sites. Emission factor models do not have the temporal and spatial resolution to capture the episodic nature of vehicle emissions [2, 22, 34-37].

TABLE 2. Traffic and Emission Performance on Walnut Street Arterial Before and After Signal Coordination -- 1999 Ford Taurus

	Before (After)	% Diff.[a]	Before (After)	% Diff.	Before (After)	% Diff.	Before (After)	% Diff.
Time Period	*Morning Peak*				*Afternoon Peak*			
Direction	Northbound		Southbound		Northbound		Southbound	
Runs	24 (24)		24 (25)		22 (16)		24 (19)	
Travel Time (sec)	336 (288)	**-14**	300 (227)	**-24**	433 (332)	**-23**	365 (366)	+0.3
Average Speed (mph)	23.9 (27.2)	**+14**	26.6 (35.1)	**+32**	18.4 (23.7)	**+29**	22.0 (21.6)	-1.8
Delay Rate [b] (sec/mi)	55.6 (33.7)	**-40**	43.9 (16.1)	**-63**	87.2 (39.0)	**-55**	65.6 (62.6)	-4.6
Stop Rate (stops/mi)	1.83 (1.29)	**-30**	1.49 (0.591)	**-60**	2.23 (1.58)	**-29**	1.52 (1.49)	-2.3
Level of Service [c]	C (C)		C (A)		D (C)		C (C)	
HC Emissions [d] (mg)	185 (164)	**-12**	167 (137)	**-18**	287 (255)	**-11**	197 (200)	+1
NO Emissions [d] (mg)	233 (215)	**-8**	316 (277)	**-12**	331 (332)	-1	268 (272)	+1
CO Emissions [d] (mg)	3442 (3041)	**-12**	4018 (3272)	**-19**	4562 (4364)	-5	3020 (3063)	+1

a. Percent Difference: (A-B)/B. Bold values indicate that average differences are statistically significant at the 0.05. significance level.
b. Frey *et. al* [21]
c. Based on HCM Exhibit 15-2 [31]
d. Calculated using average modal rates

TABLE 3. Traffic and Emission Performance on Walnut Street Before and After Signal Coordination -- 1996 Oldsmobile Cutlass

	Before (After)	% Diff.[a]	Before (After)	% Diff.	Before (After)	% Diff.	Before (After)	% Diff.
Time Period	*Morning Peak*				*Afternoon Peak*			
Direction	Northbound		Southbound		Northbound		Southbound	
Runs	25 (23)		25 (23)		21 (22)		22 (23)	
Travel Time (sec)	359 (302)	**-16**	292 (243)	**-17**	456 (359)	**-21**	387 (383)	-0.9
Average Speed (mph)	23.9 (28.2)	**+18**	29.2 (35.0)	**+20**	18.8 (24.3)	**+29**	22.8 (22.4)	-1.8
Delay Rate [b] (sec/mi)	62.8 (39.1)	**-38**	36.4 (18.2)	**-50**	95.7 (42.6)	**-56**	61.2 (66.4)	+8.5
Stop Rate (stops/mi)	1.90 (1.34)	**-29**	1.11 (0.605)	**-46**	2.34 (1.66)	**-29**	1.68 (1.49)	-11
Level of Service [c]	C (C)		B (B)		D (C)		C (C)	
HC Emissions [d] (mg)	365 (320)	**-12**	285 (251)	**-13**	426 (375)	**-12**	329 (324)	-1
NO Emissions [d] (mg)	595 (519)	**-13**	505 (439)	**-14**	695 (565)	**-19**	590 (581)	-1
CO Emissions [d] (mg)	3702 (3564)	-4	3499 (3180)	**-9**	4619 (4566)	-1	2736 (2709)	-1

a. Percent Difference: (A-B)/B. Bold values indicate that average differences are statistically significant at the 0.05 significance level.
b. Frey *et. al* [21]
c. Based on HCM Exhibit 15-2 [31]
d. Calculated using average modal rates

As shown in Figure 1, the highest NO_X emissions occurred during acceleration events. Therefore, any stop-and-go traffic that increases the number of acceleration events increases NO_X emissions. As shown in Tables 2 and 3, when the number of stops decreases, the number of acceleration events decreases as well, which leads to a decrease in NO_X emissions independent of average speed.

Overall, the Walnut Street corridor illustrates the successful application of a coordinated signal timing plan leading to a reduction in vehicle emissions. Specifically, the changes in signal timing and coordination generally had a beneficial effect in reducing average vehicle emissions on the corridor. The improvement in average emissions was associated with measurable improvements in traffic flow, as quantified based upon increases in average speed and reductions in average control delay and in the average number of stops per mile. To further illustrate the impact, Figure 5a and Figure 5c contrast speed profiles for typical before and after runs. These runs were selected to represent average speed performance in the before and after cases. Figures 5b and 5d contrast CO emissions profiles for the same before and after runs. The example trip for the before case lasted approximately 4.8 minutes and had an average speed of 26 mph, whereas example trip for the after case lasted approximately 3.7 minutes and had an average speed of 35 mph. There were four stops in the example before case, whereas there was only one stop in the example after case. Total CO emissions in the example before case were 2.06 grams compared to 1.05 grams in the example after case.

Chapel Hill Road

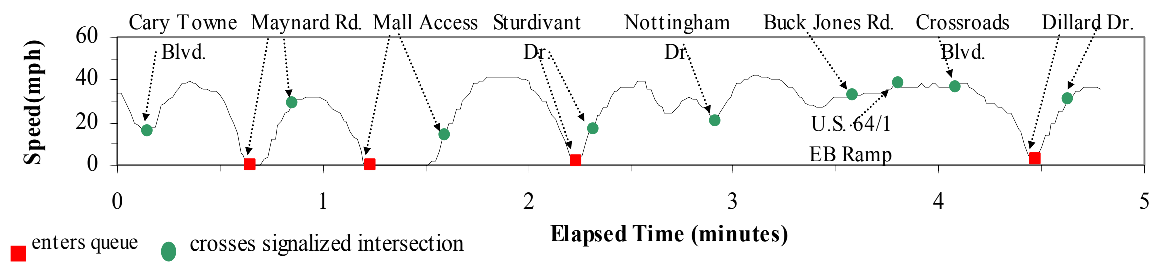
Chapel Hill Road, is a heavily traveled corridor during the morning and evening rush hours and is representative of rush-hour commuting between Cary and the Research Triangle Park, NC. Table 1 summarizes the traffic characteristics. This corridor operated at capacity in the peak direction, both in the AM and PM peak hours. Therefore, changes in signal timing and coordination resulted in relatively little or no improvement in traffic flow.

Because traffic flow on Chapel Hill road is highly directional, it is possible to compare emissions for the same direction of travel under congested and uncongested traffic conditions simply by comparing the morning and afternoon data. Traffic is very congested, with a level of service (LOS) between C and E, in the northbound direction in the morning and in the southbound direction in the afternoon. Both southbound traffic in the morning and northbound traffic in the afternoon are close to free flow conditions, with a LOS of A or B. Table 4 summarizes the key findings for the uncongested and congested cases. Total emissions were estimated using average of the modal rates in the uncongested and congested cases.

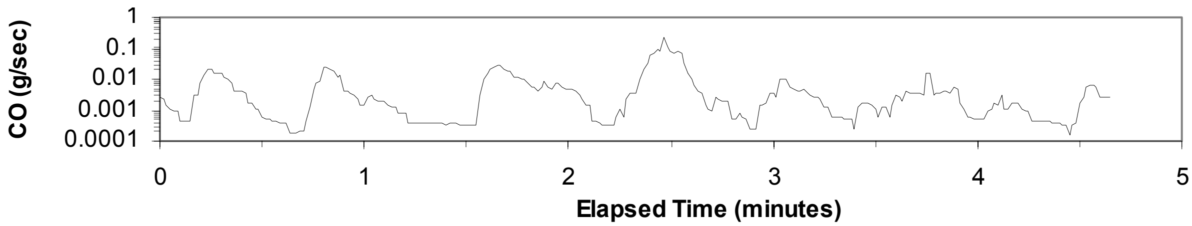
TABLE 4. Traffic and Emission Performance on Chapel Hill Road during Uncongested and Congested Cases – 1999 Ford Taurus and 1998 Chevrolet Venture

	Congested (Uncongested)	% Diff.[a]	Congested (Uncongested)	% Diff.	Congested (Uncongested)	% Diff.	Congested (Uncongested)	% Diff.
Vehicle	*1999 Ford Taurus*				*1998 Chevrolet Venture*			
Direction	Northbound		Southbound		Northbound		Southbound	
Runs	37 (31)		32 (44)		38 (30)		32 (37)	
Travel Time (sec)	616 (269)	**-56**	478 (274)	**-60**	676 (273)	**-43**	471 (264)	**-44**
Average Speed (mph)	15.3 (33.3)	**+118**	20.7 (33.3)	**+61**	15.1 (35.7)	**+137**	23.0 (37.7)	**+64**
Delay Rate [b] (sec/mi)	99.9 (23.4)	**-77**	68.4 (22.2)	**-78**	101.2 (19.9)	**-80**	50.9 (19.9)	**-80**
Stop Rate (stops/mi)	3.50 (0.603)	**-83**	2.31 (0.568)	**-75**	3.77 (0.616)	**-84**	2.19 (0.434)	**-80**
Level of Service [c]	E (B)		D (B)		E (A)		C (A)	
HC Emissions [d] (mg)	246 (113)	**-54**	173 (107)	**-38**	692 (290)	**-59**	525 (289)	**-45**
NO Emissions [d] (mg)	291 (139)	**-52**	336 (218)	**-35**	1131 (491)	**-57**	1133 (666)	**-41**
CO Emissions [d] (mg)	4413 (2105)	**-52**	6492 (3891)	**-60**	3256 (1306)	**-60**	1782 (854)	**-52**

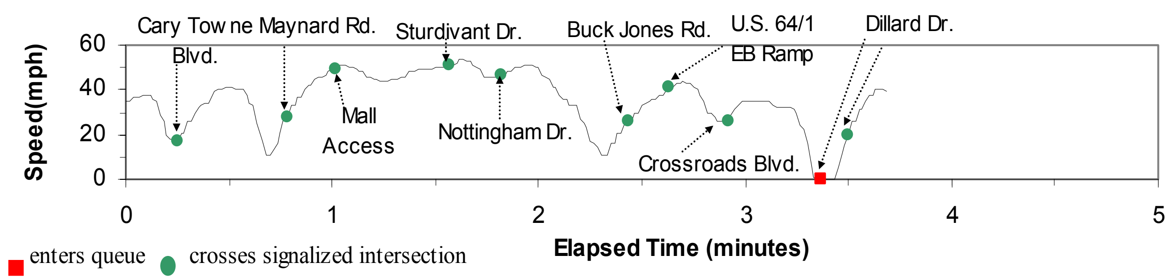
a. Percent Difference: (U-C)/C. Bold values indicate that average differences are statistically significant at the 0.05 significance level.
b. Frey *et. al* [21]
c. Based on HCM Exhibit 15-2 [31]
d. Calculated using average modal rates



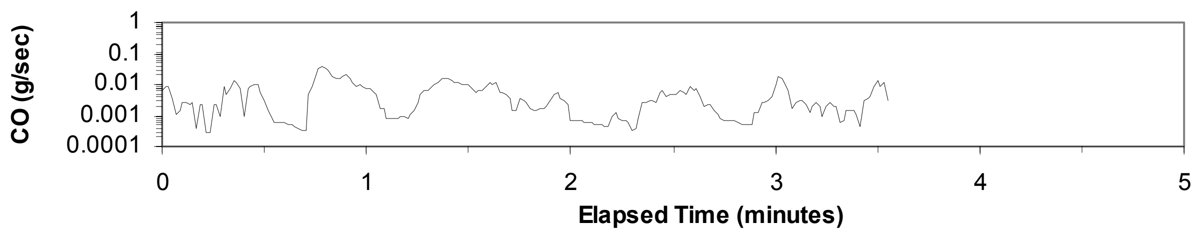
a. Example of Speed versus Time Trace in the Before Coordination Case (Data collected on 11/2/200)



b. Example of CO Emissions versus Time Trace in the Before Coordination Case (Data collected on 11/2/200)



c. Example of Speed versus Time Trace in the After Coordination Case (Data collected on 12/6/200)



d. Example of CO Emissions versus Time Trace in the After Coordination Case (Data collected on 12/6/200)

FIGURE 5 Walnut Street Speed and CO Emissions Traces for 1999 Ford Taurus Before and After Signal Coordination.

The findings from Table 4 are quite clear. There is a substantial decrease of 35 to 60 percent in emissions for all three pollutants for the uncongested cases when compared to congested cases. Thus, there would be a clear emissions benefit to reducing congestion on Chapel Hill Road if that were possible. However, because traffic flow is already at capacity for this corridor, changes in signal timing and coordination by themselves will not be effective at improving either traffic flow or emissions. Instead, other capacity expansions or demand reduction strategies would have to be employed.

CONCLUSIONS

The primary purpose of this paper was to evaluate the effects of changes in arterial signal timing and coordination with respect to emissions and LOS. Key findings and conclusions are:

(1) There is substantial episodic variability in real world on-road modal emission rates on a mass per time basis. These differences suggest that acceleration produces the highest emission rate and idle produces the lowest emission rate. Therefore, efforts aimed solely at reducing stop time only may not always be successful in achieving overall reductions in air pollution emissions.

(2) Modal emission rates were found to vary substantially for specific time of day and direction of travel combinations when comparing before and after results, which necessitated development of simplified models to help clarify before and after comparisons of total emissions and to correct for uncontrollable changes in ambient and vehicle conditions.

(3) Coordinated signal timing improved traffic flow on the Walnut Street arterial, which led to reduction in vehicle emissions and moderate improvements in LOS from LOS B/D to LOS A/C.

(4) There is a substantial decrease in estimated emissions for the same direction of travel on Chapel Hill Road when comparing uncongested (LOS A/B) to congested (LOS C/E)

conditions. Emissions of NO, CO, and HC were higher in the congested case compared to the uncongested case.

(5) Changes in emissions were associated with changes in traffic performance measures such as travel time, average speed, average control delay, and average number of stops per mile. In particular, the magnitude of the percentage decrease in travel time was typically comparable to the magnitude of the percentage decrease in emissions.

(6) This project demonstrated that a study can be designed and successfully executed to collect, analyze, and interpret real world on-road tailpipe emissions data regarding before and after comparisons associated with a change in traffic control.

(7) Since travel occurred over the same distance on both corridors, the comparison of signal timing and coordination on Walnut Street and of uncongested versus congested traffic flow on Chapel Hill Road demonstrate that *how* vehicles are driven is important, not simply how many miles, with respect to emissions.

(8) The specific objective of this study was to quantify the effect of traffic signal timing and coordination on emissions for selected corridors using selected vehicles. Any study that aims to quantify the emission impacts under similar conditions to those observed in the study can utilize its results directly. However, other studies might involve other Transportation Control Measures (TCMs) or Transportation Improvement Plans (TIPs) such as roadway facility improvement (e.g., ramps, roundabouts). In that case, one could use the derived modal emission rates from our study, along with the observed distribution of modal times due to the TCM 's in question, to arrive at a total emission estimate. It should be cautioned, however, that these modal emission rates are applicable only to similar light-duty gasoline vehicles. The methodology developed in this study can also be

applied to any study where a comparison between a set of before and after emissions is desired. It is preferable to collect real-world representative data where resources permit. The cost of on-board emissions measurements is substantially less than that of dynamometer testing.

RECOMMENDATIONS

Key recommendations of this study are:

(1) On-board emissions measurement studies need a careful experimental design that is specific to a particular study objective. Key factors in study design that should be considered in future studies are vehicle selection, driver selection, routing, deployment of instrumentation, scheduling of on-road data collection by travel direction and time period, and sample size.

(2) Often a signal coordination plan will improve the main through movements of a corridor but not consider the non-priority movements (side street and turning movements). Thus, it is important in the future to evaluate both the priority and non-priority movements to understand the overall impact of signal coordination on vehicle emissions.

(3) Substantial variability in vehicle emissions from one run to another was observed even for the same vehicle, route, driver, time of day, and travel direction. Therefore, for some study objectives, but not necessarily all, it will be necessary to repeat the data collection activities in order to obtain a statistically reliable estimate of the mean emissions for a given vehicle. For studies aimed at before and after comparisons with the same set of vehicles, this is an especially important consideration.

(4) The air quality benefits of TCMs or TIPs should not be taken for granted without empirical verification. For example, "conventional wisdom" equates idling time with

high emissions. Yet the measurements in this study indicate that for the tested vehicles the average emission rate during acceleration (on a time basis) is typically a factor of five to ten times larger than the average emission rate during idling. While very long periods of idling can lead to substantial emissions, accelerations are likely to produce a disproportionate share of the total trip emissions on a typical commuting trip. Some TCMs, e.g. traffic calming devices designed to promote a reduction in average driving speed (e.g. speed bumps or speed humps), may lead to an increase in emissions associated with more frequent accelerations on segments between the TCM's. Such hypotheses can and should be tested using real-world empirical studies as long as there is no microscale model available that can accurately predict emissions at high temporal and spatial resolutions.

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