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Examining the Effects of Variability in Average Link Speeds on Estimated Mobile Source Emissions and Air Quality

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To my daughter, Irem

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TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION ..…..… 1

CHAPTER 2. LITERATURE REVIEW ……. 5

2.2. Real-World Link Average Speeds …… 10

2.2.1. Surveillance Technologies ……..…….. 12

2.2.2. Single Loop and Double Loop Detectors ……. 13

2.2.3. Speed, Time Mean Speed and Space Mean Speed …… 14

2.2.4 Speed Estimation at Single Loop Detector Stations ...…….. 17

2.2.5. Link Average Speed Estimation ……. 24

2.3. Discussion …… 25

2.3.1. Concerns about the Current Research on Effects of Speed Variability on Mobile Source Emissions ……..... 25

2.3.2. Concerns about the Current Research Focusing on Uncertainties Mobile Source Emissions Modeling Resulting from the Differences In Travel Activity Input Data……..26

CHAPTER 3. DATA AND METHODS …….. 29

3.1. Data……...……29

3.2. Methods……..31

CHAPTER 4. THE EFFECTS OF INTRA-HOUR VARIATIONS IN AVERAGE SPEED ON RUNNING STABILIZED EMISSIONS …… 35

CHAPTER 5. EXAMINING THE IMPLICATIONS OF INCREASED RESOLUTION IN AVERAGE SPEED BY FACILITY LANE FOR MOBILE EMISSIONS INVENTORIES ……. 92

CHAPTER 6. AIR QUALITY EFFECTS OF UTILIZING HIGHLY RESOLVED AVERAGE SPEEDS FOR EMISISONS ESTIMATION …….. 122

CHAPTER 7. CONCLUSIONS AND FURTHER RESEARCH ..…….. 174

REFERENCES ..……...… 177

TABLE OF FIGURES AND TABLES

Figures

CHAPTER 2. LITERATURE REVIEW

Figure 1: Running Stabilized Emissions Estimation ……..……..… 6

CHAPTER 4. THE EFFECTS OF INTRA-HOUR VARIATIONS IN AVERAGE SPEED ON RUNNING STABILIZED EMISSIONS

Figure 1: Generalized Ideal Speed-Flow Relationship Curve ……....… 41

Figure 2: Real-world Speed and Flow Rate Observations ……... 43

Figure 3: 10 min Average Effective Vehicle Lengths (I-80 Southbound Direction) 51

Figure 4: 10 min Average Effective Vehicle Lengths (I-80 Northbound Direction) 52

Figure 5: Time-space diagram (vehicle trajectories) on a link …… 57

Figure 6: Differences in Hourly NO_x vs. V/C …….. 78

Figure 7: Differences in Hourly TOG vs. V/C …….…...……..... 79

Figure 8: Differences in Hourly CO_2 vs. V/C ..…..…….. 80

Figure 9: Locations where 1) Both Time of Day and Day of Week, 2) Time of Day, 3) Day of Week , and 4) Neither of the Factors are Significant in Los Angeles, Summer 1997……...……....…… 83

Figure 10: Sections 1 and 5 – Sections where Neither of the Factors are Significant at Most of the Locations ……..…… 84

Figure 11: Sections 2, 3 and 4 – Sections where Day of Week or both Time of Day and Day of Week are Significant at All of the Locations ……..... 85

CHAPTER 5. EXAMINING THE IMPLICATIONS OF INCREASED RESOLUTION IN AVERAGE SPEED BY FACILITY LANE FOR MOBILE EMISSIONS INVENTORIES

Figure 1: Generalized Speed-Flow Relationship Curve …….…….. 98

Figure 2: Real-world Speed and Flow Rate Observations ……..……..…… 99

Figure 3: Differences in Hourly NO_x vs. V/C ……...……...…… 110

Figure 4: Differences in Hourly TOG vs. V/C …….……. 111

Figure 5: Differences in Hourly CO_2 vs. V/C …….…. 112

Figure 6: Locations where 1) Time of Day and Day of Week, 2) Time of Day, 3) Day of Week , and 4) Neither of the Factors are significant in Los Angeles, Summer 1997…….……. 115

Figure 7: Section 1 – Section where Time of Day Alone or Both Time of Day and Day of Week are Significant at Almost All of the Locations ……..…… 116

Figure 8: Section 2 – Section where Neither of the Factors or Day of Week are Significant Most of the Time …….…….……... 116

Figure 9: Section 3 – Section where Both of the Factors or Day of Week Alone are Significant Most of the Time …….... 117

CHAPTER 6. AIR QUALITY EFFECTS OF UTILIZING HIGHLY RESOLVED AVERAGE SPEEDS FOR EMISSIONS ESTIMATION

Figure 1: Freeway Links and Single Loop Detector Stations in SCAB …..…..…. 129

Figure 2: Estimated Hourly Average O_3 Concentrations for the Base Case for 12p (ppb) ……...…… 140

Figure 3: Estimated Differences in Hourly O_3 Concentrations for 12p (ppb) when 15-minute Link Average Speeds are Used in contrast to Hourly Link Average Speeds for Mobile Source Emissions Estimation ……... 142

Figure 4: Estimated Differences in Hourly O_3 Concentrations for 12p (ppb) when Hourly Lane Average Speeds are Used in contrast to Hourly Link Average Speeds for Mobile Source Emissions Estimation ……..… 144

Figure 5: Estimated 24 hour Average $PM_{2.5}$ Concentrations for the Base Case ($\mu g/m^3$) ……..... 146

Figure 6: Estimated Differences in 24 hour average $PM_{2.5}$ Concentrations ($\mu g/m^3$) when 15-minute Link Average Speeds are Used in contrast to Hourly Link Average Speeds for Mobile Source Emissions Estimation …….……. 148

Figure 7: Estimated Differences in 24 hour average $PM_{2.5}$ Concentrations ($\mu g/m^3$) when Hourly Lane Average Speeds are Used in contrast to Hourly Link Average Speeds for Mobile Source Emissions Estimation …….. 149

Figure 8: Hourly Distribution of O_3 concentrations for Central LA (ppb) …...… 151

Figure 9: Hourly Distribution of $PM_{2.5}$ concentrations for Central LA ($\mu g/m^3$) . 152

Figure 10: Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 12p ……. 155

Figure 11: Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 1p ……... 156

Figure 12: Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 2p ……... 157

Figure 13: Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 3p ……...… 158

Figure 14: Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 4p ……...… 159

Figure 15: Estimated Differences in Hourly O_3 Concentrations for 12p (ppb) when Constant Allocation Factors versus Base Case Allocation Factors are Used (Holding Total Emissions Constant and Equal to Base Case Total Emissions) ……...… 165

Figure 16: Estimated Differences in 24-hour average $PM_{2.5}$ Concentrations ($\mu g / m^3$) when Constant Allocation Factors and Base Case Allocation Factors are Used (Holding Total Emissions Constant and Equal to Base Case Total Emissions) 166

Figure 17: Hourly Allocation Factors for Mobile Source Emissions when a) Hourly Link, b) 15-Minute Link, c) Hourly Lane Average Speeds are Used for Emissions Estimation ……...……...… 168

Tables

CHAPTER 2. LITERATURE REVIEW

Table 1: Surveillance Technologies ……. 12

CHAPTER 4. THE EFFECTS OF INTRA-HOUR VARIATIONS IN AVERAGE SPEED ON RUNNING STABILIZED EMISSIONS

Table 1: Lane $\bar{g}$ values for I-80 Southbound and Northbound Directions ……..… 55

Table 2: Differences in Running Stabilized Emissions …...……...……. 60

Table 3: ANOVA Model Results for Differences in Running Stabilized Emissions 69

Table 4: Summary Results for Link Level ANOVA ….……...… 73

Table 5: Summary of Results for Day of Week and Time of Day Factors ……..… 74

CHAPTER 5. EXAMINING THE IMPLICATIONS OF INCREASED RESOLUTION IN AVERAGE SPEED BY FACILITY LANE FOR MOBILE EMISSIONS INVENTORIES

Table 1: ANOVA Model Results for Differences in Running Stabilized Emissions ……..… 104

Table 2: Summary Results for Link Level ANOVA ……..……... 106

Table 3: Summary Results for Day of Week and Time of Day Factors ….……... 108

CHAPTER 6. AIR QUALITY EFFECTS OF UTILIZING HIGHLY RESOLVED AVERAGE SPEEDS FOR EMISSIONS ESTIMATION

Table 1: Original SCC Numbers and Their Definitions ……..... 134

Table 2: Original and Modified Source Category Classifications (SCCs) …..... 136

Table 3: Emissions from All Sources (AS) and Mobile Sources (MS) Used as Input for Photochemical Modeling – Central Los Angeles (tons/day) …….…. 162

ABSTRACT

Running Stabilized Emissions from vehicle exhausts are estimated by combining travel activity quantified as vehicle miles of travel (VMT) or vehicle hours of travel (VHT) with emissions factors which are adjusted for speeds on facility links. These speeds which are used for adjusting emissions factors are averaged for fixed periods (typically for one hour intervals) and across the lanes of multi-lane links. In real world traffic conditions, however, average speeds are variable for higher time resolutions and across lanes. Incorporating the variability in average speeds during calculation will result in different magnitudes of estimated running stabilized emissions for a given period of time and a facility link. Lane volume and occupancy measurements from 1376 single loop detector stations on 830 freeway links in Los Angeles were used to estimate flow rates, hourly average link speeds, 15-minute average link speeds and hourly average lane speeds. Then, these flow rates and average speeds were used to estimate hourly link CO, CO_2, NO_x, PM_x and TOG emissions and hourly gridded emissions based on different average speed resolutions for the summer of 1997. This study statistically examines the hourly differences in running stabilized emissions when 15-minute link and hourly lane average speeds are used in contrast to hourly link average speeds for running stabilized emissions estimation. Moreover, effects of speed variability on regional air quality are evaluated by examining the differences in estimated gridded ozone (O_3) and fine particulate matter ($PM_{2.5}$) concentrations based on different gridded emissions inventories (estimated using hourly link, 15-minute link and hourly lane average speeds). The

results show that the magnitudes of estimated hourly link running stabilized emissions are different especially when hourly lane average speeds are used in contrast to the hourly link average speeds. Estimated O_3 and $PM_{2.5}$ concentrations also differ, however, the differences in these estimated secondary pollutant concentrations show different patterns when compared to the differences in estimated emissions.

CHAPTER 1. INTRODUCTION

The 1990 Clean Air Act Amendments (CAAA) require states to adopt State Implementation Plans (SIPs) that establish emissions limits by source (mobile, stationary and area sources) for non-attainment areas. According to the rule adopted by the U.S. Environmental Protection Agency (USEPA), the conformity of new plans, projects and programs to the emissions limits must be demonstrated before they are implemented (USEPA and USDOT, 1993). This process is called the "Transportation Conformity" or the "Conformity" Rule.

In order to determine "Transportation Conformity", transportation activity data is used as an input to emissions models to predict the possible changes in total emissions created by the implementation of the proposed plans, projects, or programs (Chatterjee, Miller et al., 1997). Transportation demand models provide transportation activity data, which are vehicle miles traveled (VMT), vehicle hours traveled (VHT), speed, and volume, as input to emissions models.

In the emissions models, running stabilized emissions are basically calculated by taking the product of running emission factors and the transportation activity (VMT, VHT or volume) (SAI, 1998; Utts, Niemeier et al., 2000; CARB, 2003). In this process, emission factors are provided by emission factor models (CARB, 1996; USEPA, 2001; CARB, 2003). Currently, speeds calculated during demand forecasting processes are used as input to emissions model, or speeds are computed based on the link flow rates predicted by the transportation demand models using

speed post-processing algorithms, also called speed post-processors, integrated to the emissions model (SAI, 1998; Niemeier, Zheng et al., 2004). Even if speeds are calculated by the speed post-processor, they are average speeds based on hourly link flow rates. However, in real-world conditions, flow rates, and therefore speeds, will vary greatly within a one-hour period, and lane by lane (Hall, 1992; Ibrahim and Hall, 1994; Daganzo, 1997; Hurdle, Merlo et al., 1997). In addition, different speeds can be observed for the same flow rate.

Study Purpose

Running stabilized emissions estimated using 15-minute link and hourly lane average speeds will be different from running stabilized emissions estimated using the traditionally-used hourly average link speeds. Our purpose in this study is to address the uncertainties in the current mobile emissions inventory modeling and air quality modeling practices resulting from not taking the natural variability of average speeds for shorter periods and across lanes into consideration. In other words, we examine the implications of the assumption that average speeds are constant for fixed periods and across lanes on facility links for emissions inventories. We not only examine the differences in running stabilized emissions from links resulting from using 15-minute link and hourly lane average speeds but also the effects of these differences on estimated O_3 and $PM_{2.5}$ concentrations.

Study Contribution

In this study, we aim to:

1. Estimate reliable speeds averaged for hourly link, 15-minute link and hourly lane resolutions using lane volume and occupancy measurements at single loop detector stations.

2. Construct a framework to estimate link running stabilized emissions using different resolution average speeds and then estimate the differences in running stabilized emissions.

3. Statistically examine the differences in hourly running stabilized emissions estimated for the freeway links.

4. Evaluate when and/or where average speed variability for 15-minute periods or across lanes results in significantly different estimated emissions.

5. Integrate speed variability to estimate gridded emissions inventories which will be input to a photochemical air quality model and then examine differences in estimated gridded O_3 and $PM_{2.5}$ concentrations.

Study Organization

In Chapter 2, we will review the research efforts to date which constitute the background for the motivation of this study as well as the methodologies used for the purposes of this study. Chapter 3 describes the methods and the data used. Chapters 4

and 5 examine the differences in running stabilized emissions resulting from utilizing 15-minute link and lane average speeds in contrast to utilizing the commonly-used hourly link average speeds. Chapter 6 focuses on the effects of using higher resolution average speeds for mobile source emissions estimation on secondary pollutant formation, specifically on estimated O_3 and PM concentrations. Finally, in Chapter 7, we discuss the major findings of this study.

CHAPTER 2. LITERATURE REVIEW

Emissions from vehicles are composed of running stabilized, running evaporative (or running loss), starts/parks, idle, hot soak, diurnal, resting loss, tire-wear and break-wear emissions according to the processes in which they are produced (CARB, 1996; USEPA, 2001; CARB, 2003; Niemeier, Zheng et al., 2004). An understanding of the interrelationship between the transportation activity inputs to the emissions models (i.e., speed and VMT or VHT) and running stabilized emissions is essential to performing the analyses in this study. Running stabilized emissions for a given vehicle mix is computed as follows (USEPA, 2001; CARB, 2003):

$$\textit{Running Stabilized Emissions} = \textit{VMT} \times \textit{Running Emissions Factor} \qquad \text{(Equation 1)}$$

When running stabilized emissions are estimated, not only emissions factors are adjusted for average travel speeds on links (or link average speeds) but also the link flow rates, and therefore the VMT or VHT estimated for facility links, are related to link average speeds (Figure 1). In real-world traffic conditions, fixed period link flow rates and link average speeds, therefore the running stabilized emissions estimates, can differ by region, time of day, facility type, across lanes, zones and also the methodology used to estimate them (Page, 1995).

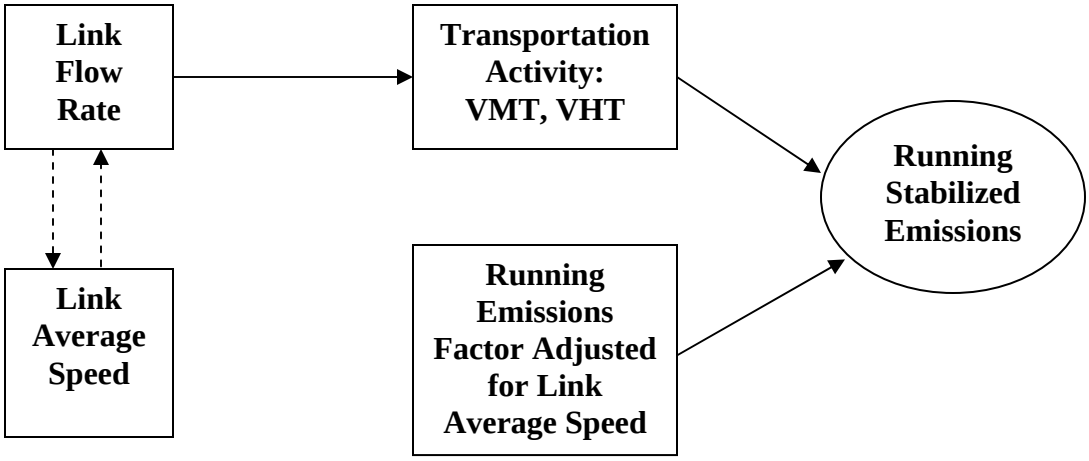

Figure 1. Running Stabilized Emissions Estimation

2.1. Speeds Used for Running Stabilized Emissions Estimation

Running stabilized emissions are estimated by taking the product of running stabilized emissions factors and the transportation activity on a link for a certain time period (VMT or VHT) (CARB, 2003). Running stabilized emissions factors are estimated by adjusting base emissions factors (BEFs) with a variety of correction factors, one set of which are the "speed" correction factors (CARB, 1996). For example in California's EMFAC model, BEFs are unit emissions estimated using Federal Test Procedure (FTP) driving cycles with average speeds of 19.6 mph (CARB, 1996). Then, these BEFs are corrected for link average speeds other than 19.6 mph. The latest version of California's Emissions Factor Model, EMFAC2002, uses 15 new correction driving cycles in order to develop speed correction factors (SCFs) (CARB, 2003). These driving cycles are representative of 15 different typical trips with different link average speeds. Therefore, link average speeds are needed for adjusting the emissions factors in the running emissions estimation process.

Moreover, in order to estimate the running stabilized emissions created by the vehicular activity on a link (i.e., VMT or VHT), link flow rates are needed (Chatterjee, Miller et al., 1997). Link flow rates are provided by transportation demand models from the traffic assignment step. Traffic assignment is the last step of 4-step demand forecasting and assigns trips between origin-destination pairs (O-D pairs) to the links of a network (Ortuzar and Willumsen, 1994). During the traffic assignment, the cost of travel on a link is usually defined by travel time (other monetary costs like fuel, fares, etc. can be considered as well) and travel time is generated from the speed-flow rate relationships which differ for different types of facilities. Therefore, link average speeds are also estimated during the traffic assignment process and these speeds are used as input to emissions models (e.g., BURDEN, DTIM, UCDrive).

However, research has shown that these speeds estimated during the traffic assignment do not represent real-world traffic link average speeds (Dowling and Skabardonis, 1992; Helali and Hutchison, 1994; Dowling, Kittelson et al., 1997). One way to improve the link average speeds used is by integrating speed post-processor algorithms to the emissions models, and a speed post-processing method has been integrated into new versions of California's Direct Travel Impact Model (DTIM) and UCDrive (SAI, 1998; Niemeier, Zheng et al., 2004). This allows link average speeds estimated by the post-processor to be used instead of the average speeds provided by the transportation demand models.

Dowling and Skabardonis (1992) developed a speed post-processor methodology to provide better speed estimates to regional emissions models. Beginning with an investigation of the speeds estimated by the Bureau of Public Roads (BPR) speed equation (Equation 2) and Highway Capacity Manual (HCM) speed-flow curves, the authors concluded that the BPR Equation gave higher estimated speed results especially as flow rate neared the capacity (Dowling and Skabardonis, 1992; TRB, 1998).

$$s = \frac{s_f}{1 + a(v/c)^b} \qquad \text{(Equation 2)}$$

where,

s = Average Speed,

s_f = Free-flow speed,

v = Volume,

c = Practical capacity,

a, b = Constants.

The authors proposed changing the coefficients of the BPR Equation so that the resulting speed-flow curve reflects the observed flow rates and speeds in a region. They also formulated a queuing analysis to be used when flow rate assigned to a link by the transportation model exceeded capacity. If the hourly flow rate exceeds the hourly link capacity, queuing analysis is performed assuming that the flow rate and capacity are constant in that hour. The first step is calculating the congested (queue) and uncongested speeds. Queue speed is the product of the estimated queue length

and the spacing whereas the uncongested speed is calculated using the modified BPR equation for the vehicles which are not in the queue. Then the average link speed is calculated by taking the weighted average of the queue and uncongested speeds. A constant spacing of 25 ft/vehicle was assumed to calculate the queue length. As the authors note, the queuing algorithm cannot reflect the temporal changes in the queue length in an hour. Also, hourly flow rates are estimated by multiplying a five-hour peak-period flow rate by peak-hour factors, so they may not be representative of actual hourly flow rates. However, the proposed methodology gave more reasonable link average speed and delay results than the link average speeds and delay values provided by the transportation demand model.

Helali and Hutchison (1994) proposed another speed post-processor methodology based on the Davidson formulation, the Dowling and Skabardonis study (1992), and a queuing analysis method from the modified Boston Central Artery/Tunnel Freeway (CA/T) Queuing Procedure. Their methodology treats arterials and freeways separately in different modules. The arterial module uses the Davidson function to estimate travel times based on free flow travel time, capacity and flow rate. The Davidson function was calibrated according to observed flow rates and travel times. Different from the Dowling and Skabardonis queuing methodology, the authors used a 22-ft spacing and estimated the average queue speed by taking the simple average of congested and uncongested speeds in the queuing period. For freeways, the speeds were modified only when the link flow rate exceeded the capacity. The queuing analysis proposed for freeways was a slightly modified version of the CA/T

procedure. When the authors of this study compared their results with transportation model outputs, they found out that the arterial module results represented the real-world speeds better than the transportation model estimates and the freeway module gave speed-flow rate relationships similar to the HCM speed-flow curves.

The speed post-processors developed by Dowling and Skabardonis (1992) and Helali and Hutchison (1994) use link flow rates to estimate hourly link average speeds and travel times. Therefore, the reliability of speed or travel time estimates that will be passed for the emissions estimation primarily depends on the reliability of the link flow rates calculated in the transportation demand models. The success of a speed post-processor also depends on how the BPR or Davidson functions are calibrated. The regional speed and flow rate data that will be used to calibrate the components of speed post-processor should be representative of the regional traffic flow conditions. Moreover, different links in a region may show different speed-flow rate relationship trends (because of bottlenecks, etc.) even if they are the same facility type. Secondly, the detector technology used to measure real-world flow rates and speeds, the locations of the detector stations and how data is aggregated are important for the calibration of the speed post-processors. It should be noted that speeds measured or calculated for calibration purposes should be space mean speeds so that they can be substituted for link average speeds.

2.2. Real-World Link Average Speeds

There has been significant research effort aimed at predicting traffic flow variables. In general, traffic flow is described by three variables:

- Flow Rate: The number of vehicles passing a point during a specified period of time (veh/min, veh/hr, etc.),
- Density: The number of vehicles on a specified segment of roadway (veh/km, veh/mi, etc.),
- Speed: The change of distance in unit time (km/hr, mi/hr, etc.).

With the surveillance technologies, acquisition of flow rate data is fairly easy (Nam and Drew, 1996). However, because density is a section measurement and it is not possible to obtain using point measurements, occupancy is commonly used instead of density. Occupancy is the ratio of time a detector is occupied by all vehicles to the total observation period (Daganzo, 1997). Speed is usually not observed but calculated using Equations 3, 4 and 5 which will be discussed in detail later in this chapter (Hall and Persaud, 1989; Daganzo, 1997; Coifman, 2001):

$$Speed = \frac{Flow}{Density}, \qquad \text{(Equation 3)}$$

and

$$Density = g \times Occupancy, \qquad \text{(Equation 4)}$$

so that

$$Speed = \frac{Flow}{g \times Occupancy} \qquad \text{(Equation 5)}$$

where g is a constant and the inverse of the sum of effective vehicle length and detector width.

2.2.1. Surveillance Technologies

As shown in Table 1, acquisition of traffic flow rate data can be accomplished using a variety of surveillance technologies (Nam and Drew, 1996):

Table 1. Surveillance Technologies

Technology	Operation	Measurement Capacity	Remark
Ultrasonics	Emit sound waves above human audible level	Flow, occupancy, queue length	Point measure, subject to weather
Active infrared	Emit a pulsed laser beam at higher frequencies	Flow, occupancy, classification, speed	Point measure, subject to weather
Passive infrared	Measure infrared energy emitted by objects	Flow, occupancy, presence	Point measures, subject to weather
Microwave radar	Similar to active infrared but emit at lower frequencies	Flow, presence, speed	Point measures, health concern
Acoustics	Detect traffic sounds generated by a vehicle	Flow, presence, vehicle classification	Point measure, subject to environment noise
Video-image processing	On-line analysis of video images by signal processing hardware and software	Flow, occupancy, speed, queue length, presence	Extensive computational task, limited spatial coverage
Aerial-video-image processing	Analyze video images taken on the plane	Flow, density, queue length	Wide-area coverage, subject to weather
Inductive loops	Detect change in inductance indicating the presence of a vehicle	Flow, occupancy, presence, speed	Point measures, widely used, maintenance problems
Global Positioning System (GPS)	Measure the time taken for signals to travel from a set of at last four satellites to receiver	Travel time, speed	Wide-area vehicle tracking, accuracy enhancement by differential GPS
Automatic vehicle identification	Communicate between in-vehicle and roadside unit	Flow, speed, travel time, vehicle classification	Toll collection, privacy concern

The surveillance technologies mentioned above can be classified according to their levels of “accuracy, reliability, consistency and efficiency” (Nam and Drew, 1996). All the technologies except the GPS provide flow rates. Ultrasonics, passive infrared, active infrared and inductive loops provide occupancies that can later be used to estimate the density and speed. On the other hand, GPS, automatic vehicle identification, video image processing, microwave radar and active infrared are capable of providing speeds directly.

Although the inductive loops, which we will refer to as loop detectors, do not provide speeds directly, they are widely used (Nam and Drew, 1996). The main reason is that the hardware, installation and maintenance of loop detectors are more economical than other technologies. A secondary reason is that they are capable of providing flow rate data. Flow rate measurements are the most acutely needed data by public agencies because they are used for transportation planning and demand management purposes. There are two kinds of loop detectors which are single loop and double loop detectors.

2.2.2. Single Loop and Double Loop Detectors

The major difference between single loop and double loop detectors becomes obvious when speed is estimated. Generally, at single loop detectors speed is estimated by dividing flow rate by density (Equation 2) and assuming that the density is linearly related to occupancy. (Equation 3) (Daganzo, 1997). It is important to mention that the estimated speed is the average speed for all the vehicles passing over the loop detector during the observation period.

A double loop detector is two single loop detectors placed a known and short distance apart. A short distance between two the loops helps to reduce the influence of acceleration and deceleration of vehicles on the estimated speeds (Barbosa, Tight et al., 2000). Although a double loop detector is capable of providing volume and occupancy data like a single loop detector, at double loop detector locations it is possible to estimate the speeds of individual vehicles using Equation 6 (Barbosa, Tight et al., 2000).

$$Speed = Distance/(t_2 - t_1) \quad \text{(Equation 6)}$$

where,

Distance = Spacing between the two loop detectors at a double loop detector,

t_1 = Time of entry of the vehicle to the first loop,

t_2 = Time of entry of the vehicle to the second loop.

Double loop detectors provide more reliable speed estimates, however, single loop detectors are widely used because they are more economical.

2.2.3. Speed, Time Mean Speed and Space Mean Speed

We previously defined speed as the time rate of change of distance of an individual vehicle. However, considering that we have to calculate average speeds for number of vehicles and for multi-segmented links we have to define time mean speed and space speeds.

The speed of an individual vehicle over a segment is calculated by the general formula (Daganzo, 1997):

$$s_i = \frac{d_i}{t_i} \qquad \text{(Equation 7)}$$

where,

d_i = Length of the segment,

t_i = Time spent by the vehicle to cross the segment.

The average speed of an individual vehicle over a link (or for a trip) with more than one segment is the harmonic mean of the speeds for each segment (Daganzo, 1997; Dowling, et al. , 1997):

$$s = \frac{D}{\sum \frac{s_i}{d_i}} \qquad \text{(Equation 8)}$$

where,

s = Average travel speed for the link (or trip),

s_i = Travel speed for segment i,

D = Total distance,

d_i = Length of segment i.

The average travel speed for all vehicles over a segment is estimated by either computing the arithmetic or harmonic mean of the individual vehicle speeds

(Dowling, Kittelson et al., 1997). The arithmetic mean of the individual vehicle speeds is the time mean speed (Daganzo, 1997; Dowling, Kittelson et al., 1997):

$$TMS = \frac{\sum s_i}{N} \qquad \text{(Equation 9)}$$

where,

TMS = Time mean speed,

s_i = Average travel speed for vehicle i,

N = Number of vehicles.

High-speed vehicles cross a given distance in shorter periods than slow-speed vehicles do (Dowling, Kittelson et al., 1997). Therefore, the time mean speed is a biased estimator of the average travel speed on a segment.

Space mean speed, the harmonic mean of the individual vehicle speeds, is given by the formula (Daganzo, 1997; Dowling, Kittelson et al., 1997):

$$SMS = \frac{Nd}{\sum \frac{d}{s_i}} = \frac{N}{\sum \frac{1}{s_i}} \qquad \text{(Equation 10)}$$

where,

SMS = Space mean speed,

s_i = Average travel speed for vehicle i,

N = Number of vehicles,

d = Distance.

In the above equation, simply total distance traveled is divided by the total travel time of all the traveling vehicles in a period of time, therefore space mean speed is an unbiased estimator of the average travel speed (Dowling, Kittelson et al., 1997).

If all the vehicles travel with the same speed and headway, time mean speed and space mean speed are identical (Dowling, Kittelson et al., 1997). Otherwise time mean speed is always higher than space mean speed. The difference between the time mean speed and space mean speed estimates increases when the variability of individual vehicle speeds increases.

The link average speeds used as inputs to emissions inventory models in practice are the space mean speed for many vehicles on multi-segment links. However, from single loop detectors we are capable of estimating average speeds at the detector locations, that is, the average speeds are point estimates. Equation 10 can be used to estimate the space mean speed which is also the link average speed, when the travel speed of each vehicle on each segment is known.

2.2.4 Speed Estimation at Single Loop Detector Stations

At single loop detector stations, speed is most commonly calculated by Equation 5. The comparison of the estimated speeds using Equation 5 with the observed speeds shows that the estimated speeds do not represent the real-world conditions (Hall and Persaud, 1989; Pushkar, Hall et al., 1994; Cassidy and Coifman, 1997; Petty, Bickel et al., 1998; Sun and Ritchie, 1999; Coifman, 2001; Hellinga, 2002). According to

Hall and Persaud (1989), the best use of single loop detectors is to use them only for flow rate measurements and not for speed estimation. However, they are usually the only source of practical data to estimate speeds and they are the only source in our case.

Given that the single loop detectors are the most common source of data used to calculate speeds, there has been extensive research to improve the speed estimates from them. Hall and Persaud (1989) have compared speeds estimated using Equation 5 with the observed speeds and found that the speeds were overestimated for observed speeds higher than 60 mph and they were underestimated for observed speeds less than 30 mph. They pointed out that the observed and estimated speeds did not match either because an incorrect g value used, or g was systematically changing with the other observed variables. In order to see if g was a constant across a range of operations, the authors calculated g values from observed speed, occupancy and volume measurements from a double loop detector station. Because speed was the traffic flow variable of interest, the variability of g with occupancy was investigated. They found that for occupancies from 8 to 20-25 % (for uncongested traffic), g values were not highly scattered. Although the calculated g is more scattered for occupancies higher than 20 % (for congested traffic), the mean values showed a declining trend with increasing occupancies. For very low occupancies with values less than 8 % the g value increased abruptly.

This study showed that the two assumptions behind Equation 5 were not met (Hall and Persaud, 1989). The first assumption is the fundamental equation of traffic flow

(Equation 3). The second is the assumption about occupancy and density linear relationship (Equation 4). According to the fundamental equation of traffic flow, all vehicles travel with identical speeds and spacings, (i.e., traffic flow is uniform). However, traffic flow is never uniform under congested traffic conditions. Vehicles frequently accelerate and decelerate and even stop. There are sudden changes in speeds and spacings that are already not identical for all vehicles. The assumption of uniform traffic flow is rarely met for free-flow conditions. Drivers do not tend to choose similar speeds. They may drive very slowly, exceed speed limits, accelerate and decelerate and change lanes frequently. These actions can affect the driving behavior of the other drivers as well (Nagatani, 2000).

The assumption of linearity between occupancy and density can only be valid if the vehicle lengths and speeds are constant (Pushkar, Hall et al., 1994). The variability of vehicle lengths is expected in real-world conditions since vehicle fleets differ both temporally and regionally (Petty, Bickel et al., 1998). Vehicle lengths can be estimated when speeds are known in addition to the loop detector flow rate and occupancy measurements (Hall and Persaud, 1989):

$$g = \frac{Flow}{Speed \times Occupancy} \qquad \text{(Equation 11)}$$

and

$$x = \frac{1}{g} - d \qquad \text{(Equation 12)}$$

which gives

$$x = \frac{Speed \times Occupancy}{Flow} - d \qquad \text{(Equation 13)}$$

where x is the vehicle length and d is the detector width. It is assumed that the occupancy is linearly related to density in Equation 12, which is not true for the real-world traffic operations. Thus, even if the correct speeds are known the vehicle lengths computed using speeds and single loop detector occupancy and volume measurements should be used cautiously.

Pushkar, Hall and Acha-Daza (1994) used catastrophe theory to estimate speeds at single loop detector locations. Because single loop detectors do not provide real-world speed measurements, they used the observed speeds from double loop detectors nearby to estimate a 3-dimensional surface such that

$$X^3 - aUX + bV = 0$$

where X, U and V are derived from speed, volume and occupancy, respectively.

Acha-Daza and Hall (1994) compared speeds estimated by the catastrophe theory model with observed speeds. They found that the catastrophe theory model gave results similar to the observed values. They claimed that catastrophe theory is capable of explaining the traffic flow dynamics.

There have been other efforts to estimate reliable speeds from single loop detectors. Nam and Drew (1996) proposed a methodology that estimates travel times from

observed volumes. The model was based on the conservation of vehicles equation and a queuing methodology to describe the temporal changes in traffic and provided speeds and densities as a function of time. Sun and Ritchie (1999) used individual vehicle waveforms for estimating speed from single loop detectors. They claimed this method had many advantages over other real-time speed estimation methods. First, single loop detectors were the most widely used traffic detection structure. The method did not depend on the assumption of constant vehicle length and uniform traffic flow. In addition, the method was not based on the assumptions about vehicle arrival times and speeds. The authors of this paper constructed a linear regression model where the dependent variable was speed and the independent variable was the slew rate in order to predict speed with slew rate measurements (Sun and Ritche, 1999).

$$Speed_i = \alpha + \beta slew_i + \varepsilon_i$$

where $Speed_i$ is the speed of an individual vehicle, $slew_i$ is the slew rate and ε_i is the error term. Slew rate[1] is related to speed and is based on extracted waveforms from the inductive loop waveforms.

Daily (1993) introduced a method that did not use the actual mean value of the volume. Instead, he used the fluctuation of volume from its time averaged mean to address the speed variability. The important assumption underlying this method was one about the propagation of traffic flow. Traffic was assumed to be propagating

[1] Slew rates are the leading and trailing edges of inductive loop waveforms which give information about the rate of movement of the vehicle over time.

rigidly, so that the fluctuations of volume from its time averaged mean could be indicators of the mean vehicle speed. The method did not predict the dynamics of traffic flow, however, it was a method to develop time-series functions to predict speeds. Daily pointed out that the assumption of rigid propagation was not always valid. Rigid propagation is possible when there are no breaks in the flowing traffic. Therefore, this method becomes questionable for stop-and-go traffic when vehicles stop for periods long enough to call them breaks. Similarly, if there is no traffic on a roadway for a long period, such as on high occupancy vehicle (HOV) lanes, rigid propagation cannot be assumed.

Daily (1999) also introduced a model which used single loop detector volume and occupancy measurements using a statistical algorithm for estimating speeds. Volume and occupancy measurements from detectors were taken as the realizations from statistical distributions and a Kalman filter was used to express the variability of the measurements. The speeds, average vehicle lengths and occupancies were assumed to have a mean and a certain deviation value, and using a Kalman filter, average vehicle length was defined as a function of occupancy, time, volume, average speed and standard deviation of vehicle lengths. Therefore, average speeds can be estimated using the means and standard deviations of vehicle lengths estimated for long time periods, volumes and occupancies.

Alternatively, the method of Petty et al. (1998) is based on estimating travel time distributions by using an approximate relationship between flow rate, occupancy and speed. The stochastic model assumes that in a certain time period, vehicles arriving at

an upstream point had travel times between that upstream point and a certain downstream point with the same probability distribution. Similar to the (1999) Daily study, the authors assume that travel times are realizations from the same stochastic process. The Daily (1993), Daily (1999) and Petty et al. (1998) studies are valuable since, in contrast to the previously reviewed ones, they integrate the statistical nature of the real-world measurements to estimate average speeds and travel times. Since they take the variability of the observations into account these methods better explain the variability of speeds (or travel times) for different vehicle lengths and different traffic operation conditions.

All of the studies reviewed in this section are conducted based on the fundamental equation of traffic flow (i.e., Flow Rate = Speed$\times$Density), and the assumption that occupancy is linearly related to density does not hold under real-world conditions. However, Cassidy and Coifman (1997) used Edie's definitions of traffic flow (Edie, 1974) in order to show that they held and demonstrated this by using real-world speed, occupancy and volume measurements at a double loop detector station. First they formulated average vehicle length in terms of occupancy using Edie's definitions of traffic flow. Then in order to prove their argument, the authors estimated density first dividing flow rate by average speed (space mean speed) and then dividing occupancy by effective length (summation of average vehicle length and the detector length) and found that these two formulations gave the same density values.

In a more current study following the Cassidy and Coifman study (1997), Coifman (2001) showed that if the vehicle lengths are similar it will be adequate to assume a

constant average vehicle length, thus a *g* value, to estimate space mean speeds when the flow rate and occupancy values are known using Equation 3. It should be noted that Hall and Persaud's (1987) findings still hold. It is true that the *g* value can be a constant only if vehicle lengths and vehicle spacings are constant. However, assuming that vehicle lengths are constant, when congestion increases (which is described by increasing occupancy in their study) and spacings become more variable, the *g* value does not decrease but the scatter of the *g* values increases (Coifman, 2001). The *g* values in Hall and Persaud's study (1987) were decreasing because the speeds utilized were time mean speeds. When vehicle lengths are similar, the speed described in Equation 3 is the space mean speed which is the total distance traveled by a number of vehicles divided by the total travel time of those vehicles.

2.2.5. Link Average Speed Estimation

To our best knowledge there is no published effort using real-world point speeds (which are average speeds for a number of vehicles in a given period of time) estimated at single loop detector locations to estimate average travel speed on a link for input to emissions models if there is more than one loop detector station on that link. However, there has been effort to estimate travel times on links which are detected by more than one double loop detector station, by constructing individual vehicle trajectories (Coifman, 2002).

In this study, we estimate lane and link average speeds (i.e., space mean speeds for lanes and links) for the links that include more than one single loop detector stations,

by assuming that those links are multi-segment links where each segment is detected by one of the single loop detector stations.

2.3. Discussion

2.3.1. Concerns about the Current Research on Effects of Speed Variability on Mobile Source Emissions

The progressing research on the effects of speed variability on emissions shows that in fact speed variability affects the magnitudes of running stabilized emissions produced by individual vehicles (e.g., Barth, Scora et al., 1998). Some of these research efforts are focused on analyzing the effects of instantaneous or short-period speeds on unit emissions (Hansen, Winther et al., 1995; Gram, 1996; Trozzi, Vaccaro et al., 1996; Andre and Pronello, 1997; Andre and Hammarstrom, 2000). Some other research efforts not only analyze the effects of speed variability but also aim to describe vehicle operation modes in real-world traffic conditions to develop driving cycles or evaluate current driving cycles which are used to produce emissions factors (Denis, Cicero et al., 1994; Joumard, Jost et al., 1995; Joumard, Andre et al., 2003; Lin and Niemeier, 2003).

In addition, there are efforts to construct modal emissions models in which the emissions are estimated based on individual vehicle operation modes (Barth, An et al., 1996; Feng, Barth et al., 1997; Barth, Scora et al., 1998; Ahn, Rakha et al., 2002). In this context, average speed for a fixed period and second-by-second variability of

speed in that period are two of the many variables to describe vehicle operations which produce running emissions.

Increasing the certainty of regional emissions inventories is essential for accurate transportation conformity analyses. Research efforts about the effects of speed variability on unit emissions, or the efforts that utilize individual vehicle speed variability as one of the variables to estimate emissions (e.g., Barth, Scora et al., 1998), do not describe the uncertainties in estimated emissions resulting from the assumption that speeds are constant for hourly periods and across lanes in the regional emissions modeling context. Our purpose in this study is to examine the uncertainties in estimated emissions for which travel activity (i.e., VMT or VHT) are combined with running emissions factors which are adjusted for and assumed constant for fixed-period average speeds. Given that VMT or VHT are estimated using link flow rates which are related to average speeds as well (e.g., Daganzo, 1997), our study is unique given that it focuses on uncertainties that were not addressed by the previous research about the effects of speed variability on mobile source emissions produced.

2.3.2. Concerns about the Current Research Focusing on Uncertainties in Mobile Source Emissions Modeling Resulting from the Differences in Travel Activity Input Data

One of the sensitivity analyses that is suggested to be performed to examine the uncertainties in estimated mobile source emissions is analyzing the differences in emissions estimates when travel activity inputs to the mobile source emissions

models are changed (NRC, 2000). The current research focuses on the impacts of differences in speed-VMT distributions (e.g., Nanzetta et al., 2000), and temporal and spatial variations in VMT (Cardelino, 1998), on estimated emissions. Moreover, there are efforts to reduce the uncertainties in the average speeds and flow rate estimates (for a given link and period of time) provided to the emissions inventory models to improve the accuracy of the emissions estimates (Dowling and Skabardonis, 1992; Chatterjee, Miller et al., 1997; Dowling, Kittelson et al., 1997).

The commonly used approach in mobile source emissions modeling is to utilize hourly flow rates and average speeds to estimate hourly mobile source emissions. This study addresses another uncertainty which was not studied earlier (related to uncertainties in travel activity inputs). Specifically, if analyzes the uncertainty in estimated emissions resulting from the assumption that hourly average link speeds are constant for shorter periods and across lanes, given that it has been shown that this assumption does not hold most of the time (Page, 1995; Daganzo, 1997).

Moreover, previous research states the inaccuracies in travel activity input data as sources of uncertainties in estimated emissions which eventually affect the pollutant concentrations (NRC, 2000). To our knowledge, there are no studies which focus on the effects of different spatial and temporal resolution travel activity data on estimated emissions and consequently on highly resolved pollutant concentration estimates. Examining the magnitudes of mobile source emissions estimates is not adequate to acknowledge the effects of the spatial and temporal differences in travel activity data on pollutant concentration estimates. This is because emissions from

area and point sources, meteorology, topography, initial boundary conditions and other variables which are used as input to photochemical air quality models also affect the concentration estimates (Seinfeld and Spyros, 1998; Wark, Werner et al., 1998).

CHAPTER 3. DATA AND METHODS

3.1. Data

We conduct our study based on real-world volumes and occupancies measured on freeway links in Los Angeles. The data sets include 30 second volumes and occupancies for each lane at single loop detector stations during the Summer of 1997.

The summer 1997 volume and occupancy measurements were provided from 1609 single loop detector stations of MODCOMP system in Los Angeles region, District 7 of Caltrans for the South Coast Ozone Study (SCOS) (Hicks, Korve et al., 1999). The data is provided for three regions, South Los Angeles, North Los Angeles and Orange County. The data retrieved from the data tapes include two files for each day. One includes the 30 second volume measurements for each lane at all the detector locations, whereas the second one includes the lane 30 second occupancy measurements. Most of the loop detectors are located on freeway links, however, a small number of them are on ramps where two or more freeways intersect. Loop detectors on freeway links are mostly located close to intersections with other freeway links or other types of facility links. We used the data from 1376 single loop detector stations which are located on freeway links given that our purpose is to estimate flow rates and average speeds on the links and also on the individual lanes of those links.

It should be noted that the data were not available for some detector stations for all the days that we focused on. Data for some detector stations were available only for

some of the days during the Summer of 1997. In addition, for some days data was not available for some of the 30 second periods but was available for the other 30 second periods during the day. The data can be missing because of malfunctions at single loop detector stations or in the system (i.e., the system which retrieves the data from single loop detector stations to the traffic operation centers (TOCs) and processes the data for volume and occupancy estimation), road constructions at or near single loop detector stations and malfunctions in the tapes on which the data sets were provided to us resulting in missing or corrupted data.

The next section in this chapter covers the methods we have used for estimating travel activity inputs (i.e., flow rates and different resolution average speeds) using single loop detector data, estimating emissions using these travel activity inputs, analyzing the differences in emissions resulting from using 15-minute link and hourly lane average speeds in contrast to hourly link average speeds, producing gridded mobile source emissions based on different resolution average speeds as input to photochemical models, and analyzing the effects of using different resolution average speeds on estimated O_3 and $PM_{2.5}$ concentrations. The methods will be briefly presented in this chapter given that they are described in detail in the chapters following this one.

3.2. Methods

To estimate flow rates and average speeds that will be used for emissions estimation, first we processed 30 second single loop detector volumes and occupancies measured on individual lanes of freeway links. Given that we needed to estimate hourly link, 15-minute link and hourly lane flow rates and average speeds, we first temporally aggregated 30 second lane volume and occupancies to produce 15-minute and hourly lane volumes and occupancies. Then we aggregated the lane volumes and occupancies across lanes and estimated 15-minute and hourly link volumes and occupancies. The resulting data sets are volume and occupancy values for each region and day aggregated for: 1) hourly periods and across lanes, 2) 15 minutes and across lanes, and 3) hourly periods for individual lanes at each of the single loop detector stations.

Then we used these aggregated volumes and occupancy values to estimate hourly link, 15-minute link and hourly lane flow rates and average speeds at the 1376 single loop detector stations located on 830 links in the region. The aggregated volumes are the flow rates. Given that daytime and night time vehicle mixes can be distinguished (Gao and Niemeier, 2003) and our study focuses on hourly periods during daytime, we used Equation 5 to estimate average speeds using a $\bar{g}$ value (i.e., inverse of average vehicle effective lengths) estimated for daytime (Coifman, 2001). We estimated the daytime $\bar{g}$ value using Equation 5 based on flow rate, occupancy and speed measurements from a double loop detector station. We used data from a double

loop detector station near Berkeley provided by Dr. Coifman given that double loop detectors were not available in Los Angeles. The details of methods used to estimate the $\bar{g}$ value used in this study are described in Chapter 4.

After we estimated flow rates and average speeds at single loop detector stations for each daytime hourly period, day and region using Equation 5, we used these flow rates and average speeds to estimate flow rates and average speeds on the 830 freeway links. If there is only one single loop detector station on a given link, we equated the flow rates and average speeds estimated at that detector station to the flow rates and average speeds of that link.

On the other hand, if there is more than one single loop detector station on a link, we equated the link total and individual lane flow rates on the link to the flow rates estimated at the single loop detector station where the highest number of lanes are detected and at the most upstream location. We estimated the average travel speeds on the links (and the individual lanes of those links) by constructing the vehicle trajectories using average link and lane speeds estimated at single loop detector stations. To construct the vehicle trajectories we assumed that vehicle speeds and spacings are constant for the hourly or 15-minute periods between two detector stations. The details of the methods and the assumptions used for link and lane flow rate and average speed estimation are presented in detail in Chapter 4.

Once the flow rates and average speeds are calculated for the freeway links, we estimated hourly link running stabilized emissions based on different resolution

average speeds. That is, we estimated hourly link running stabilized CO, CO_2, NO_x, PM_x, and TOG emissions 1) using hourly average link speeds, 2) by summing up 15-minute link emissions (estimated using 15-minute link average speeds), and 3) by summing up hourly lane emissions (estimated using hourly lane average speeds). Next, for each link, we estimated two sets of differences in running stabilized emissions for all the daytime hourly periods (6a-7p) and for the five types of emissions. One set of differences was estimated by subtracting emissions calculated by summing up 15-minute link running stabilized emissions from emissions estimated using traditionally-used hourly average link speeds. The second set was the differences between running stabilized emissions based on hourly average link speeds and the emissions estimated by aggregating hourly lane running stabilized emissions across lanes. Estimation of running stabilized emissions, the modified emissions model used for running stabilized emissions estimation and the calculations performed to estimate the differences are presented in detail in Chapters 4 and 5.

As presented in detail in Chapters 4 and 5, we then statistically examined the two sets of differences in running stabilized emissions when 15-minute link and hourly lane average speeds are used in contrast to hourly link average speeds for estimation. For this purpose, we used repeated measures analysis of variance (ANOVA) models where individual links are the blocking factors, and we tested if the differences in running stabilized emissions are statistically significant across the days of the week or hourly periods during daytime (that we focused on in this study) (Neter, Wasserman et al., 1990). In addition to the treatment factors, we also tested if the interaction term

between the day of week and time of day is significant, as well as whether the contrasts we constructed by combining different days of the week and the hourly periods are statistically significant.

For differences in each type of emissions, we applied the repeated measures ANOVA model both to the complete data set (i.e., for all hourly periods available to us and for all the links in the region) and to data sets produced for each link (i.e., for all hourly periods available to us but for each link separately). In the latter case, we omitted the blocking factor, which is the link, from the model given that each data set includes hourly differences in running stabilized emissions for a single link. Chapter 4 demonstrates the reasons for the selection of treatment factors such as day of week and time of day, the reasons for constructing the 'weekend vs. weekday', 'peak hour vs. off-peak hour', 'morning peak vs. evening peak' and 'Monday-Friday vs. Tuesday-Wednesday-Thursday' contrasts and their importance for the statistical analyses performed for the purposes of our study.

For the 6th chapter of this study, we estimated hourly gridded emissions inventories for the July 23rd, 24th and 25th in 1997 which were used as input to the photochemical air quality model to analyze the differences in estimated O_3 and $PM_{2.5}$ concentrations resulting from using different resolution average speeds for hourly gridded emissions estimation (Kleeman and Cass, 2001). The details of the methods used to estimate gridded emissions from freeway links as well as from links of other facility types are presented in detail in Chapter 6.

CHAPTER 4. THE EFFECTS OF INTRA-HOUR VARIATIONS IN AVERAGE SPEED ON RUNNING STABILIZED EMISSIONS

The following journal article presents the methods and analyses performed to describe the uncertainties in estimated running stabilized emissions resulting from using traditionally-used hourly link average speeds in contrast to using temporally more resolved 15-minute link average speeds.

The Effects of Intra-Hour Variations in Average Speed on Running Stabilized Emissions

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ABSTRACT

Average hourly roadway speeds are a key input to mobile emissions inventory models. Speeds are usually estimated using travel demand models and a range of comparisons to observed speeds are made to validate the travel demand model estimates. In both cases, speeds are estimated over an hour, despite well known and well documented variations within the hour. For the purposes of estimating air pollutants, these variations may be highly significant. In this study, we use data from 1376 single loop detector stations on 830 freeway links in Los Angeles to estimate hourly volumes based on 15-minute and hourly link flow rates and average speeds. We then use two types of volumes to estimate and statistically examine the differences in hourly estimated emissions for facility links. The results of a repeated measures analysis of variance (ANOVA) show that differences in emissions using the two types of hourly volumes are significantly different for a third to nearly half of the links depending on time of day and day of week and the pollutant. The differences in emissions are more likely to be significantly different across the hourly periods of the day and days of the week for the links where traffic flow is interrupted.

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INTRODUCTION

Regional mobile emissions inventories comprise the sum of running stabilized, evaporative, and vehicle start emissions (CARB, 1996; USEPA, 2001; CARB, 2003). To estimate total running stabilized emissions, total vehicle miles of travel (VMT) for a given average speed is multiplied by an emission factor that has been adjusted to reflect emissions at that average speed (or within a speed bin). Average hourly link travel speeds are a product of the traffic assignment step of travel demand forecasting when link flow rates are calculated (Ortuzar and Willumsen, 1994), and, prior to emissions modeling, sometimes re-calculated using speed post-processors in order to better represent real-world speed-flow rate relationships (Dowling and Skabardonis, 1992; Helali and Hutchison, 1994; SAI, 1998).

Regardless of how or when speeds are computed, they are assumed to reflect an average travel speed for a specific roadway segment across a given time period, usually an hour, and across lanes (Daganzo, 1997). Moreover, it has been shown that speeds will significantly differ for different times of the day, across the lanes for a multiple lane facility and for different regions indicating that using the same speed-flow relationship for different times of the day, different lanes, and different regions for estimating average speeds is inherently inaccurate (Page, 1995).

In this study, we focus our analysis on the differences in link stabilized emissions that can result from increasing the hourly resolution used to calculate hourly link speeds. We perform our analyses using traffic flow rates and average speeds collected from

1376 single loop detector stations on 830 freeway links in the South Coast Air Basin in California.

BACKGROUND

There have been many studies related to travel speeds. However, of these, it is the studies focusing on instantaneous speeds that motivate this research. Instantaneous speed is often used to examine the effects of changing vehicle operational modes (i.e., driving patterns) on emissions. A number of previous studies have found significant differences in emissions computed using instantaneous vehicle speeds relative to emissions calculated using emissions factors which are characterized by the averages of those instantaneous speeds (Ahn, Rakha et al., 2002; Joumard, Andre et al., 2003; Lin and Niemeier, 2003). Research focusing on the effects of instantaneous speed variability on unit emissions suggests that increasing the temporal resolution used to calculate emissions may well produce significant changes in the estimated emissions (Ahn, Rakha et al., 2002; Joumard, Andre et al., 2003; Lin and Niemeier, 2003). In this study, we examine the uncertainty in emissions in the regional emissions modeling context (as opposed to analyzing the effects of speed variability on unit emissions) by making use of real-world 15-minute and hourly average link speeds for hourly link emissions estimation.

The average link speeds passed as input to mobile emissions models from travel demand models are assumed to represent the average travel speed of vehicles traversing a roadway segment during a fixed period of time. An unbiased estimator of average link travel speed is the total distance traveled by the vehicles divided by the total time that those vehicles take to travel that section of the roadway (Daganzo, 1997). Average travel speed on a section of roadway, also known as the space mean

speed, is the harmonic mean of individual vehicle speeds (Daganzo, 1997; Dowling, Kittelson et al., 1997),

$$SMS = \frac{N \times d}{\Sigma \Delta t_i} = \frac{N \times d}{\Sigma \frac{d}{s_i}} = \frac{N}{\Sigma \frac{1}{s_i}} \qquad \text{(Equation 1)}$$

where,

SMS = Space mean speed,

Δt_i = Travel time of vehicle i,

N = Number of vehicles,

d = Length of the roadway segment,

s_i = Average travel speed of vehicle i.

Flow rates are assigned to links in the network in the traffic assignment step during the travel demand modeling. The travel time on each link is estimated using speed-flow relationships specific to the facility type and the average link travel speeds are calculated as the inverse of travel time.

However, the facility-specific speed-flow relationships used to estimate travel time in the travel demand models often do not adequately represent real-world speed-flow relationships, especially during congested conditions (Dowling and Skabardonis, 1992; Helali and Hutchison, 1994). Therefore, speed post-processors are often used to recalculate the estimated travel demand model speeds before estimating gridded emissions (Dowling and Skabardonis, 1992; SAI, 1998).

Most speed post-processor algorithms utilized in the regional emissions inventory models are designed to better reproduce observed facility speed-flow relationships and incorporate congestion effects on average travel speeds using queuing algorithms (Dowling and Skabardonis, 1992; Helali and Hutchison, 1994). Average speeds are usually estimated using link flow rates for a fixed period, typically one hour. However, we would expect that speeds will vary within an hour, not only because flow rates will change during short fixed period time intervals, but also because unique speeds cannot be observed for a given flow rate (Hall, Hurdle et al., 1992; Ibrahim and Hall, 1994; Lin, Su et al., 1996; Daganzo, 1997; Hurdle, Merlo et al., 1997). Figure 1 is an idealized speed-flow rate relationship curve, including uncongested and congested (congested: queue discharge and in-queue) traffic flow conditions, produced by Hall, Hurdle and Banks (1992).

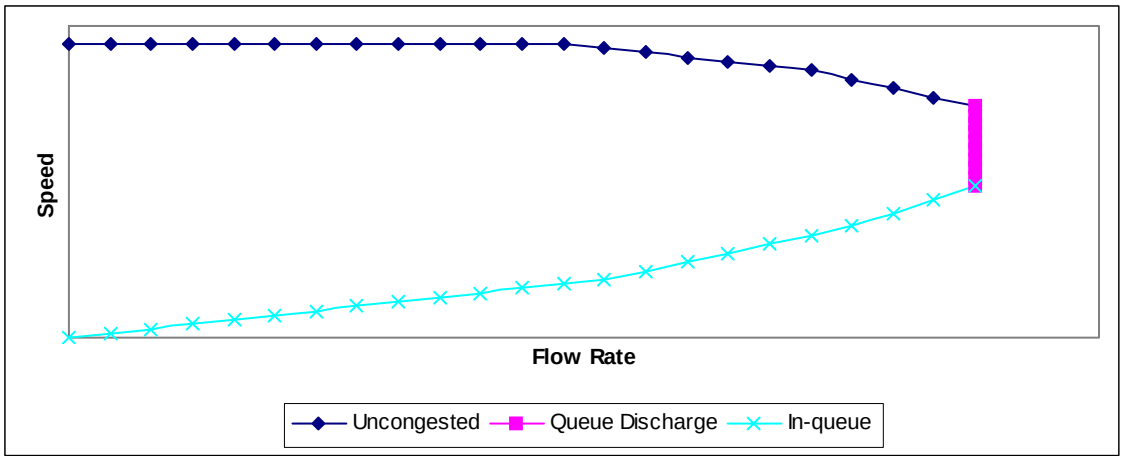

Figure 1. Generalized Ideal Speed-Flow Relationship Curve (Hall, Hurdle and Banks, 1992)

The idealized (i.e., no scatter) curve in Figure 1 shows that different speeds can be observed for the same flow rate depending on flow conditions. For a given flow rate, lane capacities and free-flow speeds, and therefore, observed speeds will differ

depending on factors such as the facility type, observation location on the facility, lane configuration, time of day and weather conditions (Hall, Hurdle et al., 1992; Ibrahim and Hall, 1994; Hurdle, Merlo et al., 1997; TRB, 1998). Moreover, under real-world traffic conditions, a range of speeds will be observed for the same flow rate within the same congestion regime (i.e., plots of observed speeds versus flow rates show scatter).

Figure 2 is an example plot of estimated 5 minute average travel speeds and observed flow rates at a detector station on Interstate 5 (I-5) in the Los Angeles Area on August 1, 2002. The plot is extracted from the Freeway Performance Measurement System (PeMS), which uses observed data to estimate traffic performance measures such as speed, flow rate, density, delay, travel time, vehicle miles traveled (VMT) and vehicle hours traveled (VHT). For example, the speeds and flow rates shown in Figure 2 are estimated using lane volumes and occupancies measured by a single loop detector located on the middle lane of the freeway segment. Although the shapes of the speed-flow rate plots will vary by day, by lane and by location, it is clear that a range of speeds can be observed for a given flow rate. The figure also suggests that scatter tends to increase when congestion (i.e., in-queue or queue discharge flow conditions) is present (i.e., when flow rates are greater than ~1400 vph).

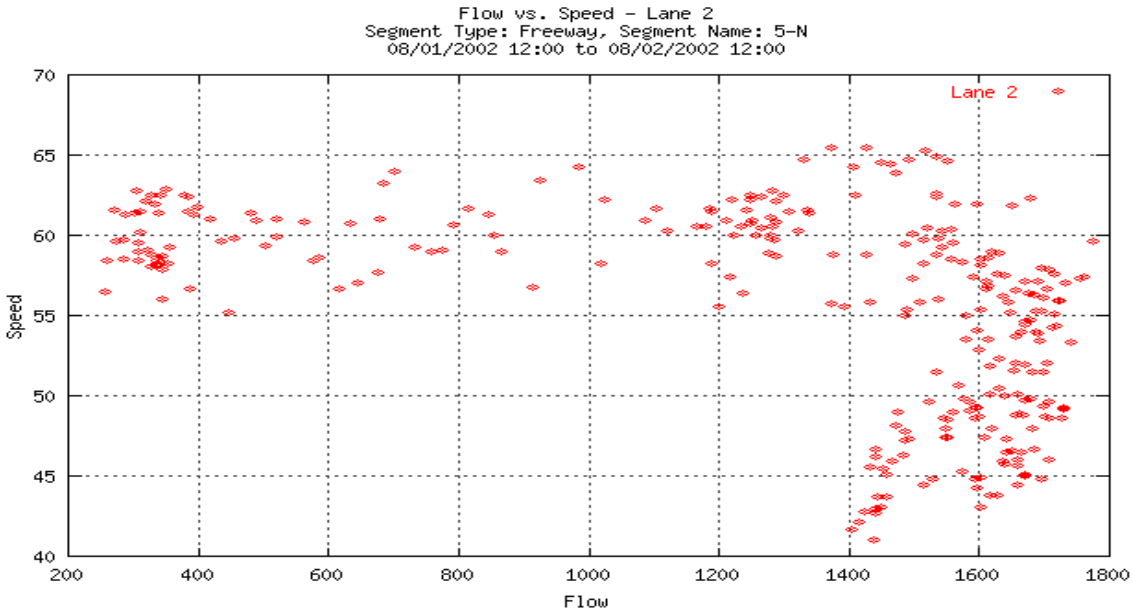

Figure 2. Real-world Speed and Flow Rate Observations (Source: Online Access: http://pems.eecs.berkeley.edu)

The variability in observed speeds for a given flow rate for a given period of time will certainly impact estimated running stabilized emissions. Emissions factors, multiplied by VMT in the emissions inventory models for running stabilized emissions estimation, are adjusted according to speed. By increasing the time resolution used to calculate average link speeds and observed flow rates, we can calculate average speed and flow rate combinations for shorter periods (e.g., 15 minutes) in a given period of time. We can then compare emissions estimated using the speeds averaged for shorter periods of time and summed to one hour and those derived using the normal hourly average speeds. The purpose of this research is to assess whether the increased resolution in speeds relative to the typical one hour average speeds has a statistically significant impact in terms of the differences in estimated running stabilized emissions at a regional level.

METHODS

Link flow rates and average travel speeds were calculated for 830 links in North Los Angeles, South Los Angeles and Orange County using 30 second volume and occupancy measurements from single loop detectors located on the individual facility lanes at 1376 detector stations. Data were collected over three months during the summer of 1997 as part of the South Coast Ozone Study.

For the purpose of this study, 30 second lane volume and occupancy measurements were first aggregated across lanes to estimate link volume and occupancy values. The aggregated link volumes and occupancies were then summed to individual 15-minute and one hour volumes and occupancies, and 15-minute and one hour average speeds were estimated for each of the single loop detector stations. Volumes and average speeds at single loop detector stations were then used to estimate link flow rates and average speeds. Using a modified version of UCDrive (Niemeier, Zheng et al., 2004), the hourly link running stabilized emissions were estimated using: 1) the average speeds estimated for each of the four 15-minute periods within a given hour, and 2) the average one hour speeds for the same hours. Differences in hourly link running stabilized emissions were then examined statistically.

Flow rates and average travel speeds at single loop detector stations

The first step in analysis uses the daily 30 second lane volumes and occupancies to compute flow rates and average travel speeds at all of the single loop detector stations. The combined 30 second volume and occupancy data were nearly 2GB for

one day. Since the purpose of this study is to analyze differences in link running stabilized emissions resulting from increased temporal resolution, we aggregated data across lanes to estimate link volumes and occupancies. The 30 second link volumes and occupancies were aggregated to estimate 15-minute and one hour volumes and occupancies.

During data processing, we discarded some data and also imputed some missing data. If volumes or occupancies were missing for all lanes at a detector station for a given 30 second period or several 30 second periods in a given hour, the volume and occupancy data for the one hour period that included those missing 30 second period(s) were discarded. Also, for those locations where data were available for some lanes and not for others, constant 30 second volume and occupancy values were used to replace the missing lane data and then the imputed and already available lane data were then aggregated across lanes for each detector station to estimate total link volume and occupancy values.

The imputed lane volume and occupancy values were calculated to represent flow conditions at times of maximum throughput on freeways. Maximum throughput is basically the flow condition when the maximum number of vehicles is observed on a facility (Cassidy and Mauch, 2001; Jia, Varaiya et al., 2001). We use the replacement volume and occupancy values for maximum throughput conditions since it will result in the maximum amount of emissions. Jia et al (2001) explored speeds at times of maximum throughput using data from the PeMS network, which provides 5 minute flow rates, occupancies and calculated speeds from 3363 single loop detectors on

freeway lanes in Los Angeles. Occupancies of between 8% and 12% were observed at the majority of the single loop detectors when maximum throughput occurred. Therefore, 10% was used to replace the missing occupancies. For missing volumes, the 30 second volume value was assigned as 15, because the chosen occupancy and volume value results in a speed in which maximum throughput generally occurs. That is, when occupancy is set to 10% and the flow rate is 15 vehicles per 30 seconds, the computed speed is 57.7 mph when we estimated our speeds using the methods described later. According to Jia et al (2001), maximum throughput speed ranged between 50 and 70 mph for 85% of the 3363 detectors used in their Los Angeles study. Moreover, speeds around 60 mph are the most frequently observed maximum throughput speeds.

It should be noted that the maximum throughput conditions do not necessarily represent traffic conditions when flow rates are lower than the maximum throughput flow rates. We used maximum throughput flow rate and occupancy values to impute missing values because magnitudes of emissions created are high when the flow rate (i.e., number of vehicles observed on a given link) is high. Assuming all the other factors which affect the magnitude of estimated emissions (i.e., temperature, speed, humidity, etc.) are constant, it is clear that the estimated emissions are highest for the maximum throughput conditions because of the high flow rates. Thus, maximum throughput is one of the critical conditions during which levels of estimated emissions are high.

Using the 15-minute and one hour link flow rate and occupancy values, average speeds were estimated for each detector station. Average travel speeds were estimated at the single loop detector stations using (Hall and Persaud, 1989; Daganzo, 1997; Coifman, 2001),

$$Average\ Travel\ Speed = \frac{Flow}{g \times Occupancy} \qquad \text{(Equation 2)}$$

where *Flow* is the number of vehicles detected by the loop detector in the observation period, *g* is a constant and the inverse of average vehicle effective length (the sum of average vehicle length and detector sensitivity region length), and *Occupancy* is the percentage of time the detector is occupied by vehicles in that observation period. In this equation, it is assumed that density is linearly related to occupancy by a constant factor.

At a detector station, average effective length can be a constant only if the traveling vehicles have the same lengths and also individual vehicle speeds (or spacings) are constant (Hall and Persaud, 1989; Cassidy and Coifman, 1997; Coifman, 2001; Hellinga, 2002). If the average vehicle length is defined as the “pace weighted” vehicle length (average vehicle length weighted by the inverse of individual vehicle speeds) as in Cassidy and Coifman’ s (1997) study, the average vehicle length is affected by individual vehicle length only. The “pace weighted” length becomes closer in value to the arithmetic average vehicle length when individual vehicle speeds, and therefore spacings, are similar for the observation period (Cassidy and Coifman, 1997; Daganzo, 1997).

When we estimated one hour and 15-minute speeds, we aggregated volume and occupancy measurements and assumed that the individual vehicle speeds (or spacings) were constant within the one hour or respective 15-minute periods. Similar to Coifman (2001), we assumed the pace weighted and arithmetic average of individual vehicle lengths were nearly equal. However, since the mixture of vehicles changes for each observation period, the average vehicle length differs for each observation period. In addition, effective vehicle length differs across detector stations depending on the sensitivity of the detectors (Coifman, 2001). The literature suggests that although average vehicle effective length may vary for different periods of the day, depending on the proportion of homogenous vehicle lengths, a constant effective length can be used if the observed vehicles have similar lengths for the periods for which the average travel speeds are estimated (Coifman, 2001).

Typically, daytime and nighttime vehicle mixes can also be distinguished (Coifman, 2001). During the night greater numbers of heavy duty vehicles are more likely to be present, while during the day passenger cars are more likely to be observed. Recent data using Weigh-In-Motion (WIM) stations indicate that hourly fractions of trucks to the total fleet are higher both for weekdays and weekends during nighttime (i.e., 7p through 6a) when compared to the hourly fractions during the day (i.e., 6a through 7p) (Gao and Niemeier, 2003). For weekdays, nighttime fractions vary between ~8% and ~30% whereas daytime fractions vary between ~8% and ~15%. The hourly truck fractions were higher between midnight and 4a. Moreover, nighttime hourly average truck lengths are longer when compared to the hourly average truck lengths during

the day. The highest average hourly truck length during the day is ~50 ft, while for nighttime, the average hourly truck length observed was ~60 ft (weekdays and weekends combined). As a result, not only the hourly truck ratios to the total fleet but the hourly average lengths for trucks are higher during nighttime.

Since our interest is in differences in running stabilized emissions occurring during morning and evening peak hours and daytime off-peak hours (6a through 7p), and considering that both the fractions and lengths of the trucks for daytime and nighttime can be distinguished, we estimated an average *g* value for the daytime. To use equation 2 for average speed estimation at single loop detector stations, the *g* value should be assumed, provided from another source or estimated using data from another traffic detection technology (Hall and Persaud, 1989; Daganzo, 1997; Coifman, 2001). We estimated the g value again using Equation 2 utilizing data from a double loop detector station, which can provide speeds, occupancies and flow rates. This is in contrast to data provided by single loop detector stations which can only provide flow rates and occupancies and thus, does not enable us to estimate *g* directly.

There are no double loop detector stations in the Los Angeles region so measurements from a double loop detector station on I-80 near Berkeley, which were provided by Dr. Coifman, were utilized to estimate *g*. These data included 30 second measurements for June 6, 1997 for southbound and northbound directions for all lanes. We combined the 30 second occupancy, speed and flow rate values for both directions, and then estimated the average effective vehicle lengths for each 30 second observation period using (Cassidy and Coifman, 1997; Coifman, 2001),

$$L_i = \frac{Speed_i \times Occupancy_i}{Flow_i} \quad \text{(Equation 3)}$$

where L_i is the 30 second average effective vehicle length, $Speed_i$ is the space mean speed, $Occupancy_i$ is the percentage of time the detector is occupied and $Flow_i$ is the number of vehicles detected in a 30 second period.

The following two figures are the scatter plots of daily 10 minute average effective vehicle length values across all of the I-80 lanes estimated using speeds, volumes and occupancies from the I-80 double loop detector. Figures 3 and 4 include the effective vehicle lengths for five southbound lanes and four northbound lanes, respectively.

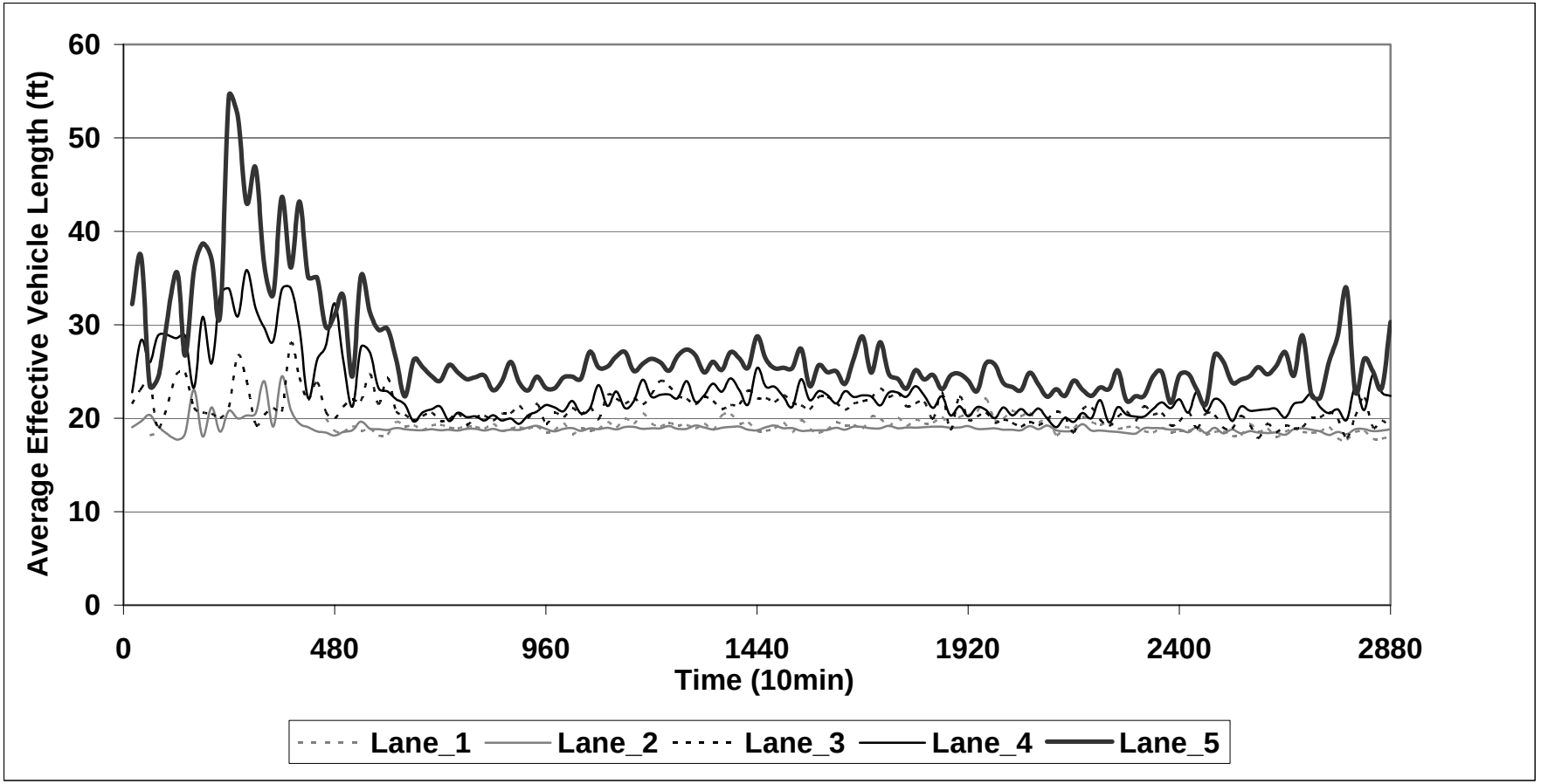

Figure 3. 10 minute Average Effective Vehicle Lengths (I-80 Southbound Direction) (The lanes are numbered in ascending order from the leftmost to the rightmost lane)

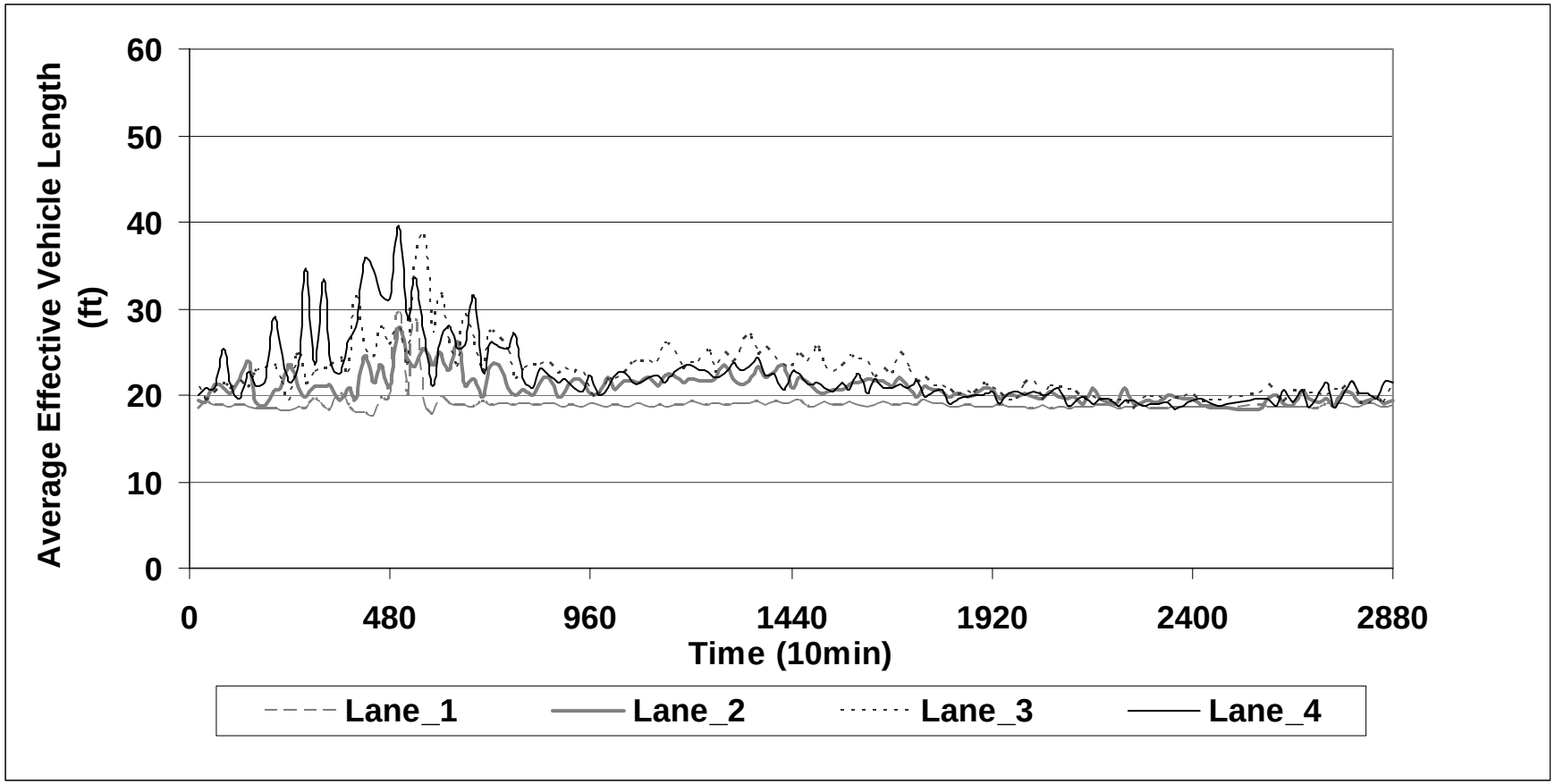

Figure 4. 10 minute Average Effective Vehicle Lengths (I-80 Northbound Direction)

In Figures 3 and 4, the horizontal axes show the 2880 cycles representing 30 second time periods in a day. The average effective vehicle lengths are estimated for each 10-minute period, so the graphs are the scatter plots of 144 10-minute average effective vehicle lengths during the 24 hours of the day for each lane in each direction. The figures indicate that high effective average vehicle lengths are observed between midnight and 6a (cycles 0 to 720) for all the lanes (observed effective average vehicle lengths are not high during nighttime for leftmost lanes (Lane_1) given that trucks are not allowed on the leftmost lane in California) indicating the presence of long heavy-duty vehicles.

Average effective vehicle lengths tend to be more similar and lower in magnitude after 6a. However, it can be seen that there were daytime 10 minute periods during which high average effective vehicle length values were observed for the rightmost lanes. However, the number of 10-minute periods with high vehicle effective length values is less in number for the daytime, especially for lanes other than the rightmost lanes when compared to those estimated for the night time. Although hourly average vehicle lengths for the total fleet are not analyzed by Gao and Niemeier (2003), the higher hourly truck fractions and average truck lengths between midnight and 6a in Los Angeles indicate higher fleet average lengths for these hours similar to the I-80 vehicle lengths for this period. Since our analyses will focus on day time (6a to 7p) running emission differences, the *g* value estimated using I-80 data should be adequate for use in Los Angeles region. We estimated average effective vehicle

lengths ($\bar{L}$) for both southbound and northbound directions using the effective length values estimated for the 30 seconds between 6a and 7p.

During the estimation of $\bar{L}$, we weighted the 30 second average lengths by the 30 second flow rates (i.e., number of vehicles observed in those 30-second periods) because an average effective vehicle length weighted by the number of vehicles is an estimator for the mean length for all the vehicles sampled in a certain period of time,

$$\bar{L} = \frac{Flow_i \times L_i}{\sum_i Flow_i} \times \frac{1}{52.8} \qquad \text{(Equation 4)}$$

where the L_i's are the estimated average 30 second effective vehicle lengths and the $Flow_i$'s are the 30 second flow rates. The 52.8 conversion factor is included because speeds were estimated in miles per hour and the occupancies provided to us were 100 times the actual occupancy values.

The calculated weighted average vehicle effective lengths for daytime are 20.84 ft for the southbound and 20.64 ft for the northbound direction. The estimated effective g value ($\bar{g}$) is derived by taking the inverse of average effective vehicle length (Hall and Persaud, 1989; Cassidy and Coifman, 1997; Coifman, 2001),

$$\bar{g} = \frac{1}{\bar{L}} \qquad \text{(Equation 5)}$$

The estimated $\bar{g}$ values are 2.53 and 2.56 for southbound and northbound directions, respectively.

From the Figures 3 and 4, it was clear that longer vehicles were more likely to be observed in the rightmost lanes, so $\bar{g}$ values were re-estimated excluding these lanes, which eliminates 13% and 21% of the total number of vehicles observed between 6a and 7p for southbound and northbound directions, respectively. With the rightmost lane traffic eliminated, we re-estimated $\bar{g}$ values of 2.60 and 2.57 for southbound and northbound directions. We also calculated $\bar{g}$ values for each lane for both of the directions (Table 1).

Table 1. Lane $\bar{g}$ values for I-80 Southbound and Northbound Directions

$\bar{g}$ **values**					
	Lane1_ $\bar{g}$	**Lane2_** $\bar{g}$	**Lane3_** $\bar{g}$	**Lane4_** $\bar{g}$	**Lane5_** $\bar{g}$
SB	2.74	2.79	2.50	2.45	2.13
NB	2.82	2.53	2.38	2.52	

In Table 1, lower $\bar{g}$ values imply higher average effective vehicle lengths which indicates the presence of longer vehicles. As we might expect, the average effective vehicle length is lower ($\bar{g}$ is higher) for the leftmost lanes (Lane 1) and higher ($\bar{g}$ is lower) for rightmost lanes (Lane 4 and 5) for southbound direction. Both the percentage of day time traffic in the northbound direction mentioned earlier and the large northbound $\bar{g}$ value in the rightmost lane (Lane 4) suggest that the actual

rightmost lane was probably not detected in that direction, and that Lane 4 is the second lane from right. For our study, we used a $\bar{g}$ value which was estimated using data by excluding the data from the rightmost lane and from the southbound direction which we believe is more reliable. (For the northbound direction, we are not entirely certain if the rightmost lane was detected or not). The $\bar{g}$ value, used in this study, for the southbound direction is 2.60 when the rightmost traffic is excluded.

Estimation of Link Flow Rate and Average Travel Speed

To estimate link flow rates and average travel speeds, detectors were matched to links specified by Caltrans District 7 and provided to us in hard copy. There were two or more detector stations on each of 318 links out of the 830 links in our data. For links where there was only one detector station, link flow rates and average travel speeds were assumed equal to the flow rates and average speeds estimated at the existing single loop detector stations. However, for links with two or more detector stations available, we assumed that hourly or 15-minute link flow rates were equal to the flow rates estimated at the detector station where the highest number of lanes was detected. If there were more than one detector station where the same highest numbers of lanes was detected, we equated the link flow rate to the flow rate estimated at the station located most upstream on the link. Here, we assumed that the number of vehicles on the segment (the section of roadway between two detector stations) that had passed the upstream detector location at the beginning of the observation period, is equal to the number of vehicles that have entered the segment but could not leave the segment

before the end of the observation period. Average link speeds were estimated assuming that all the vehicle speeds and spacings in an observation period are constant. If the average travel speed between two detectors is considered to be equal to the speed at the upstream detector location, the time-space diagram for a link can be constructed where t_0 and t_1 represent the begin/end times of the 15-minute or one hour observation periods (Figure 5).

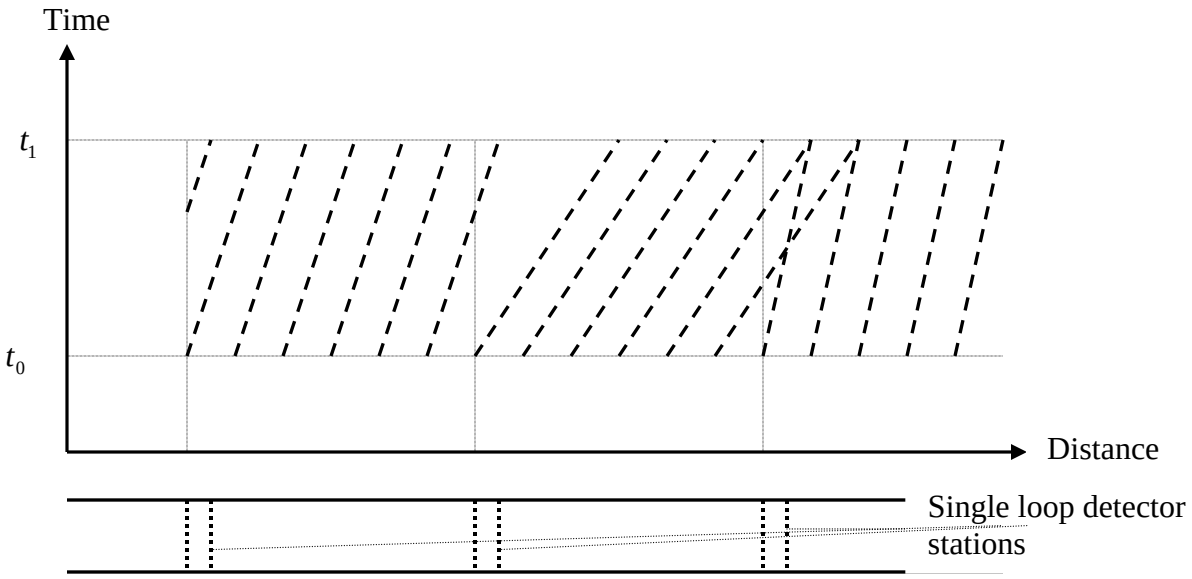

Figure 5. Time-space diagram (vehicle trajectories) on a link

It should be noted that Figure 5 shows trajectories for vehicles representing real-world conditions (i.e., not all vehicles which enter a segment by t_0 leave the segment by t_1), which was not considered for Equation 6. Unlike in our study, for shorter time intervals and longer segments, this will result in substantial errors if average travel speeds are estimated using Equation 6 presented below.

Based on these assumptions, the average travel speed, (i.e., space mean speed) is estimated as (Daganzo, 1997; Dowling, Kittelson et al., 1997);

$$\bar{V} = \frac{1}{\frac{1}{\sum_{i=1}^{m} N_i}\left(\sum_{i=1}^{m} \frac{N_i}{V_i}\right)} \qquad \text{(Equation 6)}$$

where $\bar{V}$ is the average travel speed, V_i's are the speeds of individual vehicles, which are assumed to be equal to the average travel speed estimated at the loop detector station for an observation period, N_i's are the number of vehicles observed, (i.e, flow rate for that observation period), and *m* is the number of detectors on a link.

Estimating the Differences in Running Stabilized Emissions

To analyze the differences in estimated hourly link running stabilized emissions when the hourly emissions are estimated using one hour link average speeds and when hourly emissions are estimated by summing 15-minute emissions estimated using 15-minute speeds, running stabilized emissions for carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2), total organic gasses (TOG) and particulate matter (PM_x) were calculated using a modified version of UCDrive (Niemeier, Zheng et al., 2004). The gridded emissions inventory model was modified in several ways for our analyses.

First, the modules in the model used to estimate emissions other than the running stabilized emissions were disabled. Second, the model module that allocates link level running stabilized emissions to air quality grids was disabled. UCDrive provides running stabilized emission outputs by vehicle class and technology groups based on

the regional vehicle class/technology group fractions provided as input to the model (Niemeier, Zheng et al., 2004). Since we are interested in exploring the differences in total fleet running stabilized emissions estimated for individual links, the program was also modified to estimate total fleet link running stabilized emissions; that is, link emissions estimated by vehicle class/technology groups were summed in the model to estimate link emissions for the total fleet.

A feedback loop was also incorporated so the model estimated hourly or 15-minute total running stabilized emissions for an entire day for each link. For example, a daily emissions model output file produced using 15-minute flow rate and average travel speed file will have 96 rows of data for each link. Each row in these daily files includes the link ID, 15-minute flow rate and total running stabilized emissions values for CO, NO_x, CO_2, TOG, and PM_x. On other hand, if emissions model output file is based on hourly input data file, the output will consist of 24 rows of hourly flow rate and total running stabilized emissions values for CO, NO_x, CO_2, TOG, and PM_x for each link .

Analyzing the effects of estimating emissions using average hourly speeds versus using four sets of 15-minute speeds is possible only if all other factors except speed variability are held constant. The modifications to UCDrive enabled us to estimate hourly link running stabilized emissions by summing the emissions for 15-minute periods (i.e., using 15-minute average speeds) and by using one hour link average speeds for all links in a region. Given that regional temperature and humidity defaults and hourly flow rates are constant for the same hour of the same day, any difference

between hourly running stabilized emissions estimated using one hour and 15-minute average speeds will result from increasing the resolution of the average speed from one hour to 15 minutes (Table 2).

Table 2. Differences in Running Stabilized Emissions

	15 min Flow (veh)	**15 min Speed (mph)**	**Total Running Stabilized Emissions (g)**	**1 hr Flow (veh)**	**1 hr Speed (mph)**	**Total Running Stabilized Emissions (g)**
	$N_{15\,min(1)}$	$S_{15\,min(1)}$	$R_{15\,min(1)}$	N_{1hr}	S_{1hr}	R_{1hr}
	$N_{15\,min(2)}$	$S_{15\,min(2)}$	$R_{15\,min(2)}$			
	$N_{15\,min(3)}$	$S_{15\,min(3)}$	$R_{15\,min(3)}$			
	$N_{15\,min(4)}$	$S_{15\,min(4)}$	$R_{15\,min(4)}$			
TOTAL	$\mathbf{N}_{1hr} = \sum_{i=1}^{4} N_{15min(i}$		$\mathbf{R}_{1hr}^{15min} = \sum_{i=1}^{4} R_{15min(i)}$	$\mathbf{N}_{1hr}$		$\mathbf{R}_{1hr}$
Difference in running stabilized emissions (g)=$\mathbf{R}_{1hr}$ - $\mathbf{R}_{1hr}^{15min}$						

The difference in hourly link running stabilized emissions is calculated by first estimating the 15-minute emissions and then summing each of the 15-minute estimates for each hour and link (Table 2). This calculation was performed for each day when emissions could be estimated depending on the availability of link flow rate and average speed input files produced earlier. The differences between hourly running stabilized emissions estimated with 15-minute and the one hour flow rates and average speeds (i.e., R_{1hr}^{15min} and R_{1hr}) were then calculated.

We examined differences in estimated hourly running stabilized emissions for the hourly periods from 6a through 7p for each day. Days of the week were labeled 1 to 7

representing days from Monday to Sunday and hourly periods of the day were labeled using numbers 1 to 13 representing each hour from 6a to 7p.

Earlier we noted that when volume and occupancy data files for a given day were available but the data were missing for all the lanes of all the detectors of a region for 30 second period(s), the data of the hourly periods which includes those 30 second period(s) were discarded. However, there are cases when data for all the lanes in the region are not missing, but data for all the lanes of a given link are missing for a given hour. Because of the large size of the raw data, it is a very intensive job to detect those links and the detectors located on them. If the data are missing for all the 30 second periods of an hour for all the lanes of a given detector station, all the 30 second data for that hour are replaced with the constant volume and occupancy values.

As a result, for that hourly period, the four 15-minute average speed values become equal to the one hour speed value. When the 15-minute and one hour average speeds are equal, the emissions estimated by summing up 15-minute emissions and by using hourly data become equal resulting in zero differences in hourly running stabilized emissions. Hourly running stabilized emissions differences can also have zero value when 15-minute speeds are constant in one hour by coincidence. However, if differences in hourly running stabilized emissions were zero because of missing data, hourly average speeds were 57.7 mph and hourly flow rates were multiples of 1800 vph depending on the number of lanes resulting from the replacement flow rate and occupancy values we utilized earlier. Therefore, we could distinguish actual zero

emissions differences from zero differences resulting from missing data and discard the ones resulting from missing data.

Statistical Analysis

The differences in running stabilized emissions resulting from increasing the time averaging resolution of link speeds were analyzed using repeated measures analysis of variance (ANOVA) (Neter, Wasserman et al., 1990; Girden, 1992; Dean and Voss, 1999). The dependent variables are the differences in running stabilized emissions calculated using the one hour and the comparable totaled four 15-minute speeds. The treatment factors are day of week and time of day. In the analysis, we test for the effects of day of week and time of day on differences in running stabilized emissions and we test for a significant interaction effect between the two treatment factors for differences in running stabilized emissions.

Four contrasts were also included in the ANOVA model to analyze: 1) if the weekend effect was significantly different from weekday effect (i.e., if the mean difference in running stabilized emissions for weekends is significantly different from the mean difference for weekdays), 2) if the peak hour effect was significantly different from the daytime off-peak hour effect (i.e, if the mean difference for the combination of morning peak and evening peak hours is significantly different from the mean difference for the daytime off-peak hours), 3) if the morning peak hours effect was significantly different from evening peak hour effect (i.e., if the mean difference for the morning peak hours is significantly different from the mean difference for the evening peak hours), and 4) if the combined effect of Monday and Friday is

significantly different from the combined effect of Tuesday, Wednesday and Thursday (i.e., if the mean difference for the combination of Monday and Friday is significantly different from the mean difference for the combination of Tuesday, Wednesday and Thursday).

Given that the contrasts analyze the significance of the difference across treatment levels of the differences in running stabilized emissions when 15-minute link average speeds are used in contrast to hourly link average speeds, they explore the interaction between the average speed resolution effect (i.e., the effect of using 15-minute speeds vs. one hour average speeds to estimate hourly link running stabilized emissions) and the effects created by the contrasts (Neter, Wasserman et al., 1990).

These contrasts are important to test for several reasons. First, it has been shown that pollutant concentrations differ between weekends and weekdays (Marr and Harley, 2002). However, to date, air quality research has focused on the daily distribution of volumes to analyze how traffic patterns affect the emissions for a given time of day or across days (Cardelino, 1998). Recent studies focusing on the weekday-weekend differences in pollutants, specifically ozone, rely on variability in daily total vehicle counts or vehicle counts by vehicle type as travel activity to characterize the differences in travel activity across the days of the week (Austin, 2003; Chinkin, Coe et al., 2003; Fujita, Campbell et al., 2003)

Second, efforts to better estimate traffic patterns by time of day and day of week for emissions inventories have focused on improving the volume estimates (Niemeier, Lin et al., 1999; Hicks and Niemeier, 2001), not assessing the underlying variability

associated with those estimates. Understanding variability in volumes by time of day or day of week is very important, but insufficient to fully analyze the relationship between traffic patterns and estimated emissions. When volumes are known, average speeds can also be estimated (TRB, 1998), however, depending on the magnitudes of the volumes, traffic flow conditions, and therefore speed variability within a given hour will differ. For example, when volumes are high, congestion occurs and during congested conditions speeds are more variable (e.g., Figure 2).

We constructed the levels of the contrasts to combine the effects of time of day (i.e., specific hourly periods) and day of week (i.e., specific days of the week) with similar traffic conditions. These contrasts allow us to analyze the effects of different speed variability patterns on estimated differences in running stabilized emissions. That is, they will allow us to analyze if traffic conditions which are known to have different flow conditions also have different speed variability patterns (in this study different magnitudes and different combinations of 15-minute average link speeds for a given hourly period) which will result in significantly different differences in running stabilized emissions. Research suggests that the flow rates differ across the levels of these contrasts (Cardelino, 1998; Hicks, Korve et al., 1999; Niemeier, Lin et al., 1999; Hicks and Niemeier, 2001; USEPA, 2001)

In addition to these three contrasts, we also produced a Monday-Friday vs. Tuesday-Wednesday-Thursday contrast. Research suggests that drivers do not drive similarly even under the same traffic conditions (Holmen and Niemeier, 1998). In creating this contrast, we are hypothesizing that driving variability will be more similar on

Monday and Friday and Tuesday through Thursday, but different between the two groups of days. Our purpose here is to test if the differences in the 15-minute speed variability patterns between these two sets of days is enough to result in significantly different differences in running stabilized emissions.

We use a repeated measures ANOVA model with replicates because the day of week and time of day effects are observed for each observation unit (links) and each combination of the levels of day of week and time of day are observed more than once on the same observation unit.

In experimental repeated measures studies, the experimental unit is considered a blocking factor with each unit as levels of the blocking factor given that outcomes are likely to be similar for each experimental unit and different across different experimental units (Neter, Wasserman et al., 1990). In our observational study, the link is a blocking factor because the outcomes, (i.e., differences in running stabilized emissions), are likely to be more similar within observation units (i.e., a link) and more different across observation units. For our study, recall that the differences in running emissions result from using one hour and 15 minutes average speed resolutions for estimation. In addition to the variability of 15-minute speeds around the hourly average speed for a given one hour period, the link length, hourly link flow rate, and hourly running emission factor will affect the magnitude of the hourly difference in running stabilized emissions. Given that the link lengths are constant and observed flow rates are similar for a given link, and also these values are likely to

be different across links, the differences in running stabilized emissions are likely to be more similar within each link and more different across links.

The ANOVA model can be specified as,

$$Y_{ijkl} = \mu + \rho_i + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{ijkl} \qquad i = 1,\ldots, N,\ j = 1,\ldots, 7,$$

$$k=1,\ldots, 13,\quad l=1,\ldots, M \qquad \text{(Equation 7)}$$

where Y_{ijkl} is the difference in estimated CO, NO_x, CO_2, TOG, or PM_x running stabilized emissions for the i^{th} link, j^{th} day of the week and k^{th} hour of the day, μ is the overall mean, ρ_i is the blocking factor with each link *i* as its level (a random effect) , where *N* is the number of links in each region (i.e., number of links in North LA, South LA or Orange County) which differs across regions, α_j is the day of week factor with 7 levels (*j* = day of the week) (a fixed effect), β_k is the time of day factor with 13 levels (6a-7p) (*k* = time of the day) (a fixed effect), $(\alpha\beta)_{jk}$ is the interaction factor (a fixed effect) between the day of week and time of day, ε_{ijkl} is the random error, *l* identifies each hourly difference in running stabilized emissions, and *M* is the total number of differences in running stabilized emissions analyzed for each region which differs across regions. The number of observations differs for each link.

The day of week and time of day are fixed effects since we have specifically chosen the levels of these effects (i.e., Monday, 8a, etc.) to examine their effects on differences in running stabilized emissions. Since we are concerned that levels of the fixed effects might have different effects for each link because of changing commute

direction by time of day, changing levels of congestion by time of day and day of week, etc, we use the link as the random blocking factor to control variability.

RESULTS

Table 3 presents the model results for the mean differences in running stabilized emissions for CO, NO_x, CO_2, TOG, and PM_x for North LA, South LA and Orange County. The blocking factor (i.e., link), treatment factors (i.e., day of week and time of day), the interaction term (i.e., day of week $\times$ time of day), and the contrasts (i.e., peak hours vs., off-peak hours, morning peak hours vs. evening peak hours, weekend vs. weekdays, and Monday-Friday vs. Tuesday-Wednesday-Thursday) were considered statistically significant if the p-value for the F-statistic is less than or equal to 0.05 (i.e., significant with 95% confidence level). If a treatment factor or a contrast was statistically significant, the significance was denoted by "+" and if it was not significant there is a 'NS'.

Table 3. ANOVA Model Results for Differences in Running Stabilized Emissions[1]

North LA			Blocking Factor	Treatment Factors		Interaction	Contrasts				
Pollutant	**F**	**P value**	**Link**	**Day**	**Time**	**DayxTime**	**Pk vs. Offpk**	**AM Pk vs. PM Pk**	**Wkend vs. Wkday**	**M-F vs. T-W-Th**	**Number of Observations**
CO	43.98	0.0001	+	+	+	+	+	+	+	NS	208208
CO_2	38.03	0.0001	+	+	+	+	+	NS	+	NS	208208
NO_x	57.75	0.0001	+	+	+	+	+	+	+	+	208208
PM_x	19.21	0.0001	+	+	+	+	+	+	+	+	208208
TOG	28.94	0.0001	+	+	+	+	+	+	+	NS	208208
South LA											
CO	37.79	0.0001	+	+	+	+	+	+	+	+	312420
CO_2	33.72	0.0001	+	+	+	+	+	+	+	+	312420
NO_x	56.65	0.0001	+	+	+	+	+	+	+	+	312420
PM_x	11.99	0.0001	+	+	+	+	+	+	+	+	312420
TOG	15.41	0.0001	+	+	+	+	+	+	+	+	312420
Orange County											
CO	29.78	0.0001	+	+	+	+	+	+	+	NS	104985
CO_2	24.44	0.0001	+	+	+	+	+	+	+	+	104985
NO_x	39.49	0.0001	+	+	+	+	+	+	+	+	104985
PM_x	22.96	0.0001	+	+	+	+	+	+	+	+	104985
TOG	20.08	0.0001	+	+	+	+	+	+	+	NS	104985

[1] '+' denotes statistical significance and 'NS' denotes statistical insignificance at 95% confidence level.

The R^2 values for the 15 ANOVA models (models for 5 pollutants $\times$ 3 regions) vary between 0.02 and 0.1 indicating that only 2 to 10 % of the variability in the data can be explained by the models. Although the R^2 values for the ANOVA are very low, the effects of the time of day, day of week and the interaction term are significant for all the 15 ANOVA models. The contrasts are also statistically significant most of the time. The treatment factors, interaction term and the contrasts are significant only because of the high number of observations used in each model. Therefore, given that the models explain very low percentages of the variability of the data, it is not necessarily meaningful to interpret the significance and/or insignificance of these factors. However, it is important to discuss why the R^2 values for the 15 ANOVA models are low.

Recall that we used links as blocking factors in our repeated measure ANOVA model to control the variability of outcomes (i.e., differences in running stabilized emissions). We used links as blocking factors because for a given link, length is constant and flow rates are similar, which will result in similar values of differences in running stabilized emissions. The low R^2 values indicate that controlling variability with blocking is not adequate because not only the outcomes are different across links, but also levels of the treatment factors, interaction term and contrasts have different effects on the outcomes across links. For example, the speed variability on Monday at 8 AM might be adequate to result in significant differences in running stabilized emissions for a link, however, speed variability on another link on Monday at 8 AM might not result in significant differences in running stabilized emissions.

There are two ways to improve the models. The first is by making the levels of the day of week and time of day factors independent (i.e., making each hour and each day an individual treatment factor) (Neter, Wasserman et al., 1990). The second approach is to group the data, which will result in more homogeneous data sets for each level of the treatment (i.e., data sets including similar differences for the same time of the day and day of the week).

We applied the second method, grouping the data into more homogeneous sets. The best way to produce homogeneous data sets, which include similar values of differences in running stabilized emissions for a given time of the day and day of the week, is to group the data by link. Since the flow rates, and therefore, the traffic flow conditions (as well as the speed variability patterns) are more likely to be similar for a given link at an hour and a day (Cardelino, 1998; Hicks, Korve et al., 1999), we expect the differences in running stabilized emissions to be more similar at the same hour and day for an individual link. Grouping the data by link also enables us to identify the percentages of links when the treatment factors and contrasts are statistically significant (e.g., percentage of links in the region when day of the week has a statistically significant effect on the differences in running stabilized emissions).

When we re-specified the ANOVA model to apply to each link, the model specified by Equation 7 was modified. In Equation 7, the links were levels of the random blocking factor. For a single link data set, the random blocking factor is not needed and the model becomes a two factor repeated measures fixed effects ANOVA model with an interaction term,

$$Y_{jkl} = \mu + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{jkl} \qquad j = 1, \ldots, 7 \quad k = 1, \ldots, 13,$$

$$l = 1, \ldots, N \qquad \text{(Equation 8)}$$

where Y_{jkl} is the difference in CO, NO_x, CO_2, TOG, or PM_x running stabilized emissions for the j^{th} day and k^{th} hour, μ is the overall mean, α_j is the day of week effect with 7 levels (fixed factor), β_k is the time of day effect with 13 levels (6a-7p) (fixed factor), $(\alpha\beta)_{jk}$ is the interaction term (fixed factor), l goes from 1 to N, a where N is the number of differences in hourly running stabilized emissions for each link, which varies for each link, and ε_{jkl} is the random error term.

Some of the treatment factor level combinations were not available for 1 link in North LA, 3 links in South LA and 6 links in Orange County out of a total of 830 links in the region. Therefore, the ANOVA model results for each link were explored for each pollutant for 820 links. Table 4 includes the total numbers of links when treatment factors, interaction term and the contrasts have significant effects ($p<0.05$) on differences in running stabilized emissions for CO, NO_x, CO_2, TOG, and PM_x.

Table 4. Summary Results for Link Level ANOVA

	Number (and percentage) of links when significant (p<0.05)						
	Treatment Factors		Interaction	Contrasts			
Pollutant	**Day of week**	**Time of day**	**DayxTime**	**Wkend vs. Wkday**	**Pk vs. Offpk**	**AM Pk vs. PM Pk**	**M-F vs. T-W-Th**
CO	546 (67%)	508(62%)	228 (28%)	325(40%)	376(46%)	484(59%)	288(35%)
CO_2	521 (64%)	509(62%)	244(30%)	321(39%)	288(35%)	485(59%)	299(37%)
NO_x	607(74%)	536(65%)	268(33%)	366(45%)	476(58%)	540(66%)	349(43%)
PM_x	492(60%)	455(55%)	229(28%)	339(41%)	356(43%)	480(59%)	290(35%)
TOG	481(59%)	503(61%)	232(28%)	310(38%)	370(45%)	571(70%)	261(32%)

Table 4 shows that both day of week and time of day effects are statistically significant for more than half of the links (ranging from 59% to 74%) for the differences in the five types of pollutants. The interaction term is statistically significant for about one third (ranging from 28% to 33%) of the links, whereas weekends and weekdays have significantly different effects for 38% to 45% of the links. Similarly, the peak hour effect is significantly different from the off-peak hours effect for 35% to 58%, the morning peak effect is significantly different from the evening peak effect for 59% to 70%, and the Monday-Friday effect is significantly different from the Tuesday-Wednesday-Thursday effect for 32% to 43% of the links for the five pollutants.

The percentages of links for which treatment factors and contrasts are statistically significant vary for the five types of emissions (Table 4). Treatment factors and contrasts are most often statistically significant for the differences in NO_x emissions, except for the morning peak vs. evening peak contrast for which the percentage for

NO_x is the second highest after the highest percentage for TOG. Among the percentages of statistical significant links for CO, CO_2, TOG, and CO_2, the percentages for: a) CO and CO_2 are somewhat higher for the day of week, b) CO, CO_2 and PM_x are somewhat higher for the time of day, c) CO, PM_x and TOG are somewhat higher for the peak vs. off-peak contrast, d) CO, CO_2 and PM_x are higher for the Monday-Friday vs. Tuesday-Thursday-Friday contrast. There are not any major differences across the percentages of statistically significant links for the mean differences in CO, CO_2, TOG, and CO_2 emissions for the interaction term and the weekend vs. weekday contrast.

In order to better understand the trends in the statistical significance of treatment factors, Table 5 demonstrates the percentages of links in the region when: a) only the day of week factor is statistically significant, b) only the time of day factor is statistically significant, c) both day of week and time of day factors are statistically significant, and d) both day of week and time of day factors are statistically insignificant.

Table 5. Summary of Results for Day of Week and Time of Day Factors

Number (and Percentage) of Links when Significant ($p<0.05$)				
Pollutant	**Only Day of Week Sig.**	**Only Time of Day Sig.**	**Both Sig.**	**Neither Sig.**
CO	197(24%)	173(21%)	344(42%)	106(13%)
CO_2	195(24%)	187(23%)	322(39%)	116(14%)
NO_x	221(27%)	149(18%)	385(47%)	65(8%)
PM_x	171(21%)	193(24%)	309(38%)	147(17%)
TOG	186(23%)	151(18%)	300(37%)	183(22%)

The percentage of links when both day of week and time of day and day of week are statistically significant is the highest (and both statistically insignificant is the lowest) for differences in NO_x emissions. In other words, differences in hourly link NO_x emissions are significantly different across the days of the week and hourly periods of the day for the highest percentage of links in the region. This suggests that differences in NO_x emissions resulting from using 15-minute average speeds in contrast to hourly average speeds show the highest variability among differences estimated for all five types of emissions.

On the other hand, the differences in TOG and PM_x emissions are not as variable as the differences in other types of emissions. This lower variability for the differences in TOG and PM_x emissions result in lower percentages of links when differences are significantly different for different days of the week and hourly periods of the day.

Research shows that speed variability is likely to increase with congestion (i.e., volume to capacity ratio (V/C)) (e.g.,(Daganzo, 1997). Figures 1 and 2 (from Hall, Hurdle and Banks, 1992 and Online Access: http://pems.eecs.berkeley.edu)) also demonstrate that the speeds for a given flow rate, thus for a given V/C, are variable and this variability increases for in-queue and queue discharge traffic flow conditions. Thus, next, we examine the relationship of congestion level to the differences in running stabilized emissions. Our purpose here is to examine if the increase in the variability of average speeds for highly congested traffic flow conditions results in higher differences in running stabilized emissions. Figures 6 through 8 demonstrate

the 5^{th}, 50^{th} (i.e., median), 95^{th} percentile values for the differences in NO_x, TOG and CO_2 emissions with respect to V/C. We focus our analyses on these three types of emissions given that NO_x and TOG are ozone precursors, and also ozone and CO_2 are the major air pollutants in urban areas (Seinfeld and Pandis, 1998).

It should be noted that while performing this analysis, we did not distinguish the analysis for different periods (e.g., for peak and off-peak periods) or days (e.g., for weekdays or weekends). This is because our purpose is to relate congestion level to percentage differences in emissions and V/C is independent from hourly periods of the day and days of the week. That is, a given V/C value describes the same congestion level independent from the time period or day for which it is estimated. Moreover, using percentage differences in running stabilized emissions for all the hourly periods available to us enables us to use the highest possible number of percentage difference values for each V/C value we present in Figures 6 through 8.

Figures 6 through 8 show that, for NO_x, TOG and CO_2, using 15-minute link average speeds in contrast to commonly-used hourly link average speeds yields at most ~ 2.5% to ~ 3% higher magnitude running stabilized emissions when V/C is 1 (i.e., when the links are operating at capacity). On the other hand, the estimated running stabilized NO_x, TOG and CO_2 emissions decrease at least by ~ 0.5% to 1.5% when 15-minute link average speeds are used in contrast to hourly link average speeds when V/C is 0.3 (i.e., when there is free-flow traffic), 5% of the time.

The 50th percentile (i.e., median) values for the percentage differences, which are indicators of central tendency, are around zero for the three types of emissions (Figures 6 through 8). That is, for different values of V/C (i.e., levels of congestion) our approach of using 15-minute link average speeds yields higher magnitude running stabilized emissions, 50% of the time and lower magnitude emissions 50% of the time. Thus, compared to the old method, the new approach leads to higher estimates of emissions about as often as it leads to lower estimates. However, the distribution of the relative magnitudes of the differences is clearly not symmetric: when the new estimate is higher, it tends to be higher by a greater percentage than when it is lower. Thus, the overall effect of the new method is to produce a higher estimate of emissions.

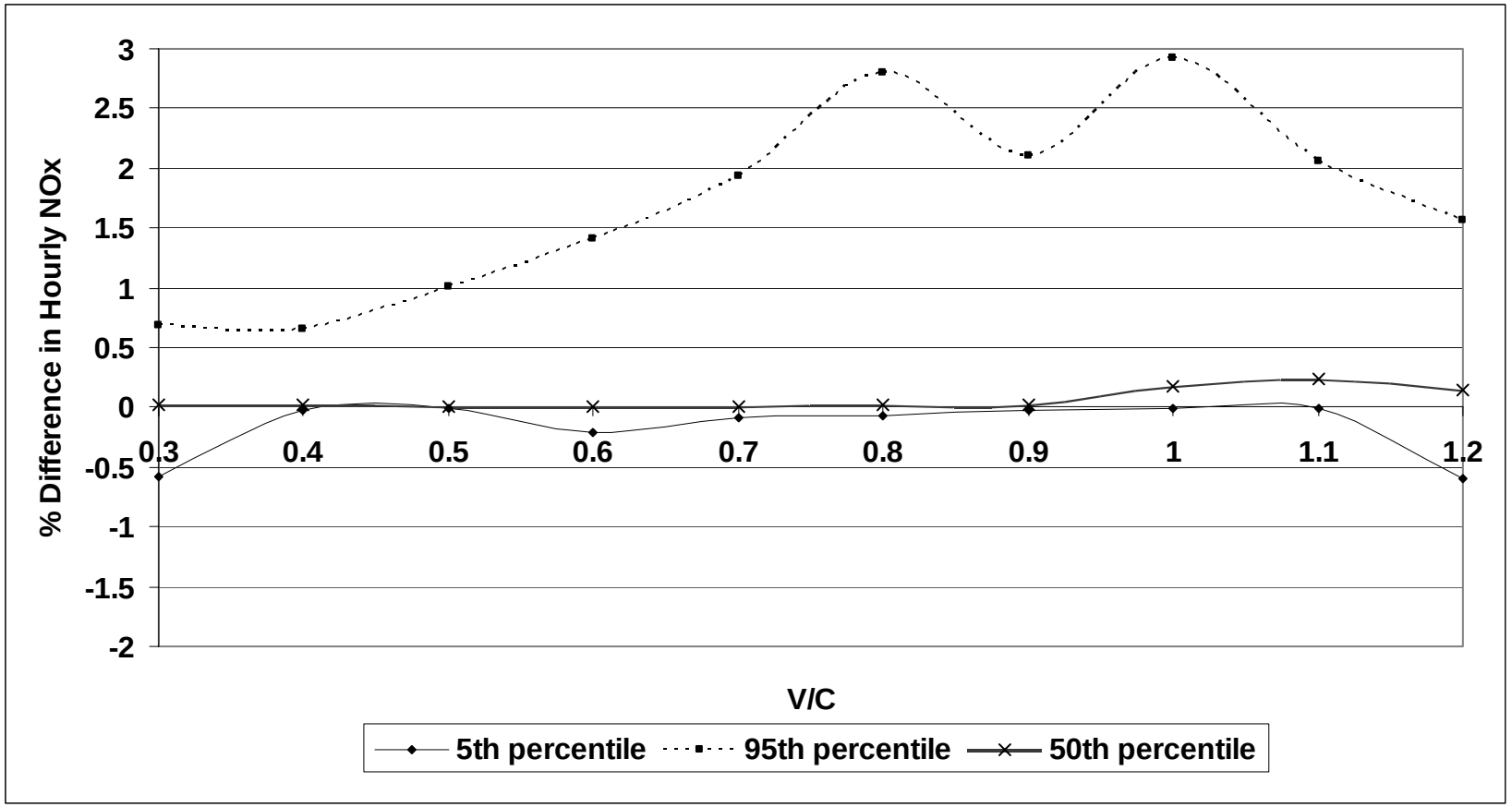

Figure 6. Differences in Hourly NO_x vs. V/C

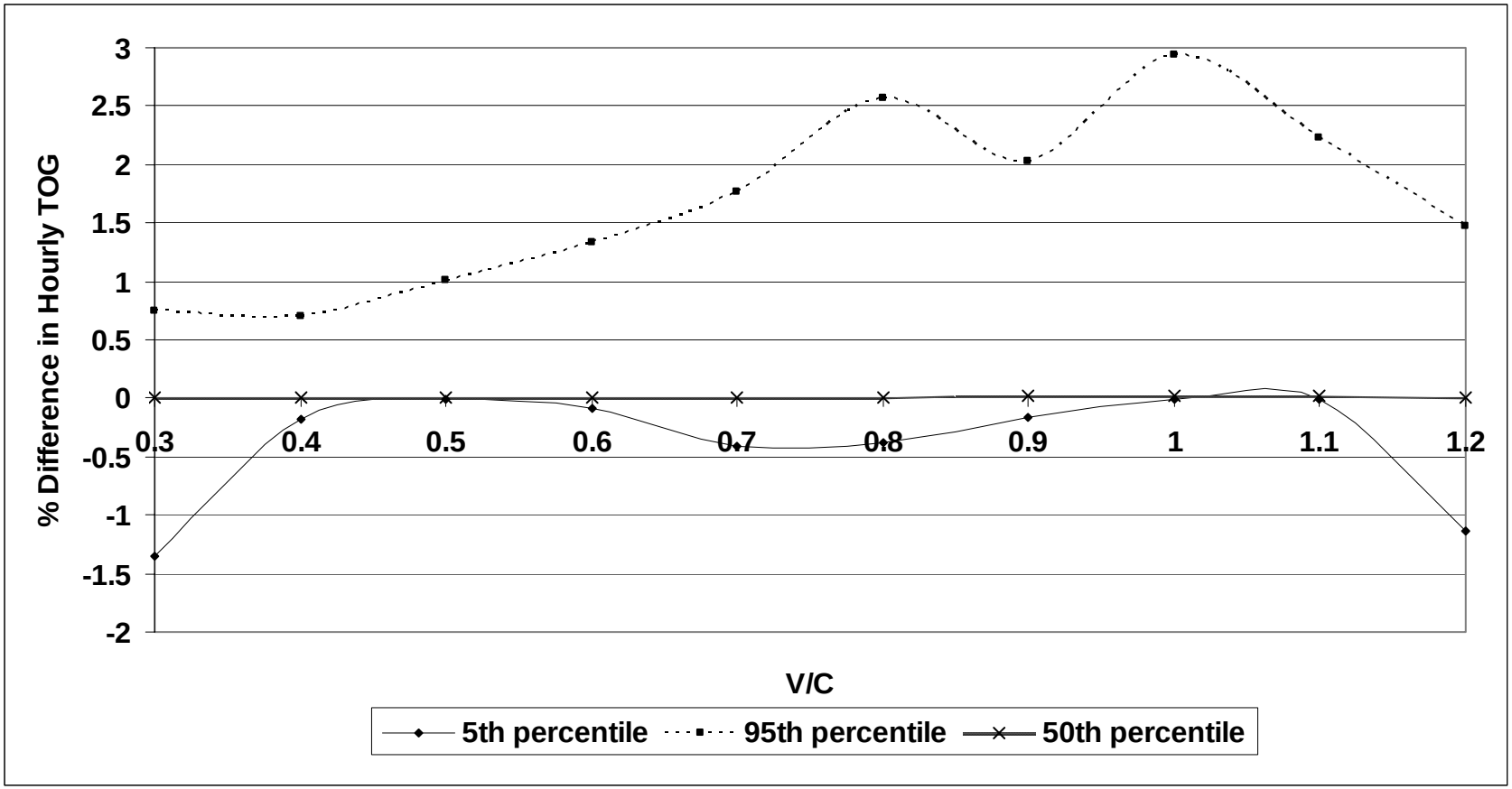

Figure 7. Differences in Hourly TOG vs. V/C

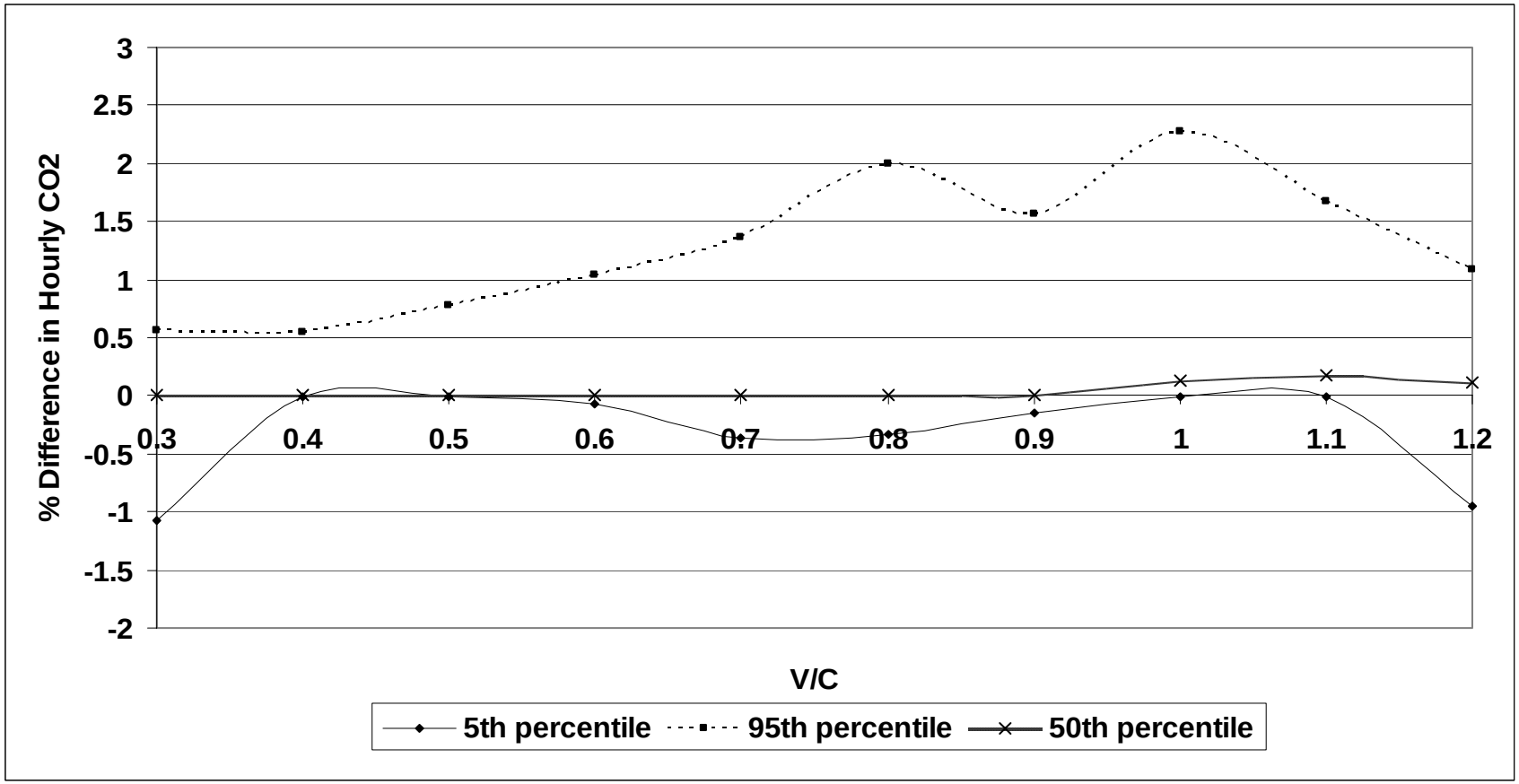

Figure 8. Differences in Hourly CO_2 vs. V/C

The percentage differences in hourly NO_x, TOG and CO_2 emissions are only loosely correlated to the V/C (i.e., the level of congestion) on freeway links in Los Angeles. The one-tailed Pearson correlation coefficients are estimated as 0.136, 0.139 and 0.145 (with 0.01 significance level) for the bivariate correlations between V/C and the percentage differences in hourly NO_x, TOG and CO_2, respectively. This indicates that 15-minute speed variability patterns are not sufficiently different for congested or uncongested traffic conditions (i.e., for different V/C values) to result in different magnitudes of hourly differences in running stabilized emissions. In other words, speed variability during uncongested traffic flow conditions results in differences in running stabilized emissions not that different from the differences resulting from speed variability during congested traffic conditions on the freeway links.

Given that speed variability under different traffic flow conditions results in similar differences in running stabilized emissions, just the knowledge of the traffic conditions on individual freeway links is not sufficient to identify locations where 15-minute speed variability results in significantly different running stabilized emissions. Based on Table 5, we graphed the locations where only day of week is significant (i.e., differences in emissions are significantly different across the days of the week), only time of day is significant (i.e., differences in emissions are significantly different across hourly periods of the day), where both factors are significant and where neither of the factors are significant for differences in hourly NO_x emissions (Figure 9). We focused on the

differences in hourly NO_x emissions because the treatment factors are significant for a higher percentage of links for differences in NO_x emissions (Tables 4 and 5).

We then selected sections to demonstrate sections where the time of day and day of week are significant (Sections 2, 3 and 4), and where neither of the factors are significant (Sections 1 and 5) for most of the locations in these sections (Figures 10 and 11). Figure 10 shows Section 1 on Interstate 5 in Santa Clarita and another section, Section 5, composed of two links on the intersection of State Roads 60 and 57 in Pomona. For these sections, neither of the factors are significant for most of the locations, indicating that 15-minute average speed variability does not result in significantly different differences in NO_x emissions across the days of the week and hourly periods of the day. These regions are rural residential areas where there are lower numbers of intersections, merges, diverges, signal controlled intersections and therefore, interruptions to the traffic flow, resulting in similar 15-minute average speed variability patterns most of the time.

Day of week or both day of week and time of day are statistically significant for all the locations on Sections 2, 3 and 4 which are presented in Figure 11. Section 2 constitutes the part of Interstate 10 connecting East Los Angeles to Santa Monica, Section 3 constitutes the part of Interstate 110 between Interstate 10 and Interstate 105, and Section 4 constitutes the part of Interstate 405 between Interstate 105 and Interstate 110. These sections are located in central Los Angeles where there are high numbers of intersections, merges, diverges, signal controlled intersections, and therefore, higher differences in 15-

minute speed variability patterns, which produces significantly different differences in NO_x for different time periods.

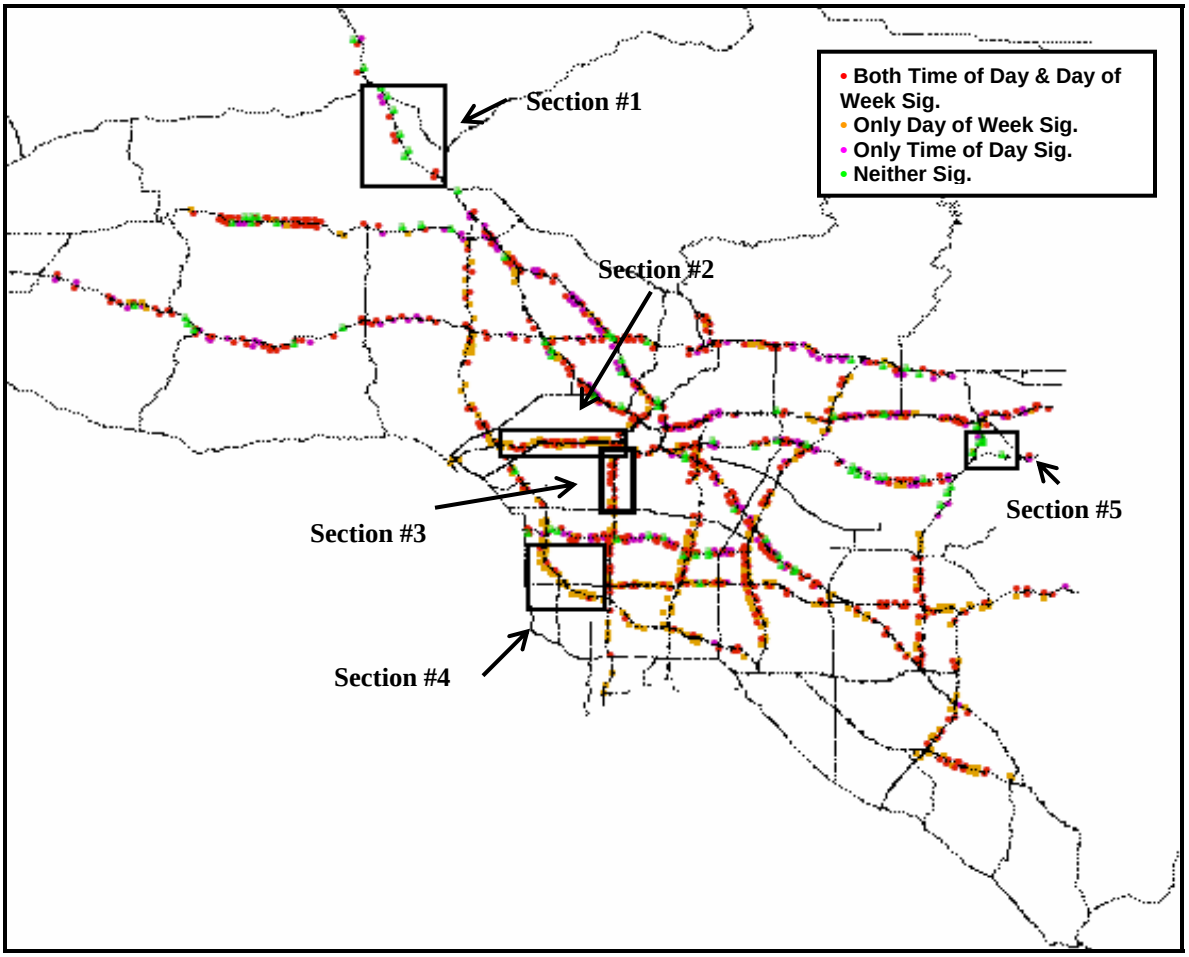

Figure 9. Locations where 1) Both Time of Day and Day of Week, 2) Only Time of Day, 3) Only Day of Week , and 4) Neither of the Factors are Significant in Los Angeles, Summer 1997

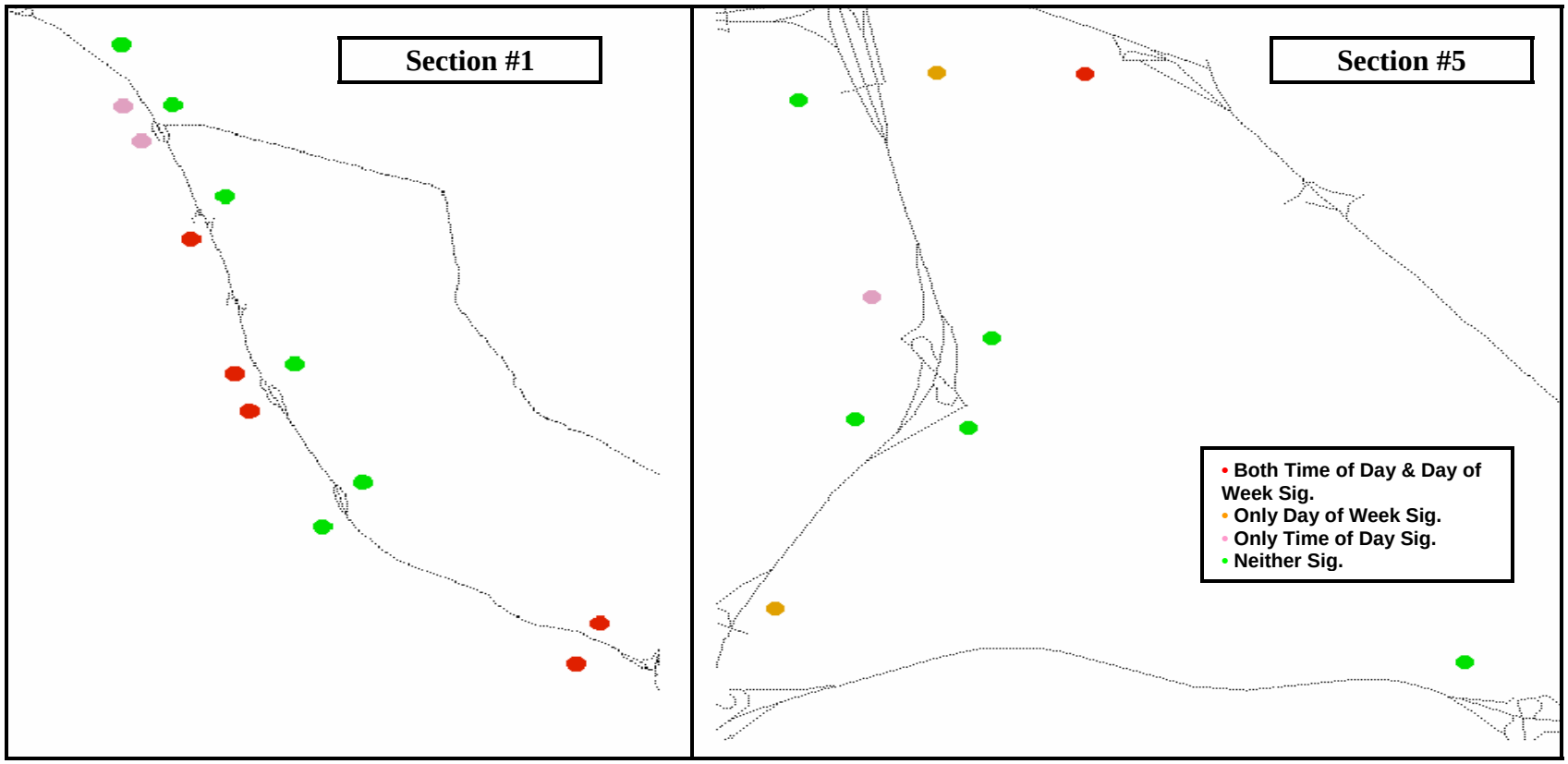

Figure 10. Sections 1 and 5 – Sections where Neither of the Factors are Significant at Most of the Locations

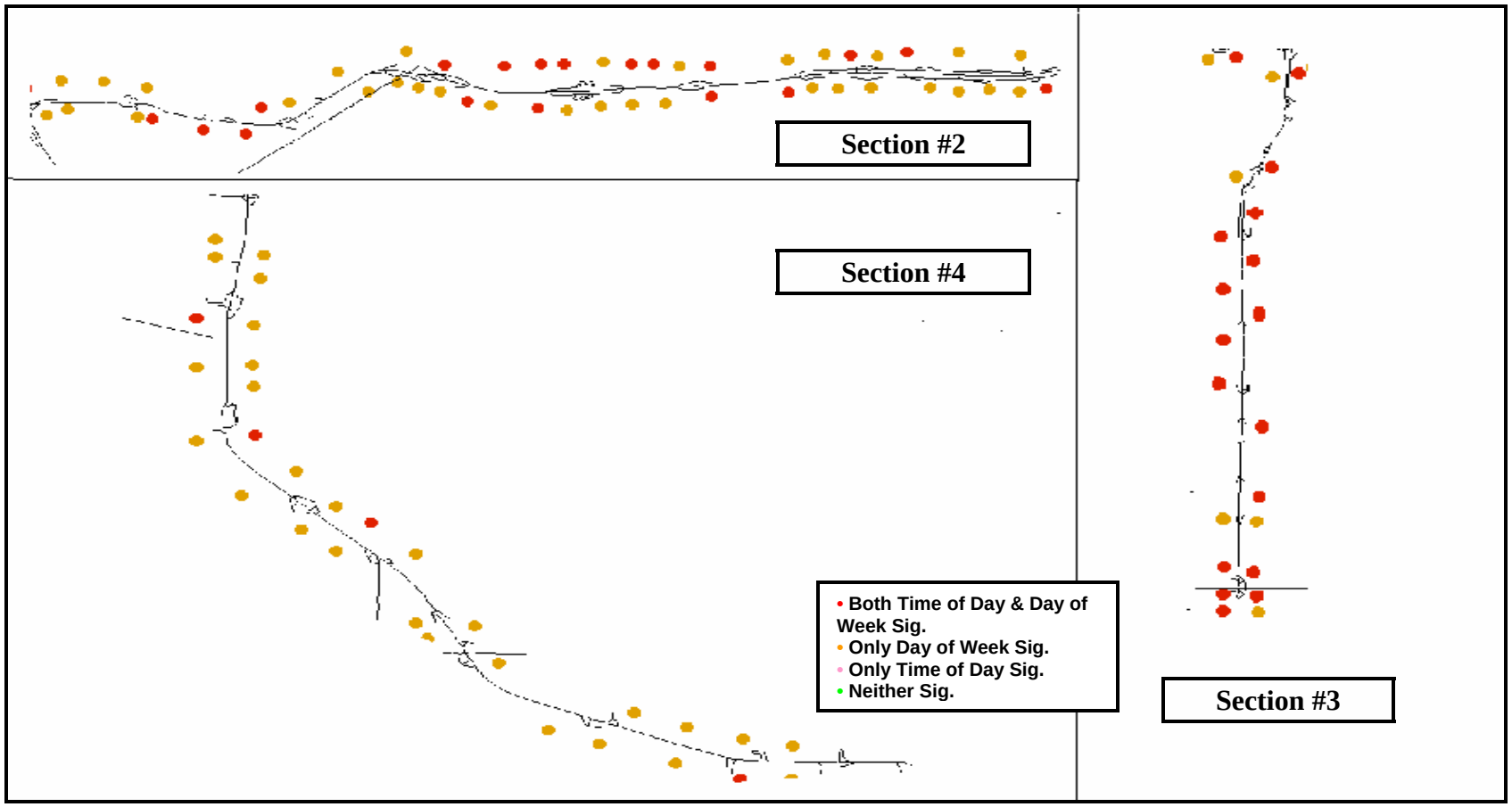

Figure 11. Sections 2, 3 and 4 – Sections where Day of Week or both Time of Day and Day of Week are Significant at All of the Locations

Summary and Conclusions

Regional mobile emission inventory models utilize average link speeds for an hour or longer periods for estimating link running stabilized emissions. This study shows that using 15-minute average link speeds results in different magnitudes of hourly link running stabilized emissions, compared to the frequently used hourly link average speeds. Moreover, day of the week, hourly period of the day and combinations of different days and hourly periods have significantly different effects on the mean differences in running stabilized emissions. That is, differences in running stabilized emissions are significantly different across the days of the week and hourly periods we focused on, for one-third to more than two-thirds of the links.

In this study, we found that the level of congestion is loosely correlated to the differences in running stabilized emissions and also that the percentage of differences in running stabilized emissions is usually positive but small. This shows that temporal speed variability during congested traffic conditions has similar effects on the differences in running stabilized emissions when compared to the temporal speed variability during uncongested traffic conditions. In another study for which we focus on the differences in running stabilized emissions resulting from using lane average speeds in contrast to link average speeds, our results differ. The percentage differences in running stabilized emissions are much higher, whereas, the correlations between level of congestion and differences in running stabilized emissions are zero, that is, there is not even a loose correlation.

Using graphical representation, we showed that when there are more interruptions to the traffic flow, differences in running stabilized emissions are more likely to be significantly different across different time periods. Although we found out that the percentage differences in hourly link emissions are low, this finding suggests that for interrupted traffic flow conditions such as the conditions on major and minor arterials and local roads, it will be valuable to examine the differences in estimated emissions when 15-minute or shorter period average speeds are used for emissions estimation.

It is known that different traffic control strategies such as signalized vs. unsignalized intersections, different signal timings or presence of ramp metering can result in different vehicle operational modes (one of which is the instantaneous vehicle speed) which produce different magnitudes of unit emissions for a given average speed (e.g., Barth, Scora et al., 1998). This study shows that average speed variability during a fixed period of time affects the estimated running stabilized emissions in the regional emissions modeling context, for which it is assumed that unit emissions are constant for a given average speed independent from vehicle operational modes. Describing the uncertainties in emissions resulting from speed variability based on research about effects of instantaneous speeds on emissions is not sufficient to address the problem for regional emissions estimation.

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CHAPTER 5. EXAMINING THE IMPLICATIONS OF INCREASED RESOLUTION IN AVERAGE SPEED BY FACILITY LANE FOR MOBILE EMISSIONS INVENTORIES

The following journal article analyzes and quantifies the differences in running stabilized emissions when hourly lane average speeds in contrast to hourly link average speeds are used for emissions estimation in the regional emissions modeling context. The purpose of the analysis is to examine the uncertainties in estimated running stabilized emissions resulting from the assumption that the average speeds are constant across lanes of a multi-lane link.

Examining the Implications of Increased Resolution in Average Speed by Facility Lane for Mobile Emissions Inventories

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ABSTRACT

Link travel activity is combined with running stabilized emissions factors to estimate running stabilized emissions from links in mobile emissions inventory models. Link travel activity is the vehicle miles of travel for a given period of time estimated using the flow rates forecasted in travel demand models. Emissions factors are estimated in emissions factor models and adjusted for average speeds. This study analyzes the effects of average speed variability across the lanes of multiple-lane links on estimated emissions and addresses the uncertainties in emissions traditionally estimated using link average speeds. Hourly lane and link flow rates and average speeds for 830 freeway links in Los Angeles were estimated using 30 second lane volume and occupancies from 1376 single loop detectors located on the links. Hourly link running stabilized emissions were estimated using link average speeds and by

summing up emissions calculated for each lane using lane average speeds. Differences in link running stabilized emissions are analyzed using repeated measures analysis of variance (ANOVA) models. The days of the week, hourly periods of the day and combinations of days and hourly periods have significantly different effects on the differences in running stabilized emissions for the majority of studied links in the region.

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INTRODUCTION

Running stabilized, evaporative and start emissions from vehicles are calculated and then combined to estimate total vehicular emissions in regional mobile emission inventory models (CARB, 1996; USEPA, 2001; CARB, 2003). In regional emissions models, running stabilized emissions factors, which are adjusted for average speeds and passed from emissions factor models, are multiplied by vehicle miles of travel (VMT) grouped by average speed (i.e., apportioned in speed bins). The VMT is estimated using fixed period flow rates assigned to network links during travel demand forecasting (Ortuzar and Willumsen, 1994). The other piece of travel activity information, average link speed, is also estimated during travel demand forecasting. More current emissions inventory models can either use the average link speeds estimated in travel demand models or the speeds are re-estimated via speed post-processor algorithms integrated to the emissions inventory models (Helali and Hutchison, 1994; Dowling, Kittelson et al., 1997; SAI, 1998).

Average link speeds estimated in travel demand models or re-estimated speed post-processors are assumed to be constant for a fixed period of time and across lanes. However, average speeds show variability across lanes (Page, 1995; Hurdle, Merlo et al., 1997) and during shorter time periods (e.g., Daganzo, 1997). Moreover, it has been stated that speed-flow relationships differ across lanes indicating that utilizing the same speed-flow relationships to estimate emissions for individual lanes of a facility is a misleading practice (Page, 1995).

This study analyzes the uncertainties in estimated running stabilized emissions resulting from speed variability across lanes. For this purpose, we utilize flow rates and average speeds estimated for 830 links and the individual lanes of these 830 links in the Los Angeles, California region to estimate hourly link stabilized emissions based on link and lane average speeds. We then statistically analyze the differences in the emissions estimated using link and lane average speeds.

BACKGROUND

Vehicles are assigned to the facility links of the traffic network during the traffic assignment step of travel demand forecasting. The cost of travel to complete a trip is defined as the travel time, and facility-specific speed-flow rate relationships are used to estimate travel time as the inverse of average speed (Ortuzar and Willumsen, 1994). That is, when the travel demand is assigned on the links, average travel speeds are also calculated. The Bureau of Public Roads (BPR) equation is one of the methods used to estimate average travel speeds in transportation demand models (Equation 1) (Chatterjee, Miller et al., 1997):

$$s = \frac{s_f}{1 + a(v/c)^b} \qquad \text{(Equation 1)}$$

where,

s = Mean speed

s_f = Free-flow speed

v = Volume

c = Practical capacity

a,b = Constants.

Research shows that the speed-flow relationships, such as the relationship represented by the BPR equation (Equation1), utilized for average speed estimation in the planning models, do not represent real world speed-flow rate relationships, especially during congested traffic conditions (Dowling and Skabardonis, 1992; Helali and Hutchison, 1994; Chatterjee, Miller et al., 1997). However, even when the speeds are

estimated using speed post-processors integrated to emissions models, they are based on fixed period (usually one hour) flow rates assigned on the links. That is, the flow rate on a multi-lane link is assumed to be observed on a single lane which has the capacity of the entire link. In addition, it is assumed that the individual vehicle speeds and spacings are constant for all the vehicles across lanes and for the observation period (Hall and Persaud, 1989; Hall, Hurdle and Banks, 1992; Daganzo, 1997). However, not only flow rates differ across lanes but also there are different speed-flow relationships for different freeway lanes (Page, 1995; Hurdle, Merlo et al., 1997). Therefore, even if the flow rates are similar across lanes, the average speeds on each lane can still be different at the same location on a facility.

The generalized speed-flow relationship demonstrated in Figure 1, which was produced to investigate the shape of the freeway speed-flow relationship curve by Hall et al. (1992), shows that different speeds can be observed at a given flow rate, depending on whether the traffic flow condition is uncongested, in-queue or in queue discharge. The figure also illustrates that a range of speeds can be observed for a given flow rate during queue discharge conditions. The speed and flow rate values are not shown on the figure because they differ depending on the free-flow speed and the capacity values for each facility type, geometric configuration, weather condition, vehicle fleet, grade, lane configuration and more importantly for different number of lanes of the link (Hall, Hurdle et al., 1992; Ibrahim and Hall, 1994; Smith, Hall et al., 1996; Daganzo, 1997; Hurdle, Merlo et al., 1997; TRB, 1998).

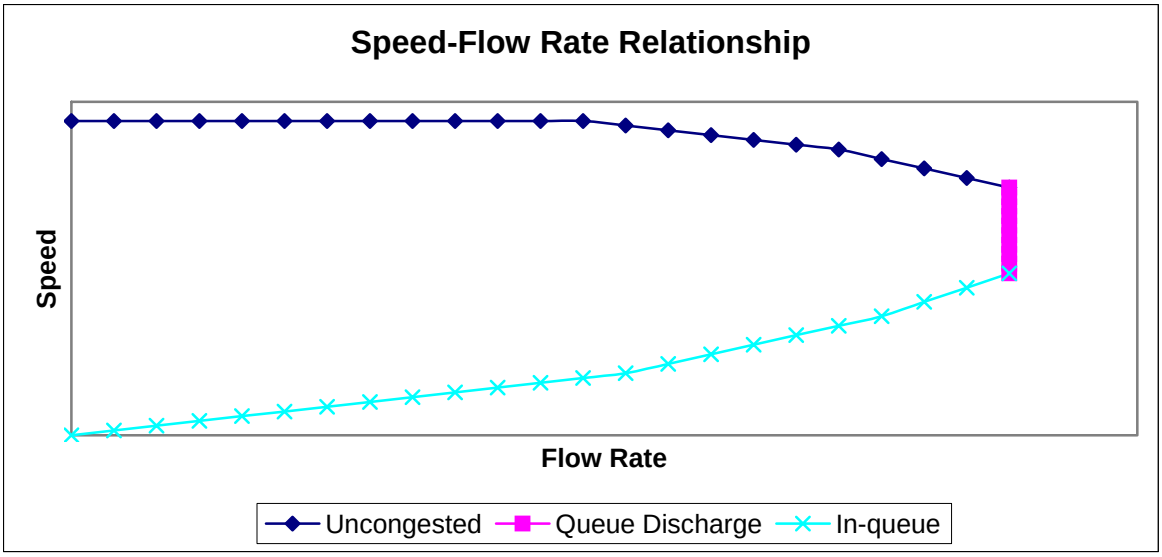

Figure 1. Generalized Speed-Flow Relationship Curve (Hall, Hurdle and Banks, 1992)

Moreover, in real-world traffic, different speeds can be observed for a given flow rate even in the same traffic condition. This can be seen in the scatter plot of five minute average speeds and flow rates presented in Figure 2 which are extracted from the Freeway Performance Measurement System (PeMS) database. The purpose of the system is to analyze the quality of service on freeways by estimating performance measures such as VMT, vehicle hours of travel (VHT), travel time, delay, speed, flow rate and density. The measurements are from a detector station on Interstate 5 (I-5) in the Los Angeles Area on August 1, 2002.

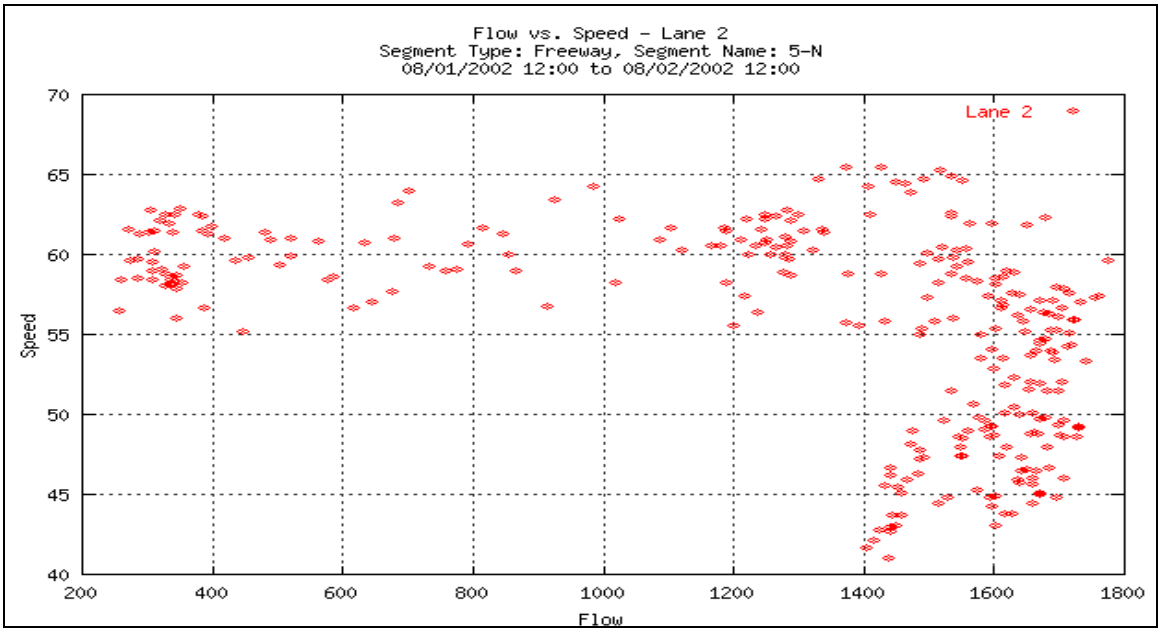

Figure 2. Real-world Speed and Flow Rate Observations (Source: Online access: http://pems.eecs.berkeley.edu)

In summary, different average speeds are observed across lanes because: 1) different flow rates can be observed across lanes, 2) different average speeds can be observed for a given flow rate on a given lane, and 3) there are different speed-flow relationships across the lanes of a multiple lane facility (Hall, 1992; Daganzo, 1997; Hurdle, Merlo et al., 1997). Given that the VMT values are estimated using flow rates which are related to average speeds and running stabilized emissions factors are adjusted for average speeds, link running stabilized emissions will differ when link average speeds are used compared to when lane emissions based on lane average speeds are added together for the estimation of link emissions.

METHODS

Hourly link and lane flow rates and average speeds averaged for links and individual lanes of those links and were estimated using 30 second lane volume and occupancy measurements from single loop detectors located on individual lanes of 1376 single loop detector stations. These 1376 single loop detector stations were located on 830 freeway links in Los Angeles. Measurements were taken for the South Coast Ozone Study for three months during the summer of 1997. The 30 second volumes and occupancies were aggregated across lanes to estimate link volume and occupancy values. Then, 30 second link (i.e., aggregated across lanes) and lane (i.e., not aggregated across lanes) volumes and occupancies were aggregated to estimate hourly link and lane volume and occupancy values. Using one hour link and lane volumes and occupancies, hourly link and lane average speeds were estimated at single loop detector stations which were then used to estimate hourly link and lane average speeds on facility links. Hourly link running stabilized emissions were estimated using a modified version of UCDrive (Niemeier, Zheng et al., 2004) by: 1) aggregating hourly lane emissions estimated using hourly lane speeds, and 2) using hourly average link speeds. Then, differences in running stabilized emissions were analyzed using repeated measures analysis of variance (ANOVA) models.

The methods used for estimating flow rates and average speeds at single loop detector stations, estimating link and lane flow rate and average speeds, estimating the differences in running stabilized emissions, and statistical analysis are explained in detail elsewhere (Sogutlugil, Niemeier, 2004). Although the methods are the same

for the two studies, in contrast to our previous study, instead of estimating 15-minute link flow rates, average speeds and running stabilized emissions, we now calculate hourly lane flow rates, average speeds and running stabilized emissions. Then, differences in running stabilized emissions are estimated by subtracting hourly link emissions estimated using hourly link average speeds from hourly link emissions calculated by summing up hourly lane emissions.

Statistical Analysis

Repeated measures analysis of variance (ANOVA) models are used to statistically examine the differences in running stabilized emissions (Neter, Wasserman et al., 1990; Girden, 1992; Dean and Voss, 1999). The differences in running stabilized emissions resulting from using hourly lane speeds relative to hourly link speeds are the dependent variables. The treatment factors are selected so that significant effects of the day of week, the time of day and the interaction between these two factors are analyzed. Moreover, four contrasts are constructed in the ANOVA models to analyze: 1) if the weekends and weekdays, 2) if the peak hours and day-time off-peak hours, 3) if the morning peak hours and evening peak hours, and 4) if the combination of Monday-Friday and the combination of Tuesday-Wednesday and Thursday have significantly different effects on the differences in running stabilized emissions. The reasons for the selection of the treatment factors, treatment factor effects (i.e., whether the treatment factors are fixed or random effects) and the construction of the contrasts are explained in detail elsewhere (Sogutlugil and Niemeier, 2004).

The ANOVA model used to examine the differences in hourly link running stabilized emissions of CO, NO_x, CO_2, TOG, and PM_x is,

$$Y_{ijkl} = \mu + \rho_i + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{ijkl} \qquad i = 1,\ldots, N,\ j = 1,\ldots, 7,$$

$$k=1,\ldots, 13,\quad l =1,\ldots, M \qquad \text{(Equation 2)}$$

where Y_{ijkl} is the difference in estimated hourly link running stabilized emissions (for link *i,* day *j* and hour *k),* μ is the overall mean, ρ_i is the random effect blocking factor with each level *i* denoting the links , thus *i* changes from 1 through *N* and *N* is the number of links in North LA, South LA or Orange County, α_j is the fixed effect day of week factor where *j* ranges from 1 through 7 denoting the days Monday through Sunday, β_k is the fixed effect time of day factor where *k* changes from 1 through 13 denoting the hourly periods from 6a through 7p, $(\alpha\beta)_{jk}$ is the fixed effect interaction factor, ε_{ijkl} is the random error, *l* denotes each hourly estimated difference, and *M* is the total number of hourly periods for which the differences in running stabilized emissions are analyzed for each region. The value of *M* differs for North LA, South LA and Orange County data sets because both the number of links and the number of hourly differences estimated for each link are different for the three regions.

RESULTS

The ANOVA models were used for analyzing the differences in CO, NO_x, CO_2, TOG, and PM_x for North LA, South LA and Orange County. Table 1 presents the results for the five types of emissions and the three regions. The statistically significant treatment factors and contrasts were denoted by "+", and statistically non-significant treatment factors and contrasts were identified by "NS".

Table 1. ANOVA Model Results for Differences in Running Stabilized Emissions

North LA			Blocking Factor	Treatment Factors		Interaction	Contrasts				
Pollutant	F	p value	Link	Day	Time	DayxTime	Pk vs. Offpk	Morpk vs Evepk	Wkend vs. Wkday	M-F vs. T-W-Th	Number of Observations
CO	582.9	.0001	+	+	+	+	+	+	+	+	210821
CO_2	577.8	0001	+	+	+	+	+	+	+	+	210821
NO_x	583.0	0001	+	+	+	+	+	+	+	+	210821
PM_x	328.9	0001	+	+	+	+	+	NS	+	+	210821
TOG	382.7	0001	+	+	+	+	+	NS	+	NS	210821
South LA											
CO	231.6	0001	+	+	+	+	+	+	+	+	325535
CO_2	248.6	0001	+	+	+	+	+	+	+	+	325535
NO_x	244.9	0001	+	+	+	+	+	+	+	+	325535
PM_x	227.6	0001	+	+	+	+	NS	+	+	+	325535
TOG	245.2	0001	+	+	+	+	NS	+	+	+	325535
Orange County											
CO	288.9	0001	+	+	+	+	+	NS	+	+	105305
CO_2	261.8	0001	+	+	+	+	+	+	+	+	105305
NO_x	372.6	0001	+	+	+	+	+	+	+	NS	105305
PM_x	329.0	0001	+	+	+	+	+	+	+	+	105305
TOG	270.4	0001	+	+	+	+	+	+	+	+	105305

The R^2 values for the 15 models that were created for three regions and five pollutants change between 0.24 and 0.52. Although the R^2 values indicate that 24 to 52 percent of the total variability is explained by the model, the values are much higher than the R^2 values estimated in our previous study in which the dependent variables were the differences in running stabilized emissions resulting from using 15-minute link average speeds in contrast to using hourly link average speeds (Sogutlugil and Niemeier, 2004).

Using the same methodology as in the previous study, we grouped the data for each link and analyzed the differences statistically (Sogutlugil and Niemeier, 2004). Grouping the data for each link achieves the following: 1) controls the variability of the differences in emissions across lanes for the levels of the treatment factors (i.e., days of the week and hourly periods of the day are likely to have different effects on differences estimated for different links), and 2) enables us to estimate the percentage of links when treatment factors and contrasts are significant. The blocking factor, which is the link, is omitted from Equation 2 to construct the ANOVA models which are utilized to analyze the differences for each link. Equation 3 demonstrates the fixed effects repeated measures ANOVA model with the interaction term,

$$Y_{jkl} = \mu + \alpha_j + \beta_k + (\alpha\beta)_{jk} + \varepsilon_{jkl} \qquad j = 1, \ldots, 7 \;\; k = 1, \ldots, 13,$$

$$l = 1, \ldots, N \qquad \text{(Equation 3)}$$

where Y_{jkl} is the difference in CO, NO_x, CO_2, TOG, or PM_x running stabilized emissions for the j^{th} day and k^{th} hour, μ is the overall mean, α_j is the fixed effect

day of week factor with 7 levels (Monday through Sunday), β_k is the fixed effect time of day factor with 13 levels (6a-7p), $(\alpha\beta)_{jk}$ is fixed effect the interaction term, *l* changes from 1 to *N*, *N* is the number of differences in hourly running stabilized emissions for each link, and ε_{jkl} is the random error term.

This model is constructed for the five pollutants and 830 links in the region, thus, it was repeatedly applied 4150 times for each pollutant and link. Then, the outputs for each link and each pollutant were summarized. The numbers and percentages of links when the treatment factors, interaction term and the contrasts are statistically significant ($p<0.05$) are calculated for the 819 links for which differences in running stabilized could be estimated for all the seven days and 13 hourly periods analyzed in this study. Data for some of the days and/or hourly periods were not available for 11 out of the 830 links in the region. The percentages of links when treatment factors and contrasts are statistically significant are presented in Table 2.

Table 2. Summary Results for Link Level ANOVA

	Number (and percentage) of links when significant (p<0.05))						
	Treatment Factors		**Interaction**	**Contrasts**			
Pollutant	**Day of week**	**Time of day**	**DayxTime**	**Wkend vs. Wkday**	**Pk vs. Offpk**	**Morpk vs Evepk**	**M-F vs. T-W-Th**
CO	740(90%)	486(59%)	228(28%)	601(73%)	495(60%)	450(55%)	223(27%)
CO_2	655(81%)	491(59%)	233(28%)	614(75%)	493(60%)	452(55%)	228(28%)
NO_x	717(87%)	454(55%)	216(26%)	546(67%)	451(55%)	439(54%)	192(23%)
PM_x	668(81%)	468(57%)	231(28%)	607(74%)	470(57%)	465(57%)	347(42%)
TOG	767(94%)	522(64%)	256(31%)	651(79%)	483(59%)	502(61%)	242(30%)

The differences in running stabilized emissions resulting from using lane average speeds compared to link average speeds are most often significant for the day of week

effect (81%-94% of links for the 5 types of emissions) (Table 2). Also, the differences in running stabilized emissions are significantly different between the weekdays and weekends for 67% through 79% of the links. The percentages of links when time of day effect, peak vs. off-peak contrast and morning peak vs. evening peak contrasts are statistically significant are somewhat lower than the percentages of links for the day of week effect and the weekday vs. weekend contrast. However, these effects are statistically significant for more than half of the links in the region. The day of week and time of day interaction is statistically significant for 26%-31%, and the Monday-Friday vs. Tuesday-Wednesday-Thursday contrast is statistically significant for 23%-42% of the links for the five types of pollutants.

Table 3 presents the percentage of links when only 'day of week', only 'time of day', both of the factors, and neither of the factors are statistically significant. The percentage of links when both 'day of week' and 'time of day' are statistically significant is highest for differences in TOG and lowest for differences in NO_x emissions. On the other hand, only 'day of week' or only 'time of day' is statistically significant for the highest percentage of links (for 49 % of the links) for differences in NO_x emissions. Neither of the factors are statistically significant for 3 to 4% of the links for differences in all five types of emissions. In contrast to our previous study for which we statistically examined the differences in emissions when we used 15-minute in contrast to hourly link average speeds, the percentages of links when only 'time of day' and/or 'day of week' are statistically significant differ very slightly across the five types of emissions (Sogutlugil, Niemeier, 2004).

Table 3. Summary Results for Day of Week and Time of Day Factors

Number and Percentage of Links when Significant (p<0.05)				
Pollutant	**Only Day of Week Sig.**	**Only Time of Day Sig.**	**Both Sig.**	**Neither Sig.**
CO	315 (38 %)	62 (8 %)	417 (51 %)	25 (3 %)
CO_2	310 (38 %)	50 (6 %)	434 (53 %)	25 (3 %)
NO_x	327 (40 %)	72 (9 %)	382 (47 %)	38 (4 %)
PM_x	332 (41 %)	33 (4 %)	429 (52 %)	24 (3 %)
TOG	282 (34 %)	35 (4 %)	481 (59 %)	21 (3 %)

Table 3 demonstrates that the differences in CO, CO_2, NO_x, PM_x and TOG emissions are significantly different across the days of the week and/or hourly periods of the day for the majority (96%-97%) of the links in the region. This shows us that speed variability patterns across lanes are sufficiently variable to produce significantly different differences in emissions for different days and/or hourly periods.

Next, we examine the relationship of traffic congestion level (i.e., V/C) to the differences in running stabilized emissions. For this purpose, we present the percentage differences in NO_x, TOG and CO_2 (which are ozone precursors and primary air pollutants for urban areas (Seinfeld and Pandis, 1998)) versus V/C. Figures 3 through 5 demonstrate the 5^{th}, 50^{th} and 95^{th} percentile values for differences in NO_x, TOG and CO_2 for all the hourly periods on which we focused for our statistical analyses. The 5^{th} percentile values for percentage differences in NO_x, TOG and CO_2 emissions are as low as ~ -8 %, -20 % and -15 %, respectively. In other words, for TOG, for example, our method of computing running stabilized emissions using lane average speeds gives a result that is at least 20% lower than the

usual link level approach, 5% of the time. On the other hand, 95th percentile values are as high as ~17 %, 17 % and 14 % for differences in NO_x, TOG and CO_2 emissions, respectively. That is, for TOG, for example, our lane-level approach yields emissions estimates that are at most 17% higher than the conventional link-level approach, 95% of the time.

The 50th percentile (i.e., median) values for the percentage differences in NO_x, TOG and CO_2 emissions indicate that using lane average speeds instead of link average speeds results in at most ~5% higher magnitude estimates, 50% of the time when V/C is equal to 1. For other congestion levels (i.e., when V/C is different from 1), the median values of percentage differences vary between ~0% and ~4%. They are nearly always greater than zero, however, indicating that the lane average speed method most often yields a higher estimate of emissions than does the link average speed method. The fact that the 95th percentile trace is greater in magnitude than the 5th percentile trace also indicates that, overall the new approach leads to higher estimates of emissions.

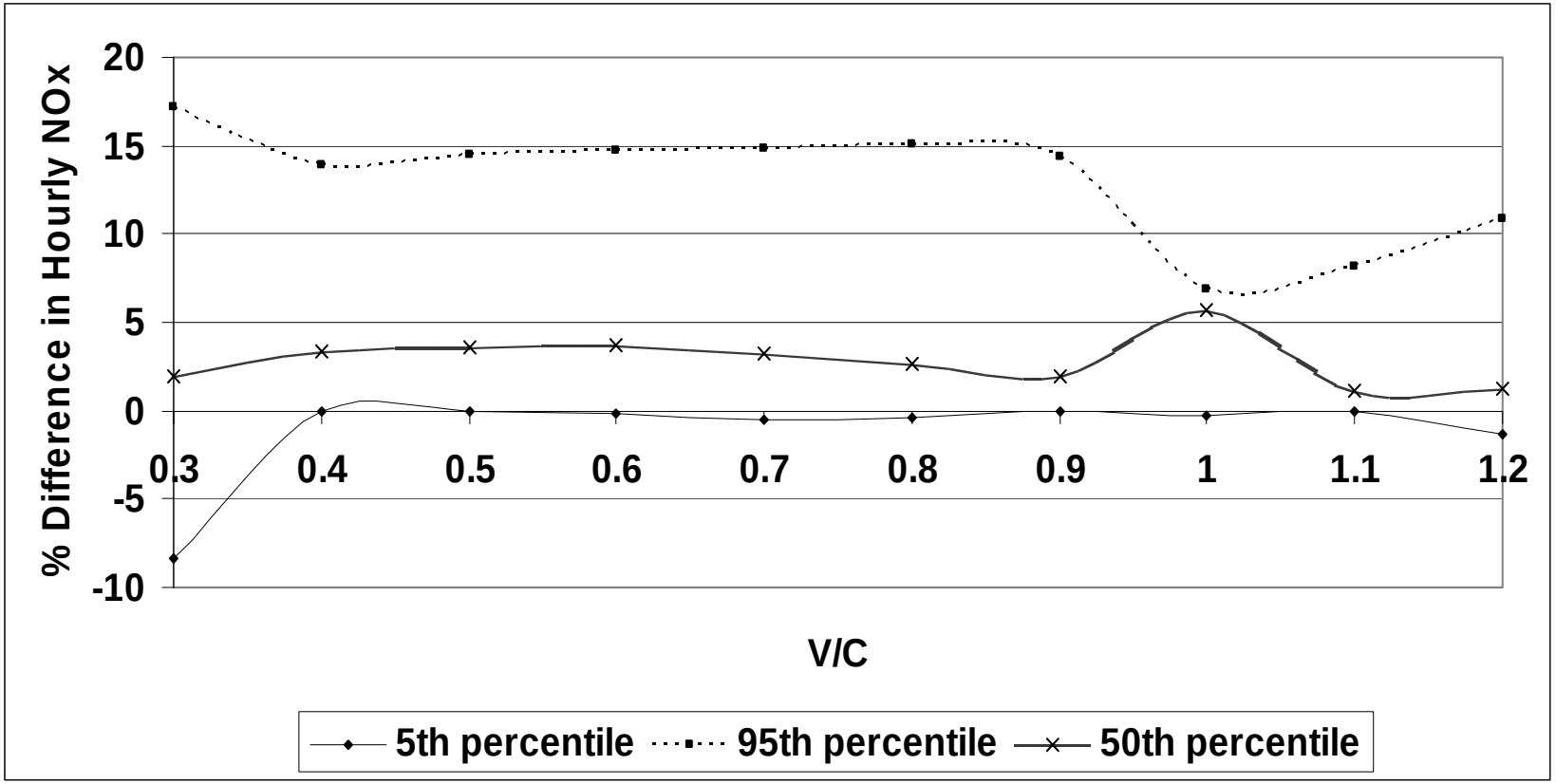

Figure 3. Differences in Hourly NO_x vs. V/C

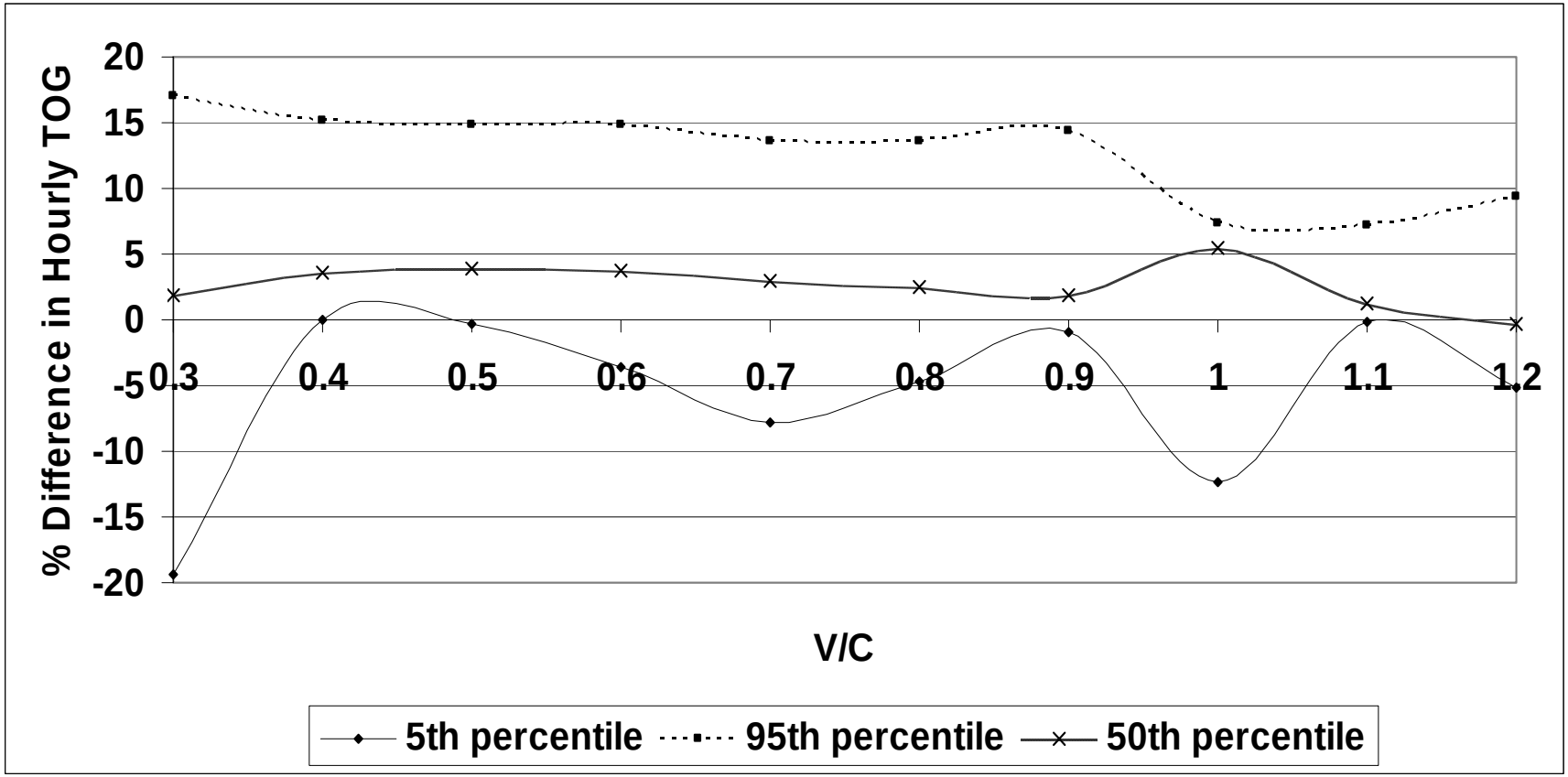

Figure 4. Differences in Hourly TOG vs. V/C

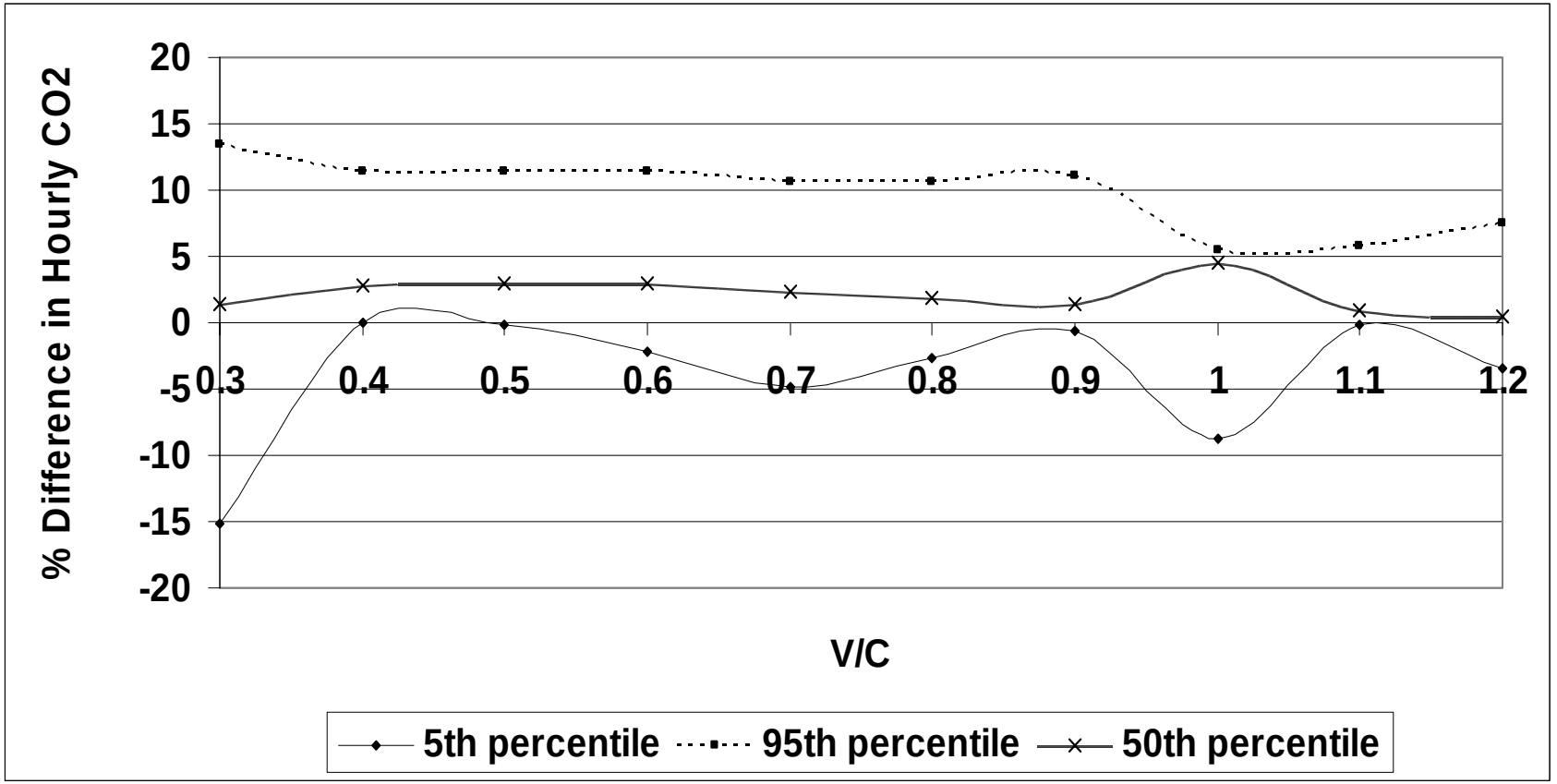

Figure 5. Differences in Hourly CO_2 vs. V/C

The percentage differences in emissions resulting from using hourly lane average speeds are higher in value compared to the percentage differences in emissions resulting from 15-minute link average speeds (Sogutlugil, Niemeier, 2004). In the latter case, the 5^{th} percentile values for percentage differences in hourly emissions are as low as ~-1.5 % and the 95^{th} percentile values are as high as ~3 %.

Both the plots of percentage hourly differences (Figures 3 through 5) with respect to V/C, and the one-tailed Pearson correlation coefficients (with values around zero) estimated for bivariate correlations between V/C and percentage differences, show that the differences in running emissions are not correlated to the congestion level. The facts that 1) there is no correlation present between differences and V/C and 2) the percentage differences in running stabilized emissions are high indicate that, independent from the congestion level, estimated running stabilized emissions will differ and can differ by relatively high magnitudes when lane average speeds are used in contrast to typically used hourly speeds.

Moreover, the estimated percentage differences are higher for less congested traffic conditions (i.e., when V/C is lower than 0.9) indicating that the variability of average speeds across lanes results in higher magnitude differences when traffic is uncongested (Figures 3 through 5). This suggests that variability in average speeds across lanes resulting from irregularities in driving during uncongested conditions is likely to result in higher value differences in running stabilized emissions.

The shapes of Figures 3 through 5 are somewhat similar. However, it is important to note that 5th percentiles are closer to zero for percentage differences in NO_x emissions. This shows that the speed variability across lanes results in higher value (more positive) differences in NO_x emissions compared to the differences in TOG and CO_2 emissions.

The 5th and 95th percentile difference values are lower and 95th percentile difference values are higher for the V/C of 0.3 when compared to the other V/C values for the three types of emissions (Figures 3 through 5). We should note that the number of observations for V/C=0.3 were low, thus, the data set was not representative enough to robustly estimate 5th and 95th percentile values.

Given that the magnitudes of differences in running stabilized emissions are not correlated to congestion levels (i.e., V/C), next we graphically represent the locations where the differences in NO_x emissions are significantly different across different days and times. As illustrated by summarizing the ANOVA model results in Table 3, the differences in running stabilized emissions are significantly different for different days and/or hourly periods for 97 % of the links for NO_x (Figure 6). Figure 7 through 9 shows three sections more closely. Section 1 presented in Figure 7 is a section where either time of day or both time of day alone and day of week are statistically significant. On the other hand, Section 2 shows locations where neither of the factors and day of week is significant most of the time (Figure 8). Section 3 presents a larger

area where either day of week alone, or both day of week and time of day, are significant for most of the locations (Figure 9).

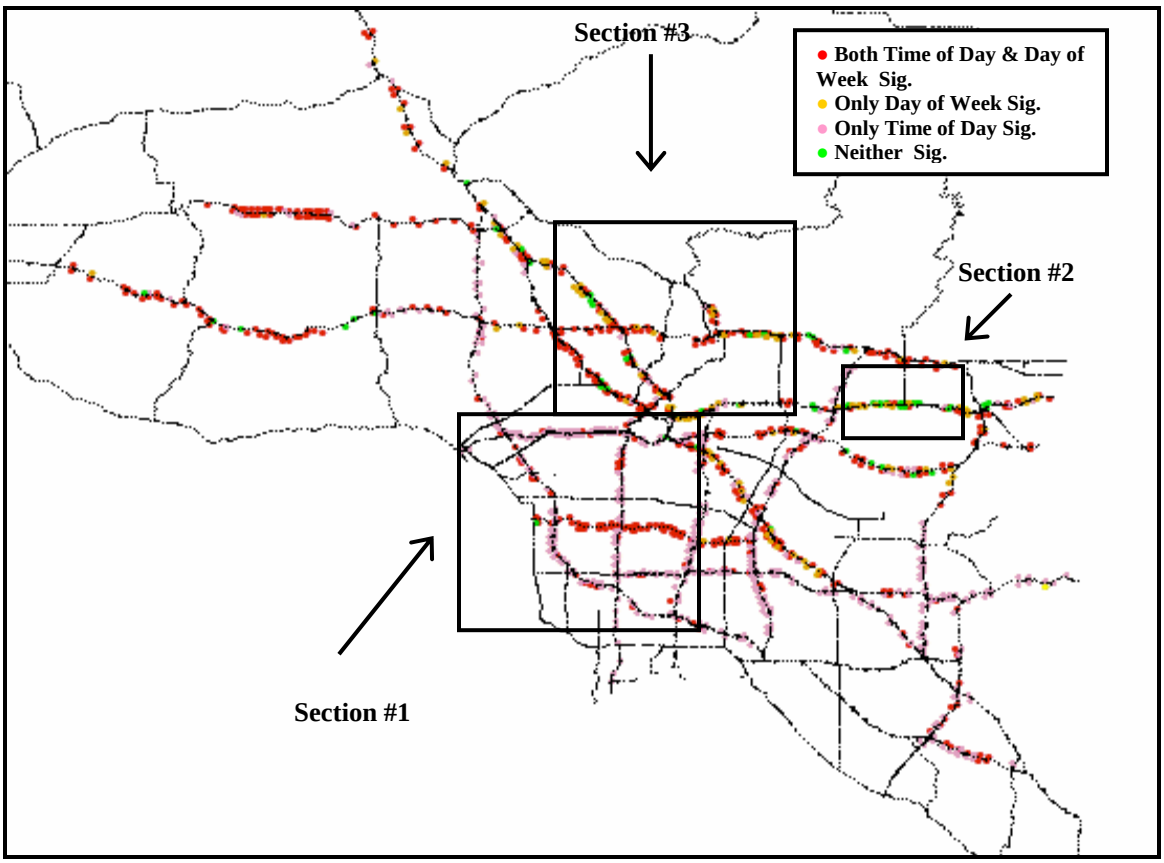

Figure 6. Locations where 1) Time of Day and Day of Week, 2) Only Time of Day, 3) Only Day of Week , and 4) Neither of the Factors are Significant in Los Angeles, Summer 1997

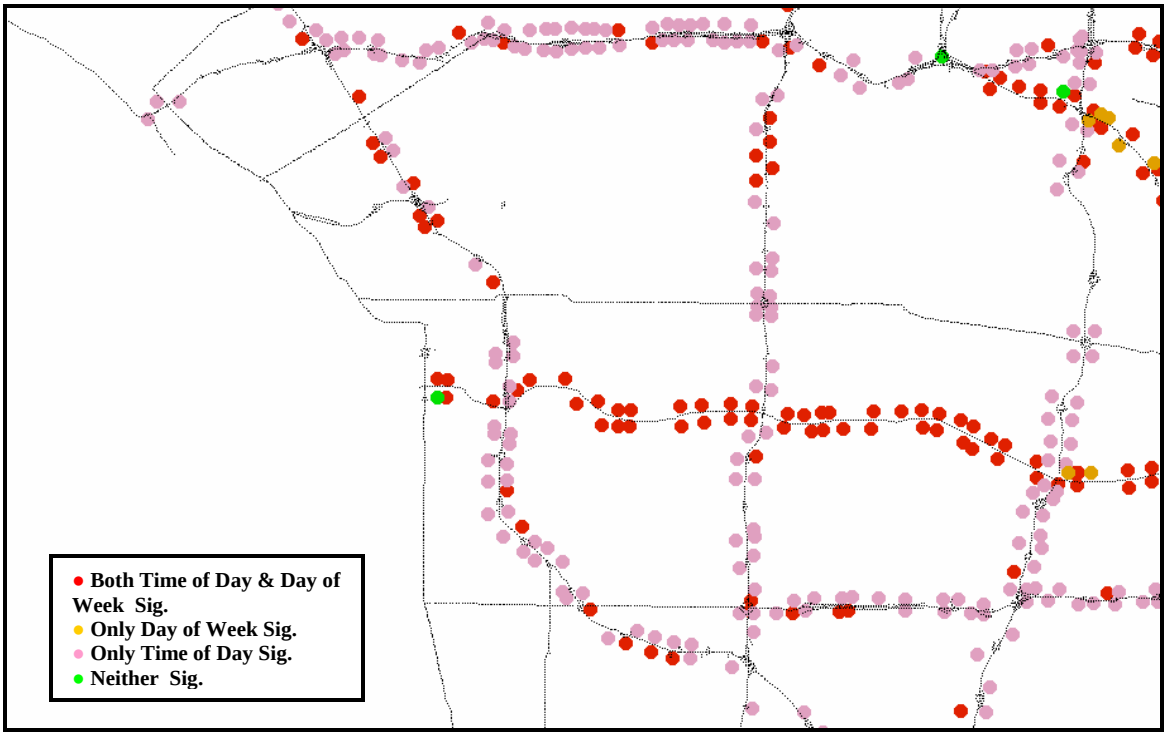

Figure 7. Section 1 – Section where Time of Day Alone or Both Time of Day and Day of Week are Significant at Almost All of the Locations

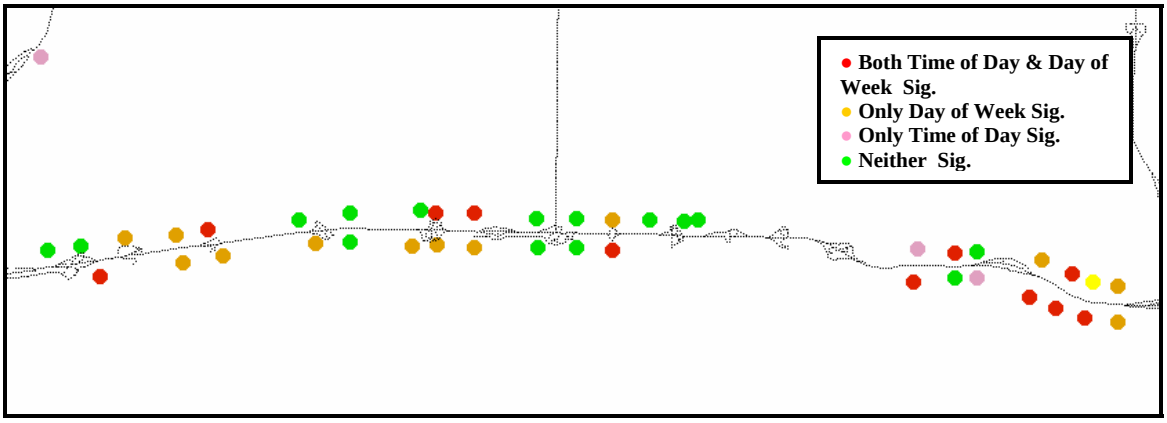

Figure 8. Section 2 – Section where Only Day of Week or Neither of the Factors are Significant Most of the Time

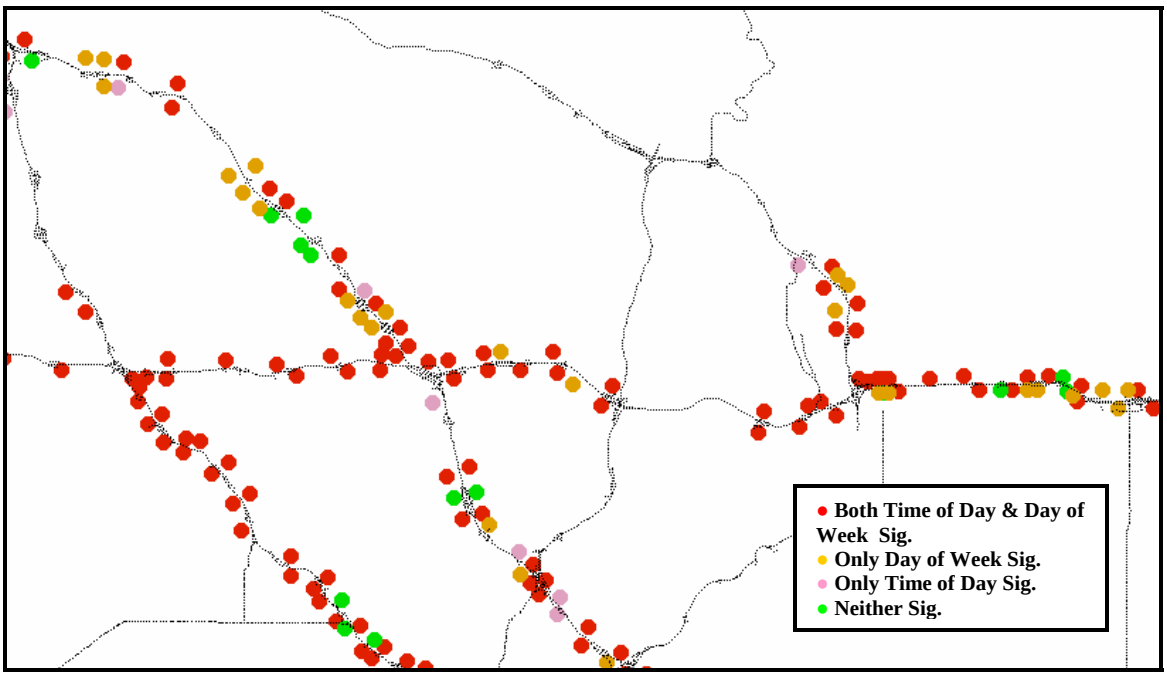

Figure 9. Section 3 – Section where Day of Week Alone or Both of the Factors are Significant Most of the Time

The percentage of links when only time of day is significant is 9% whereas it is 40% when only day of week is significant (Table 3). It should be noted that the length of the freeway links and also the number of detectors located on the links differ. From Figure 6, it can be seen that only time of day tends to be statistically significant for long links whereas only day of week tends to be statistically significant for short links.

Summary and Conclusions

It has previously been shown that average speeds are significantly different across lanes and assuming the same average speeds for all the lanes on a facility link for emissions estimation is misleading (Page, 1995). This study demonstrates that using speeds averaged for individual lanes in contrast to link average speeds in fact results in different magnitudes of estimated running stabilized emissions from facility links. Therefore, there is uncertainty in estimated mobile emissions resulting from using fixed-period link average speeds provided by travel demand models.

Moreover, speed variability across lanes differs considerably across days of the week and hourly periods of the day, resulting in significantly different differences in running stabilized emissions for different time intervals. This shows that not only speed variability across lanes but the differences in these speed variability patterns affect the impacts of individual lane speed variability on estimated running stabilized emissions.

The findings from this study suggest that, when emissions from a link have to be estimated for planning purposes, it is important to incorporate the speeds for each lane especially for time periods when emissions produced are different than the typical values. That is, if the emissions produced from a facility link are higher than the emissions produced from the same type of facility with the same number of lanes, emissions estimated using lane average speeds should be analyzed. Under similar conditions (i.e., temperature, humidity, link average speed and flow rate for a given

period of time), average lane speeds highly different from the link average speed will result in highly different magnitudes of estimated emissions.

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CHAPTER 6. AIR QUALITY EFFECTS OF UTILIZING HIGHLY RESOLVED AVERAGE SPEEDS FOR EMISSIONS ESTIMATION

The paper presented in this chapter investigates the effects of using 15-minute link average and hourly lane average speeds in contrast to hourly link average speeds for producing gridded emissions inventories on secondary pollutant concentrations. It analyzes the differences in estimated O_3 and $PM_{2.5}$ concentrations when different resolution average speeds are used to produce gridded mobile emissions inputs for the photochemical air quality model.

Air Quality Effects of Utilizing Highly Resolved Average Speeds for Emissions Estimation

Mihriban Sogutlugil, Debbie A. Niemeier *, Michael J. Kleeman

ABSTRACT

Photochemistry modeling is often used to estimate the impact of future changes in pollutant sources. Prior research has established that there are significant uncertainties associated with the inputs to the photochemical models. One major uncertainty is the modeled pollutant impact associated with varying the spatial and temporal resolutions of gridded mobile source emissions. Using photochemistry, this study examines the air quality effects of using average speeds calculated for different time resolutions. We calculated 15-minute and the standard hourly average speeds from 1376 single loop detector stations on 830 roadway segments and for individual lanes in Los Angeles. Flow rates and two different average speeds were then combined with travel activity for other types of facilities in the region to estimate mobile source emissions, which were added to area and point source emissions to estimate total gridded emissions for July 23rd, 24th and 25th in 1997. Total gridded emissions for these three days were used as input to the photochemical air quality model for the estimation of regional and gridded ozone (O_3) and particulate matter (PM) concentrations. Based on photochemistry results, pollutant concentration estimates do not significantly differ for O_3 but significantly differ across scenarios for PM as result of differences

in the hourly allocation of gridded emissions throughout the day which in fact resulted from using different resolution average speeds.

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INTRODUCTION

Photochemical air quality models combine mobile, area, point and biogenic source emissions, meteorology and the regional topography to estimate pollutant concentrations (Seinfeld and Spyros, 1998; Russell and Dennis, 2000). Gridded mobile source inventory emissions are a key input to the photochemical air quality models (Flagan and Seinfeld, 1988; Seinfeld and Spyros, 1998; Wark, Werner et al., 1998; Kleeman and Cass, 2001). The emissions inventories used in the photochemical air quality models, of which the mobile source share is high, are very important but also very uncertain (Russell and Dennis, 2000). One of the uncertainties related to emissions inputs is related to the impact of the temporal and spatial resolutions on estimated pollutant concentrations (NRC, 2000).

There is little question that greater sensitivity analysis of estimated inventory emissions as inputs provided to the photochemistry models is needed (NRC, 2000). For example, one recent analysis showed that increasing the time resolution used to calculate the hourly roadway segment average speeds, and differentiating these speeds by lane when estimating running stabilized emissions, resulted in significant differences in hourly link running stabilized emissions in Los Angeles (Sogutlugil and Niemeier, 2004a; Sogutlugil and Niemeier, 2004b). However, whether or not these differences are of sufficient significance to influence photochemistry and thus, estimated O_3 and PM pollutant concentrations, has not been established.

BACKGROUND

Previous research has focused on how different temporal and spatial resolutions used in the emissions models affect the magnitudes and ratios of O_3 and PM precursors (i.e., magnitudes of volatile organic compounds (VOCs), nitrogen oxides (NO_x) and VOC/ NO_x ratios) (NRC, 2000). However, examining the magnitudes and also the ratios of VOC and NO_x do not address the uncertainties for the secondary formation of O_3 and PM, particularly estimates of photochemical air quality models since other variables such as the topography and meteorology as well as the temporal and spatial resolutions of these variables also affect the concentration estimates (Wark, Werner et al., 1998).

Previous studies have shown that emissions produced by vehicular activity significantly differ when different instantaneous speed variability patterns are present for a given average speed (e.g., (Ahn, Rakha et al., 2002; Joumard, Andre et al., 2003; Lin and Niemeier, 2003). Recent studies by Sogutlugil and Niemeier (2004a; 2004b) showed that running stabilized VOC and NO_x tailpipe emissions can vary across days of the week and hourly periods of the day. For that study, we estimated the differences in estimated running stabilized emissions when 15-minute link average speeds and hourly lane average speeds are used in contrast to commonly-used hourly link average speeds. The magnitudes of the differences in running stabilized emissions are higher for hourly lane average speeds compared to the magnitudes of the differences resulting from using 15-minute link average speeds. Having shown

that estimated link emissions vary when different resolution average speeds are used to calculate running stabilized emissions, our motivation in this study is to examine if these differences in estimated running stabilized emissions have significant effects on estimated O_3 and PM concentrations[1].

Ozone is a secondary pollutant photochemical oxidant produced by the reaction of VOCs and NO_x in sunlight. PM is an atmospheric aerosol which is formed directly from source and also by gas-to-particle conversion during which the reaction of VOCs and NO_x is important (Kleeman and Cass, 2001; Nguyen and Dabdub, 2002). Ozone and PM concentrations are high in many urban areas and downwind of many urban areas in the US (Flagan and Seinfeld, 1988; Seinfeld and Spyros, 1998). The South Coast Air Basin (SCAB), which encompasses urban Los Angeles, was designated as an "extreme" non-attainment region for National Ambient Air Quality Standards (NAAQS) for O_3 in 1990 and is targeted for attainment by 2010 (Wark, Werner et al., 1998). The NAAQS for $PM_{2.5}$ are also often exceeded in the region (CARB, 2004).

Given that O_3 and $PM_{2.5}$ formation is a major air quality problem in Los Angeles and with the impending urgency for meeting NAAQS, increasing the accuracy of O_3 and $PM_{2.5}$ concentration forecasts is essential. Nearly 52.3% of daily NO_x and 39.6% of daily VOCs (major contributors to O_3 and $PM_{2.5}$ formation) and also 2.4%

[1]We focus our analyses on $PM_{2.5}$ concentrations. $PM_{2.5}$ is particulate matter with aerodynamic diameter less than or equal to 2.5 micrometers.

of PM are produced by on-road vehicular activity in California in 2001 (CARB, 2001).

The accuracy of traffic activity inputs (for our study, average speeds) for O_3 and $PM_{2.5}$ concentration estimates becomes important when estimated mobile source emissions inventories are used as one of the input data sets to the photochemical air quality models. Temporal and spatial variations in VMT, average speed and vehicle mix information have all been identified as sources of uncertainty for mobile source emissions estimates (Chatterjee, Miller et al., 1997; NRC, 2000). However, the sensitivity of estimated O_3 and $PM_{2.5}$ concentrations to the travel activity inputs will be different from the sensitivity of mobile source emissions estimates to the travel activity inputs, given that the atmospheric chemical and physical processes simulated in the photochemical air quality models affect the magnitudes of the concentration estimates (Flagan and Seinfeld, 1988). To our knowledge, sensitivity of secondary pollutant concentration estimates to differences in travel activity inputs has not been examined.

METHODS

In Sogutlugil and Niemeier (2004a; 2004b), we estimated four types of travel activity data: 1) hourly link flow rates (volumes), 2) hourly link average speeds, 3) 15-minute link average speeds and 4) hourly lane average speeds for 830 freeway links in Los Angeles. Hourly link flow rates are the number of vehicles observed on the links over an hourly period. Hourly link average speeds are the average speeds of all vehicles traversing a link for hourly periods. The 15-minute link average speeds are the average speeds of vehicles traversing a link for 15-minute periods. Hourly lane average speeds are the average speeds of vehicles traversing the individual lanes of links for hourly periods. Flow rates and average speeds were calculated using volumes and occupancies measured in individual lanes by 1376 single loop detector stations located on the 830 freeway links. The freeway network for which we estimated the flow rates and average speeds is presented in Figure 1.

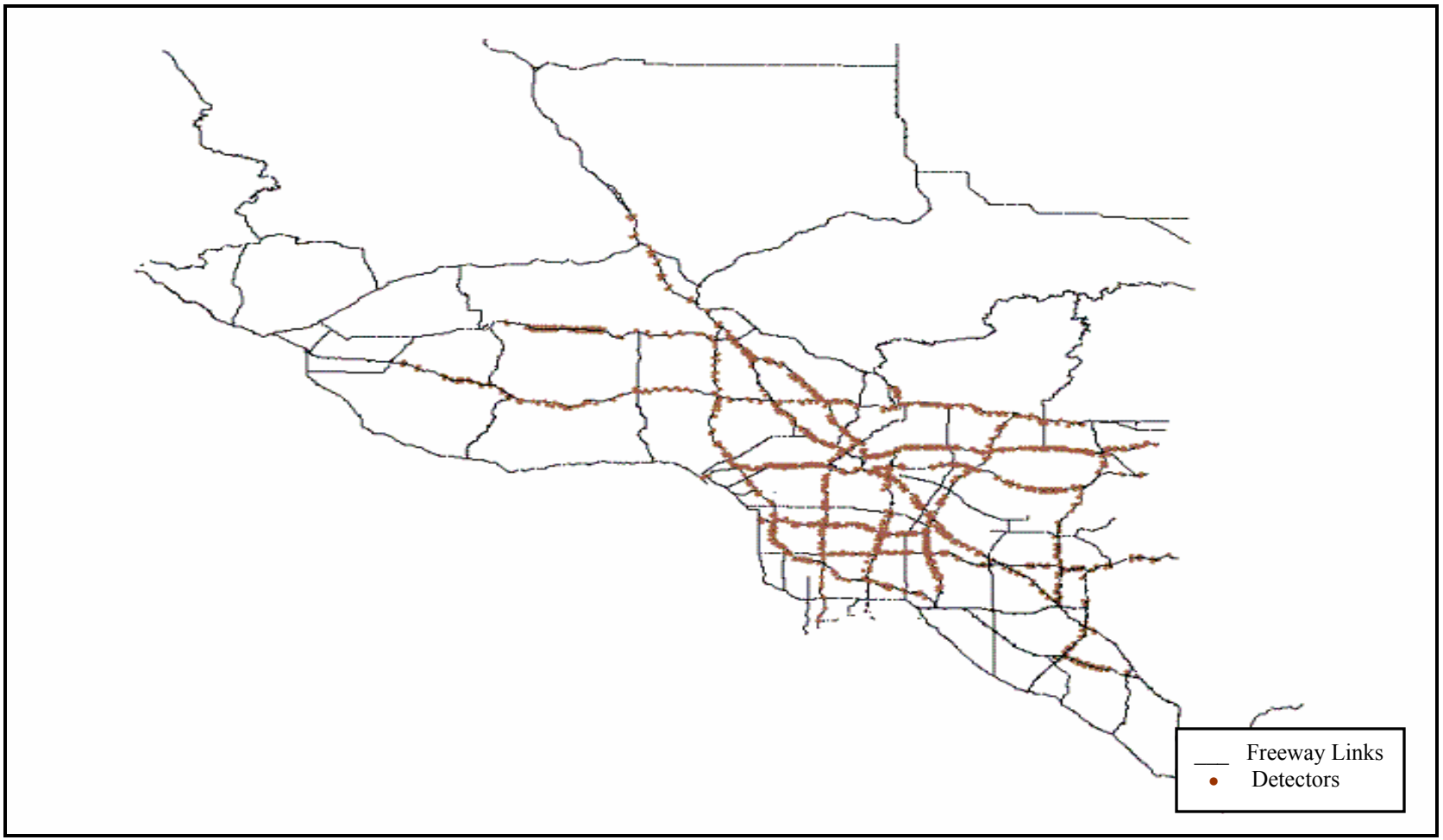

Figure 1. Freeway Links and Single Loop Detector Stations in SCAB

This study extends previous work by evaluating whether the differences in estimated mobile source emissions identified in Sogutlugil and Niemeier (2004a; 2004b) produce significant differences in estimated O_3 and $PM_{2.5}$ concentrations. We use the 3D Source Oriented Eulerian Air Quality Model for photochemistry modeling (Kleeman and Cass, 1997; Kleeman, Hughes et al., 1999; Kleeman and Cass, 2001), and UCDrive to produce gridded mobile source emissions (Niemeier, Zheng et al., 2004).

We produced gridded mobile source emissions inventories for the 23rd, 24th and 25th of July in 1997 for Los Angeles. Using UCDrive, carbon monoxide (CO), NO_x, sulfur oxide (SO_x), total organic gas (TOG) and PM (also called total suspended particles (TSP)) emissions from mobile sources were estimated for all of the 1764 (63×28) 5 km $\times$ 5 km grid cells specified in the region for each hourly period. The emissions differences between these three sets of three-day inventories (i.e., three-day gridded mobile source emissions inventories based on 1) hourly link, 2) 15-minute link, and 3) hourly lane average speeds) are the differences in running stabilized emissions estimated for freeways. Emissions for roadways other than freeways (e.g., arterials and collectors) were estimated using travel activity data for SCAB which were produced as input for the DTIM4 mobile emissions inventory model to forecast regional mobile source emissions for the SCAB Air Quality Management Plan (AQMP) (SCAQMD, 1997; SAI, 1998).

Mobile source emissions are classified into hot soak, idle, start, diurnal, resting loss, tire- and brake-wear and running stabilized emissions according to the process by

which they are produced. For each type of emission (i.e., CO, NO_x, SO_x, TOG and TSP), the calculations and data described in the following sections were performed to estimate gridded total mobile source emissions (i.e., mobile emissions produced by all processes) from all types of facilities.

Hourly Gridded Running Stabilized Emissions from Facilities other than Freeways

Mobile source inventories include emissions generated by many types of roadways, including freeways, arterials and collectors. With our single loop detector data we were able to directly produce travel activity (i.e., flow rates and average speeds) for freeway links which we later used as input for estimating running stabilized emissions. However, in order to estimate emissions from all types of roadways, we still need travel activity information for other facility types[2]. We used the South Coast Air Quality Management District (SCAQMD) travel activity data which was used for the AQMP to estimate running stabilized emissions for facilities other than freeways in Los Angeles (SCAQMD, 1997).

The data were originally produced as input to the California Department of Transportation (Caltrans) DTIM4 model (SAI, 1998). To use the data for our study, we re-formatted them as input to UCDrive and the travel activity data for freeways and other facility types were separated so that we could estimate running stabilized emissions for all facility types. All other inputs to UCDrive, such as the temperature

[2] The travel activity data for other roadway facilities are typically produced from the travel models and direct (but non-continuous) monitoring (e.g., traffic counts and speed studies).

and humidity defaults and vehicle mix information, are SCAB defaults provided in EMFAC2002 for calendar year 1997. The allocation factors used to distribute daily travel activity by hour are the allocation factors provided in UCDrive (Niemeier, Zheng et al., 2004), which were previously estimated based on allocation factors estimated for SCAB (Hicks and Niemeier, 2001).

The results of this process produced 1990 and 2010 hourly gridded running stabilized emissions based on 1997 defaults. Then, we linearly interpolated 1990 and 2010 running stabilized emissions (both estimated using 1997 defaults) for 1997. The resulting data set is the 1997 hourly gridded running stabilized emissions for facilities other than freeways.

Hourly Gridded Running Stabilized Emissions from Freeways

To test the effects of changing the resolution of average speeds to estimate hourly link running stabilized emissions, we estimated hourly gridded running stabilized emissions based on previously estimated hourly link, 15-minute link and hourly lane average speeds for freeway links. We established hourly gridded freeway running stabilized emissions as our base case given that using hourly average link speeds for gridded emissions estimation is the commonly-used approach. The other two sets of hourly gridded running stabilized emissions, based on 15-minute link and hourly lane average speeds, are the alternative cases.

Since not all of our study freeway links have single loop detector volume and occupancy measurements, we also had to estimate running stabilized emissions for

the grids that include those freeway links for which we had little or no real-world data. For these cases, we applied the same method discussed earlier for estimating running stabilized emissions for facilities other than freeways. That is, we estimated freeway gridded stabilized emissions using the SCAQMD travel activity data partioned for freeway links (SCAQMD, 1997) and then used these emissions values for the grids where there are freeway links but real-world travel activity data were not available. Daily running stabilized emissions estimated for the links where real-world data were not available (freeway running stabilized emissions estimated using SCAQMD data) was around 30% of the daily total running stabilized emissions from freeways for the three study days we focused on.

Hourly Gridded Mobile Source Emissions

Mobile source emissions comprise hot soak evaporative, idle, parks, diurnal, resting loss, running loss, tire- and brake-wear emissions in addition to running stabilized emissions (CARB, 2003). To account for mobile emissions other than running stabilized emissions, we estimated ratios of regional emissions produced by other mobile source processes (i.e., idle, parks, etc.) to regional running stabilized emissions for each pollutant type. For this process, regional emissions values for SCAB for calendar year 1997 were estimated using the BURDEN module of EMFAC2002 (CARB, 2003). The regional ratios for each pollutant type and the running stabilized emissions values estimated for each grid for the base case (i.e., gridded running stabilized emissions estimated using freeway hourly average link

speeds) were multiplied to calculate emissions produced by other processes for each grid.

Finally, three sets of hourly gridded mobile source emissions were estimated by summing up the same hourly gridded emissions from other processes and the three different sets of hourly gridded running stabilized emissions, which are based on different time resolutions for calculating freeway average speeds.

Gridded Mobile Emissions Inputs for the Photochemical Air Quality Model

Gridded mobile emissions are distributed by source category classifications (SCCs) which are identified by numbers 1 through 9 before they are used as input for the photochemical air quality model (Kleeman and Cass, 2001). The original SCCs defined for the mobile source emissions inputs of the photochemical air quality model are presented below (Table 1) (Kleeman, 2004).

Table 1. Original SCC Numbers and Their Definitions

SCC#	Definition
1	Light Duty Vehicles (LDV) Exhaust; No TOG Emissions Here
2	Catalyst LDV Exhaust, Cold
3	Catalyst LDV Exhaust, Hot
4	Non-Catalyst LDV Exhaust, Cold
5	Non-Catalyst LDV Exhaust, Hot
6	Hot Soak Evaporative
7	Diurnal (Fuel Tank) Evaporative
8	On-Road Diesel Exhaust
9	Running Losses

The SCCs are based on the assumption that all the vehicles other than the ones which operate with diesel fuels are light duty vehicles. However, in the latest release

emissions inventory model EMFAC2002 (CARB, 2003), 13 vehicle types are defined. Vehicles in each of these 13 vehicle type categories can be either gasoline-powered (therefore catalyst or non-catalyst) or diesel-powered vehicles. Moreover, the exhaust emissions from catalyst and non-catalyst gasoline vehicles are not grouped as "hot" or "cold" in the more current mobile emissions inventory models. In the photochemical air quality model source categorization, the SCCs which include exhaust emissions (i.e., SCC#'s 2, 3, 4, 5, 8) stand for all the emissions produced from vehicles' exhausts, that is, running stabilized, idle and starts emissions, thus, they are not as detailed as those contained in EMFAC2002.

To successfully group the total mobile source emissions we have estimated in the previous steps by SCC, we distributed exhaust emissions (i.e., running stabilized, idle and starts emissions) from all 13 types of vehicles to catalyst exhaust, non-catalyst exhaust and diesel exhaust emissions categories. Moreover, because the grouping of exhaust emissions as "cold" and "hot" exhaust emissions is not available in the current mobile emissions models (CARB, 2003), we used the SCCs numbered as 3, 5 and 8 (i.e., to "hot" categories only) for exhaust emissions [3]. For our categorization, given that resting losses are not identified among the original SCCs, we assumed that resting losses were part of diurnal emissions. Tire- and brake-wear particulate matter (PM) emissions were also not identified in any of the original SCCs, thus, we included these emissions in SCC category 1. Table 2 presents the SCC numbers in

[3] The previously defined 'cold' and 'hot' category exhaust emissions (i.e., running, idle and starts emissions) are used by the same processes represented in the photochemical air quality model. However, it is important to distribute the total ('cold' and 'hot' category exhaust emissions) for catalyst, non-catalyst and diesel vehicles given that exhaust emissions produced by different vehicle technology groups show different characteristics in terms of photochemical reactions.

which we distributed the mobile source emissions alongside their original and modified definitions. It is important to note that we did not use all the previously defined SCCs in Table 1 for producing the SCCs in Table 2, and we also somewhat modified their definitions in order to distribute all the calculated gridded mobile source emissions by SCC.

Table 2. Original and Modified Source Category Classifications [4](SCCs)

SCC#	Original Definition	Modified Definition
1	Light Duty Vehicles (LDV) Exhaust	**Tire- & Brake- Wear**
3	Catalyst LDV Exhaust, Hot	**Running Stabilized, Starts and Idle, Gasoline-Powered, Catalyst (All Types of On-Road Vehicles)**
5	Non-Catalyst LDV Exhaust, Hot	**Running Stabilized, Starts and Idle, Gasoline-Powered, Non-Catalyst (All Types of On-Road Vehicles)**
6	Hot Soak Evaporative	**Hot Soak Evaporative**
7	Diurnal (Fuel Tank) Evaporative	**Diurnal Evaporative and Resting Losses**
8	On-Road Diesel Exhaust	**Running Stabilized, Starts and Idle, Diesel-Powered (All Types of On-Road Vehicles)**
9	Running Losses	**Running Losses**

Similar to the method used for estimating mobile source emissions produced by processes other than running stabilized emissions, we estimated regional ratios for each pollutant type to distribute total mobile source emissions by SCC. We estimated these ratios utilizing regional daily mobile source emissions detailed by the source categories defined in Table 2 estimated using EMFAC2002 (CARB, 2003). For example, tire- and brake-wear emissions, partitioned to SCC#1, are PM emissions. The ratio of PM in SCC#1 to the total PM in a given grid is equal to the ratio of regional PM produced by tire- and brake-wear to the PM produced by all the PM

[4] The original SCCs defined in the air quality model were created to be used with EMFAC7G (CARB, 1996) outputs, that is with the outputs of the earlier version emissions inventory model. We produced the modified SCCs to apply the most current source category classifications included in EMFAC2002 (CARB, 2003) to the estimated emissions.

producing processes (PM is produced by running stabilized, idle and starts in addition to tire- and brake- wear).

Other Inputs for the Photochemical Air Quality Model

Additional input data needed for photochemistry modeling were taken from a previous study performed by Kleeman and Cass for the SCAB (Kleeman and Cass, 2001). Other emissions inventory data sets include the small point and area source emissions inventories for 1995 and large point source emissions provided for 1997 by SCAQMD. The PM emissions from point and area source were distributed using previously published particle size and composition profiles estimated earlier (Kleeman, Hughes et al., 1999). In addition, ammonia emissions were based on 1982 ammonia emission inventory estimated by Gharib and Cass (1984) and emissions from biogenic sources (from vegetation) were also used as emissions input data (Gharib and Cass, 1984; Kleeman, Hughes et al., 1999)

Meteorology input data, which includes wind speed, wind direction, temperature, relative humidity, total solar radiation and ultraviolet solar radiation measurements from various sites, were also used in the photochemistry modeling (Kleeman and Cass, 2001). The wind data were processed to estimate the wind field input.

Finally, the initial and boundary conditions must be specified for the model. The initial conditions represent the initial concentrations of O_3, NO_x, SO_x, CO, CO_2, VOC, nitric acid, ammonia and initial particle size and composition profiles whereas the boundary conditions represent the values of these pollutant concentrations at the

edges of the study region (Kleeman and Cass, 2001). The initial condition O_3, NO_x, SO_x, CO, CO_2, VOC concentrations were estimated by interpolating observed concentration values at 28 sites of SCAQMD. On the other hand, initial condition nitric acid, ammonia concentrations and initial particle size and composition profiles were estimated based on measurements from 3 sites. The boundary conditions were taken from previous studies focusing on photochemical modeling of the same region (Grosjean, Grosjean et al., 1996; Kleeman, Hughes et al., 1999).

RESULTS

Differences in Ozone Concentrations

Three sets of average hourly gridded O_3 concentrations based on the three different average speed resolutions for 12p were estimated in the photochemical air quality model (Kleeman and Cass, 2001). Figure 2 shows the hourly gridded O_3 concentrations estimated for the region in ppb (parts per billion) for the base case, that is, based on gridded mobile source emissions estimated using hourly link average speeds. Similar to the previous studies focusing on photochemistry modeling of the region (Kleeman and Cass, 2001), the O_3 levels are moderate to low in Central LA (shown as Section#1) given that NO_x levels are high, resulting in high NO_x/VOC ratios. The O_3 levels are high in Sections 2 and 3, where NO_x levels are lower and O_3 formation is not suppressed by high NO_x/VOC ratios.

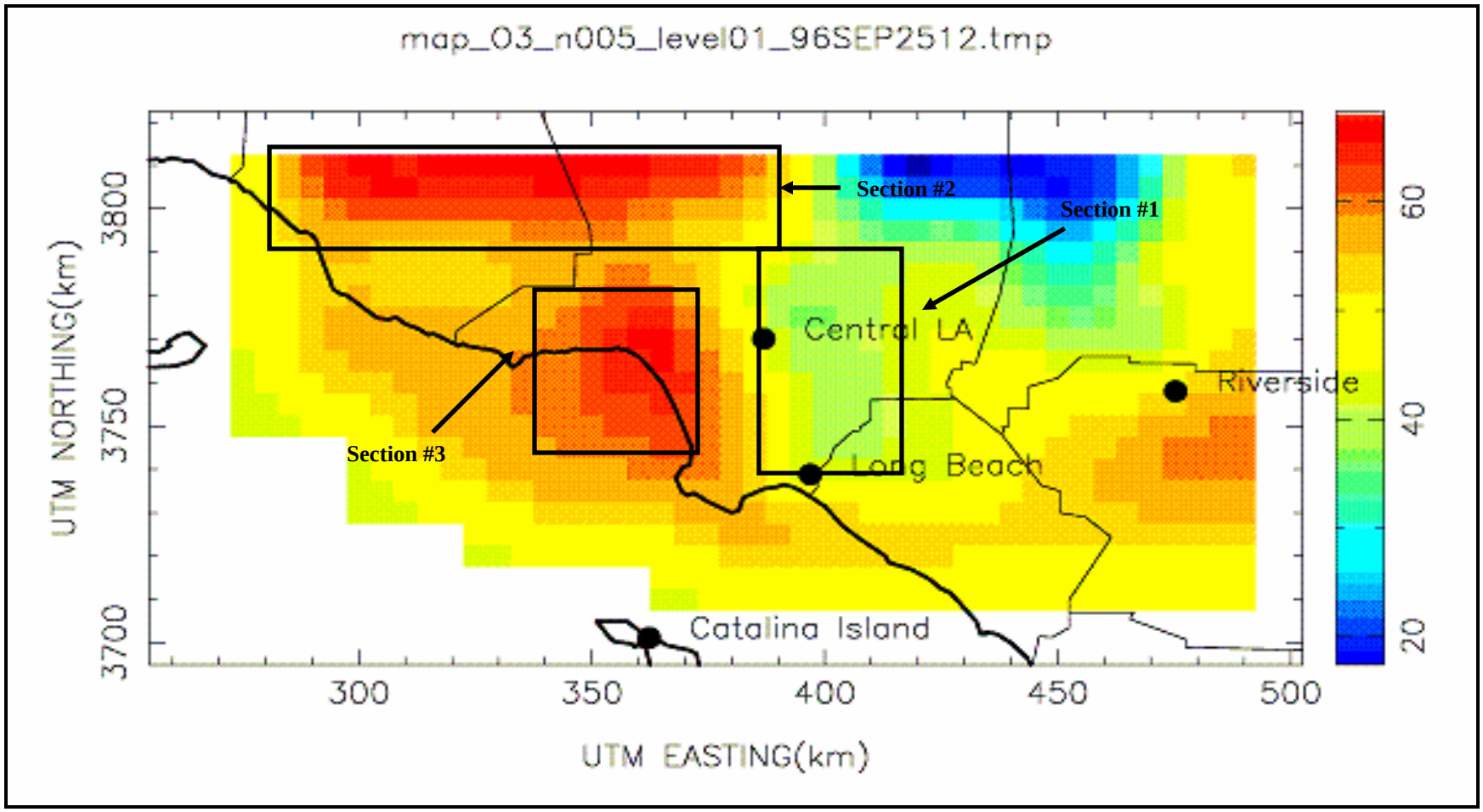

Figure 2. Estimated Hourly Average O_3 Concentrations for the Base Case for 12p (ppb)

Figure 3 demonstrates the differences in hourly gridded O_3 concentrations when 15-minute link average speeds are used for gridded mobile source emissions estimation. Based on the photochemistry results, the differences in O_3 estimated for each grid range between -5.9% and 7.1%.

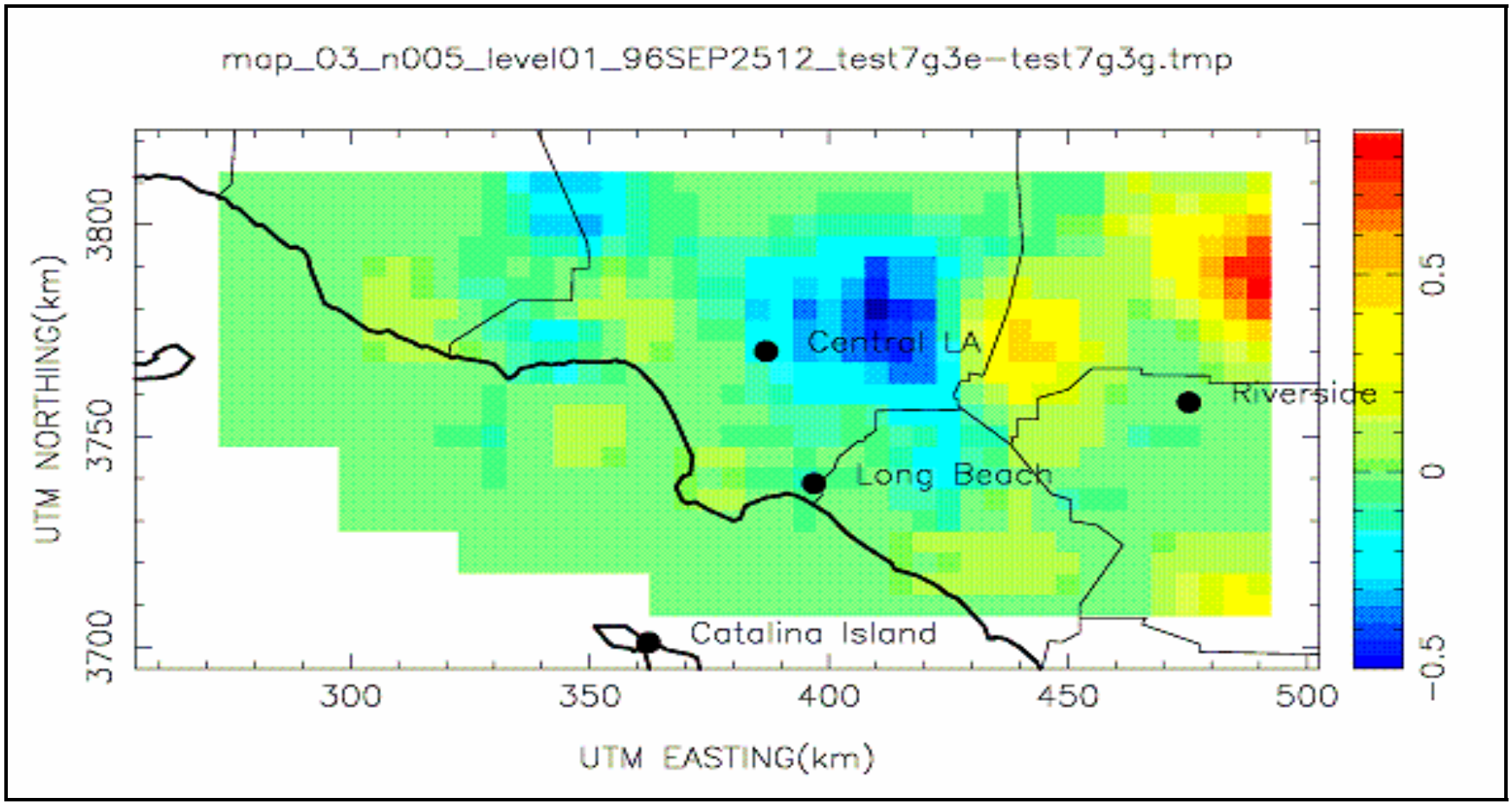

Figure 3. Estimated Differences in Hourly O_3 Concentrations for 12p (ppb) when 15-minute Link Average Speeds are Used in contrast to Hourly Link Average Speeds for Mobile Source Emissions Estimation

Figure 4 presents the differences in hourly O_3 concentration estimates when the speeds were differentiated by facility lanes on freeway links. The estimated differences in O_3 concentrations range from -7.9% to 2.9%.

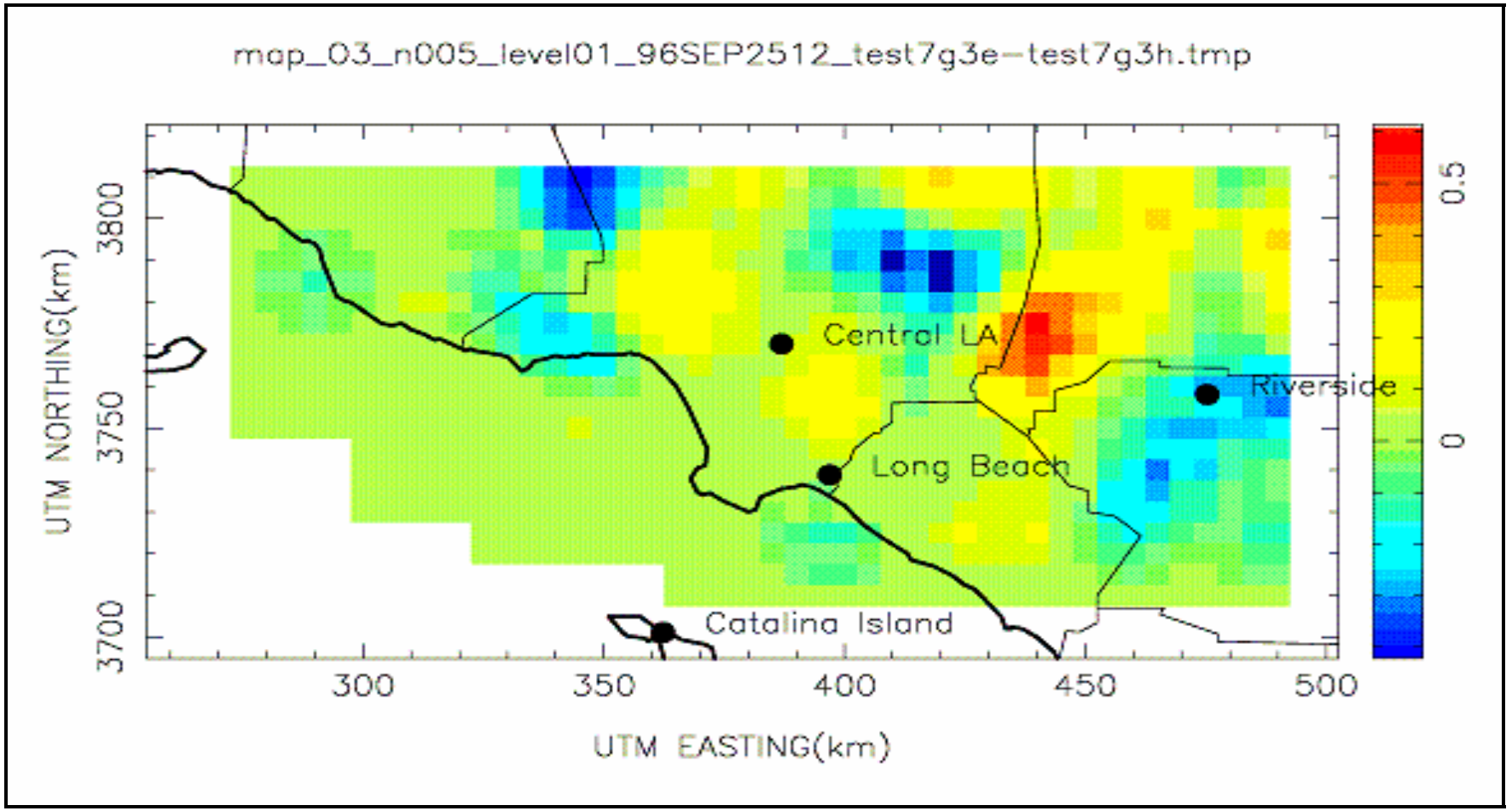

Figure 4. Estimated Differences in Hourly O_3 Concentrations for 12p (ppb) when Hourly Lane Average Speeds are Used in contrast to Hourly Link Average Speeds for Mobile Source Emissions Estimation

Differences in $PM_{2.5}$ Concentrations

Hourly average $PM_{2.5}$ concentrations were estimated using three different gridded mobile source emissions inventories based on hourly link, 15-minute link and hourly lane average speeds. Figure 5 presents the base case 24 hour average $PM_{2.5}$ concentration estimates in $\mu g / m^3$. The $PM_{2.5}$ concentrations are higher in the Central and South East parts of the study domain whereas the concentrations are lower at the coast.

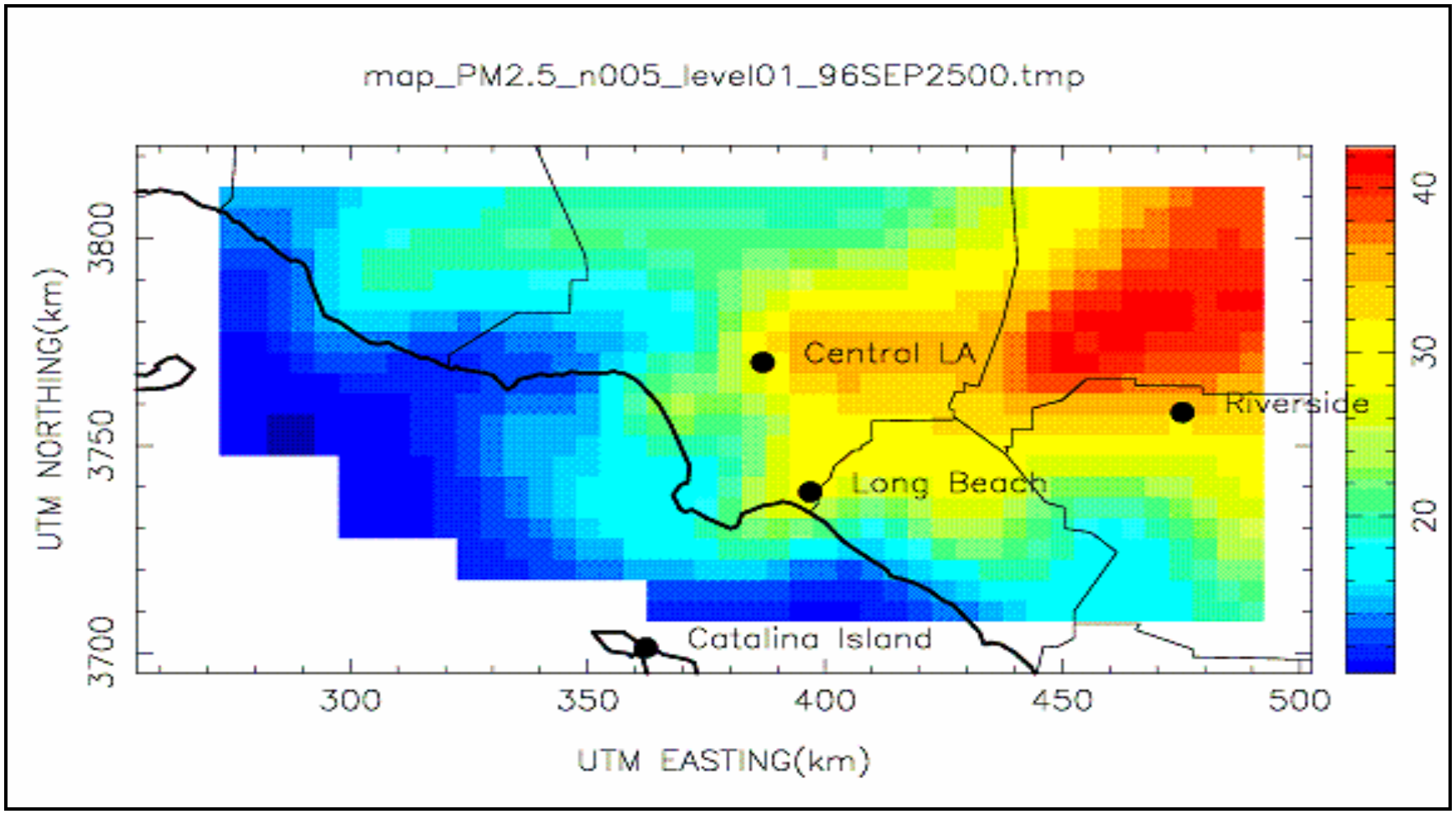

Figure 5. Estimated 24 hour Average $PM_{2.5}$ Concentrations for the Base Case ($\mu g / m^3$)

Figures 6 and 7 present the differences in 24 hour average $PM_{2.5}$ concentrations when 15-minute link average and hour lane average speeds are used for gridded mobile source emissions estimation. The estimated differences in $PM_{2.5}$ concentrations range from -9.1% to 5.26% when 15-minute average link speeds are used in contrast to hourly average speeds for estimating emissions from freeways. On the other hand, estimated differences range between -5.3% and 5.3% when hourly facility lane speeds are used for estimating freeway emissions.

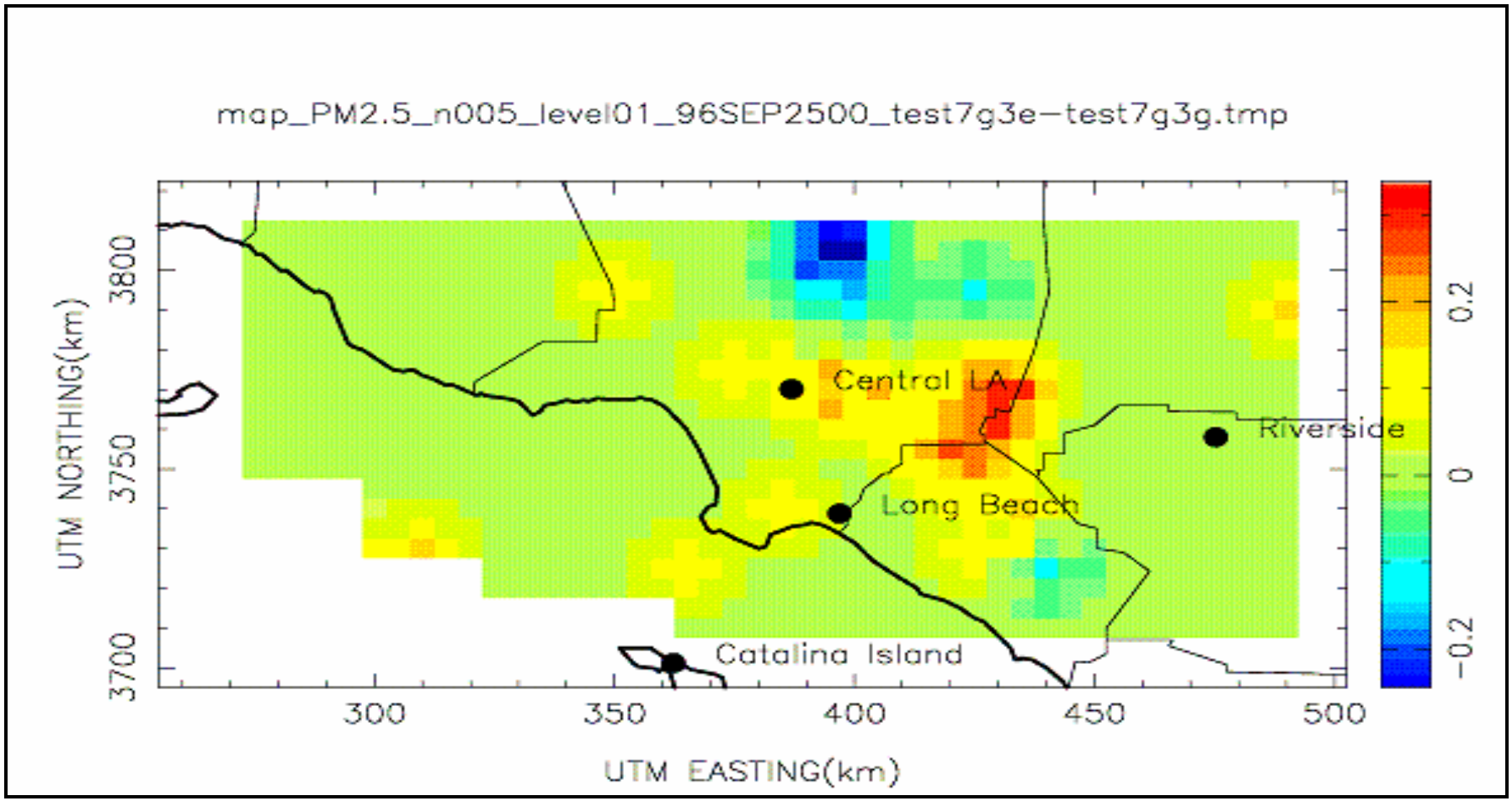

Figure 6. Estimated Differences in 24 hour average $PM_{2.5}$ Concentrations ($\mu g/m^3$) when 15-minute Link Average Speeds are Used in contrast to Hourly Link Average Speeds for Mobile Source Emissions Estimation

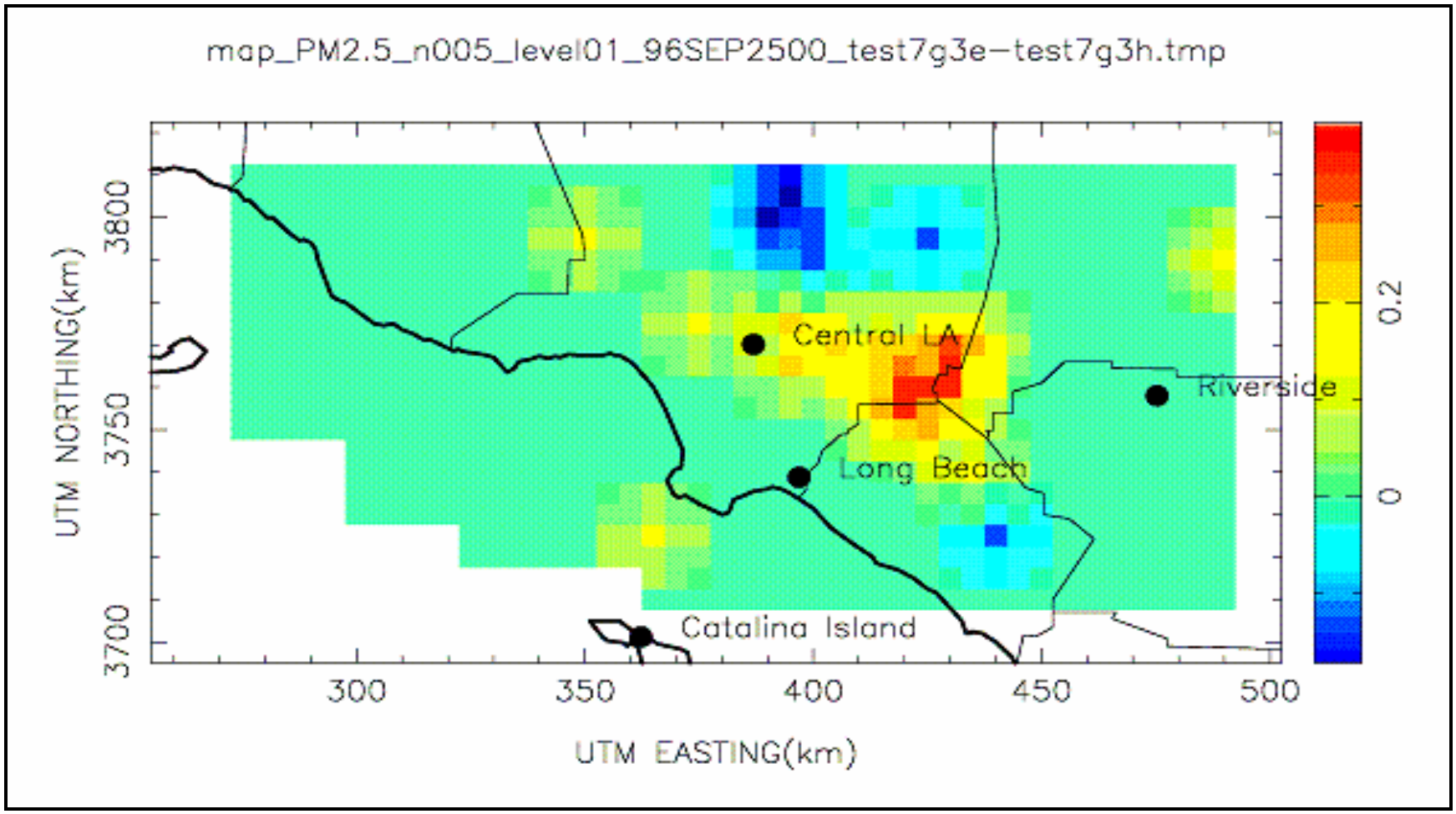

Figure 7. Estimated Differences in 24 hour average $PM_{2.5}$ Concentrations ($\mu g/m^3$) when Hourly Lane Average Speeds are Used in contrast to Hourly Link Average Speeds for Mobile Source Emissions Estimation

Univariate t-testing was also performed to test if base case gridded O_3 and $PM_{2.5}$ estimates are significantly different from gridded O_3 and $PM_{2.5}$ estimates based on 15-minute link and hourly lane average speeds. The results based on concentrations estimated for all the grids in the region showed that O_3 estimates were not, however, $PM_{2.5}$ estimates were significantly different across scenarios.

To examine the differences in estimated O_3 and $PM_{2.5}$ based on hourly link, 15-minute link and hourly lane average speeds , we also estimated the hourly distribution of O_3 and $PM_{2.5}$ concentrations for Central LA (Section covering between 400 m and 440 m in the x-direction and 3750 m and 3790m in the y-direction in the UTM coordinate system). Figures 8 and 9 show that the estimated hourly concentrations of O_3 and $PM_{2.5}$ do not significantly differ when hourly link, 15-minute link and hourly lane average speeds are used for estimating emissions from freeways.

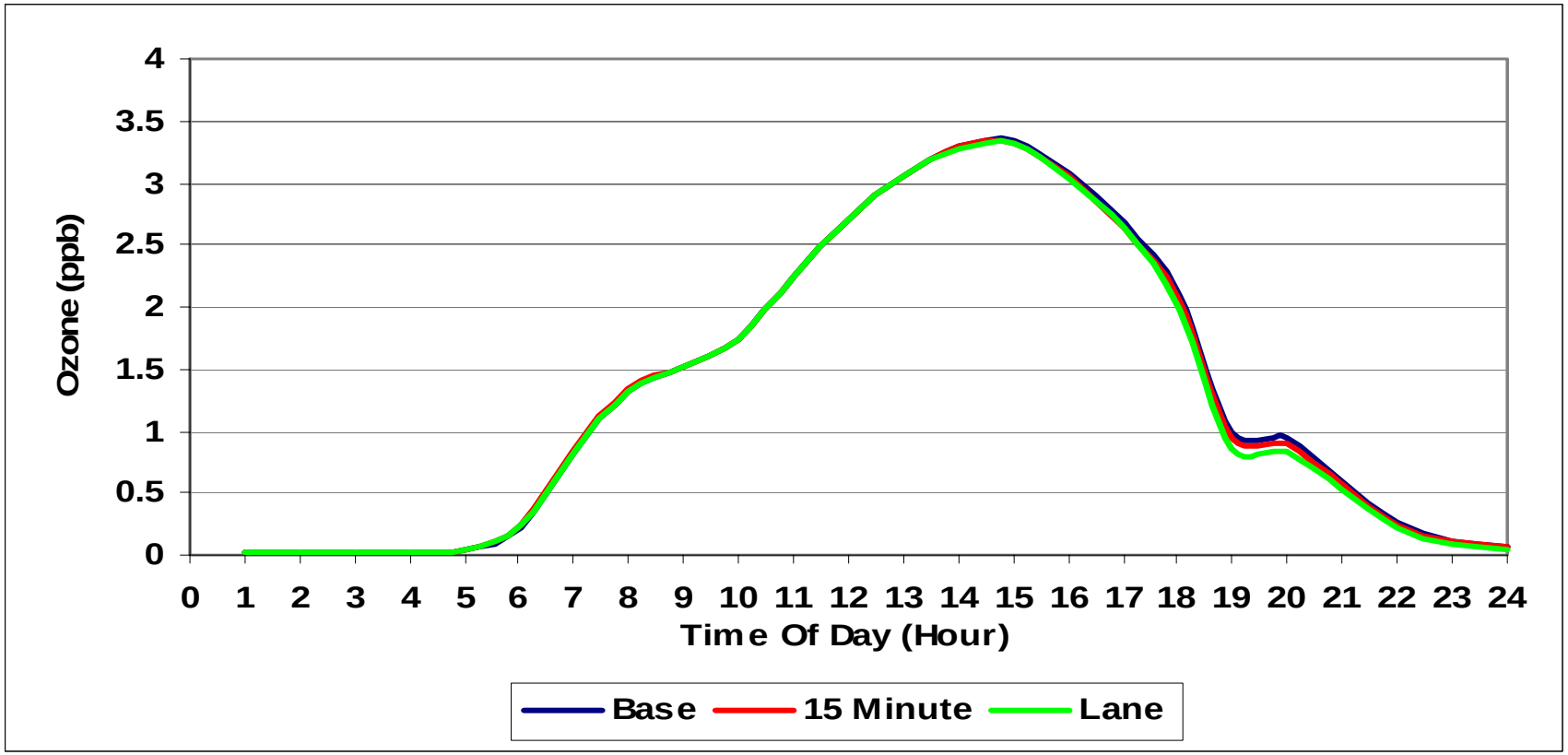

Figure 8. Hourly Distribution of O_3 concentrations for Central LA (ppb)

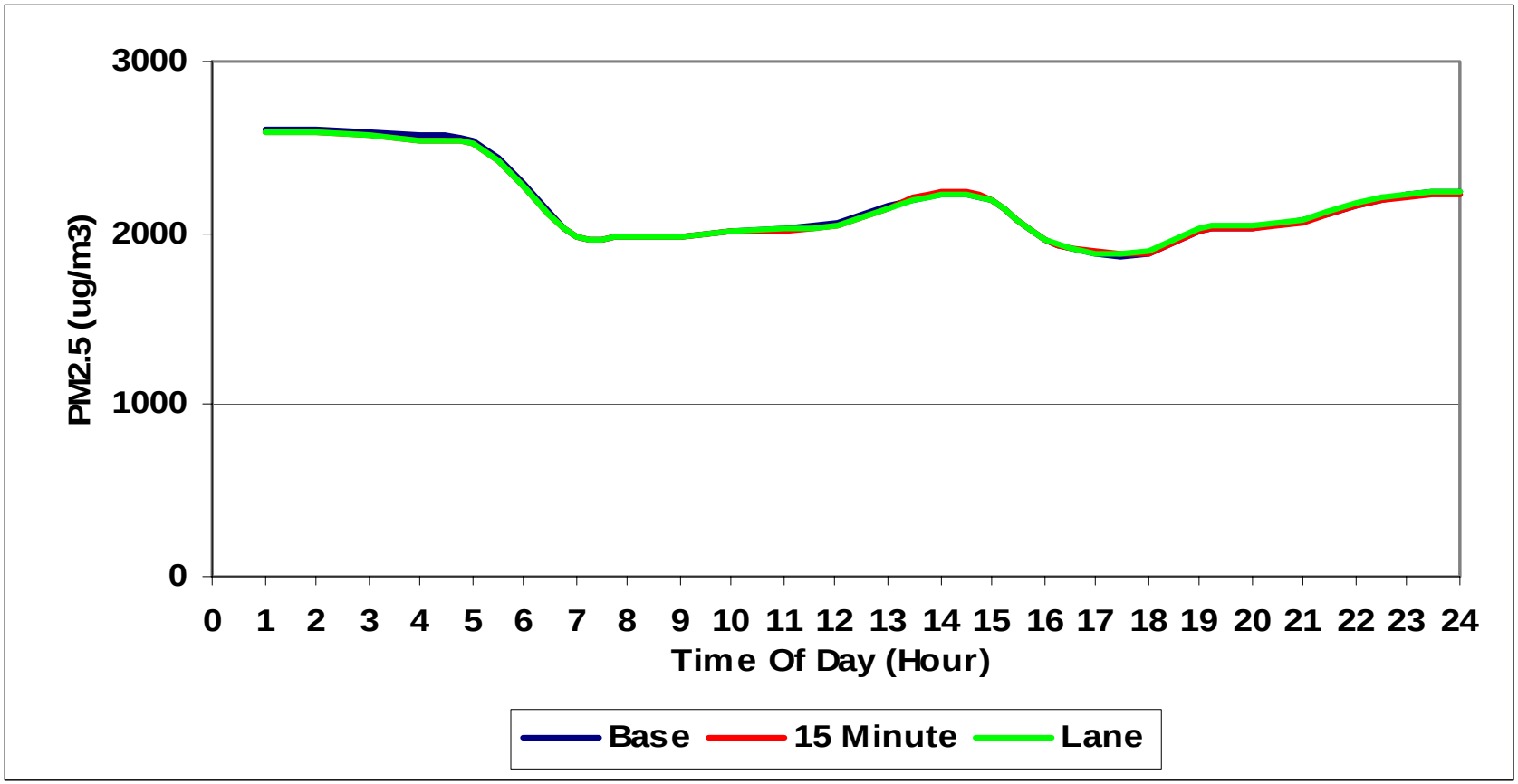

Figure 9. Hourly Distribution of $PM_{2.5}$ concentrations for Central LA ($\mu g/m^3$)

Since hourly concentration estimates do not differ significantly when hourly link, 15 minute link and hourly lane average speeds are used for mobile source emissions estimation for a given section, next we examine the variation of hourly O_3 estimates for the 64 grid cells for only one set of concentration estimates (base case). Figures 10 through 14 present hourly O_3 estimates alongside the TOG and NO_x emissions (O_3 precursors) produced by mobile sources for hourly periods from noon through 4p (i.e., the hourly periods during which the estimated O_3 concentrations are high (Figure 8)). The figures show that not only the concentrations but also the mobile source emissions differ across the grid cells. Moreover, these differences across grids show different characteristics for different hourly periods.

For example, the TOG and NO_x emissions from mobile sources are zero and O_3 concentrations are high compared to the concentrations in other grids for the grid identified as 1 for 12p through 4p (north-east corner of the section) (Figures 10 through 14). On the other hand, for the grid identified by 2, the TOG and NO_x emissions from mobile sources are high compared to the emissions from other grids. The O_3 concentrations estimated for this grid are very low for 12p and 1p (Figures 10 and 11), however, they are high for 2p, 3p and 4p (Figures 12, 13 and 14).

The TOG and NO_x emissions from mobile sources differ across the grids located along the west border of the section. However, the O_3 concentrations estimated for these grids are similar and low in magnitude for these grids (although there are increases in the concentrations after 2p at the south-west of the section, still these

concentrations are lower than the concentrations at the north-east of the section). These results show that based on ozone precursor magnitudes from mobile sources, it is premature to comment on secondary pollutant concentrations such as O_3, especially for high spatial and temporal resolutions.

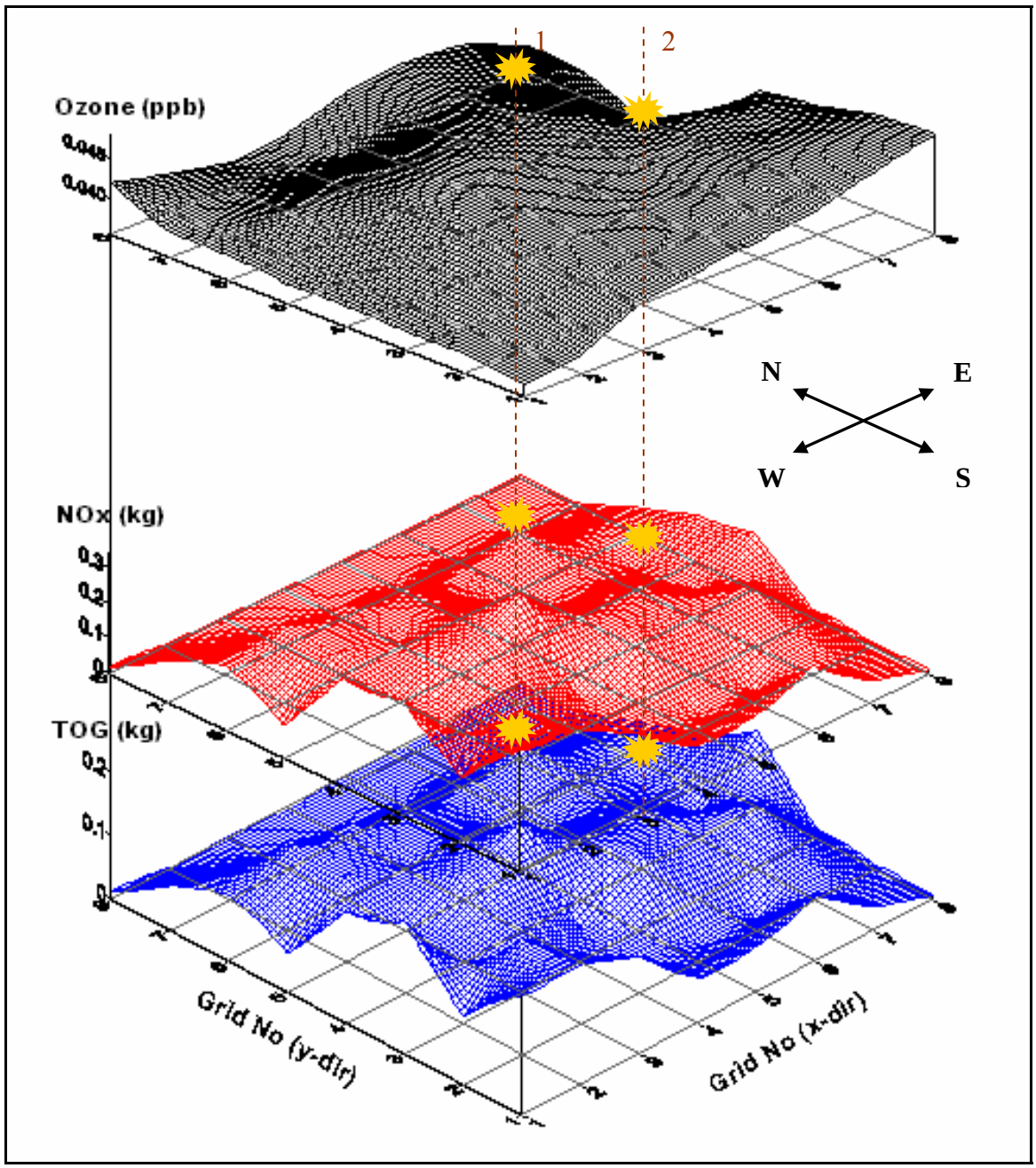

Figure 10. Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 12p

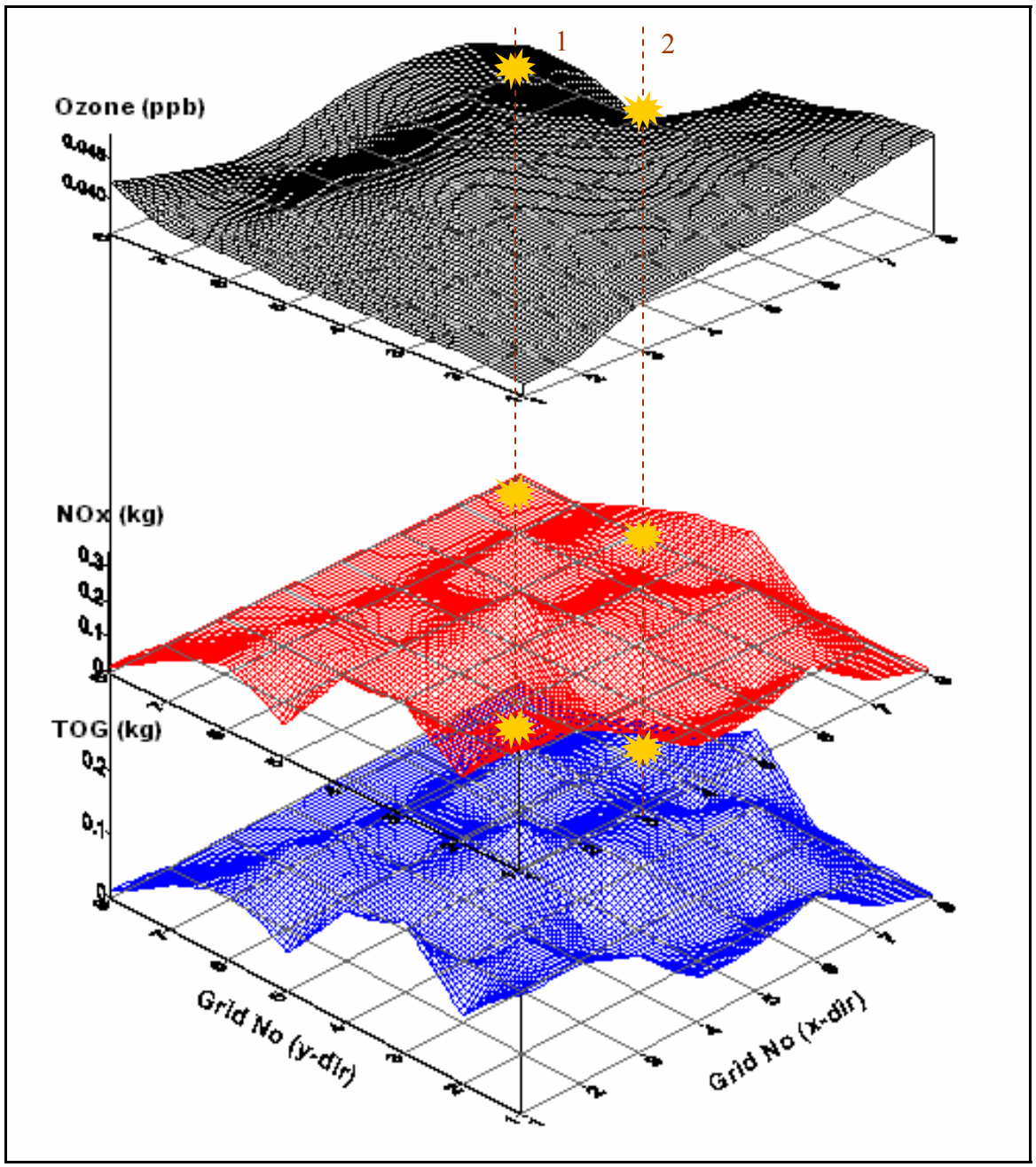

Figure 11. Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 1p

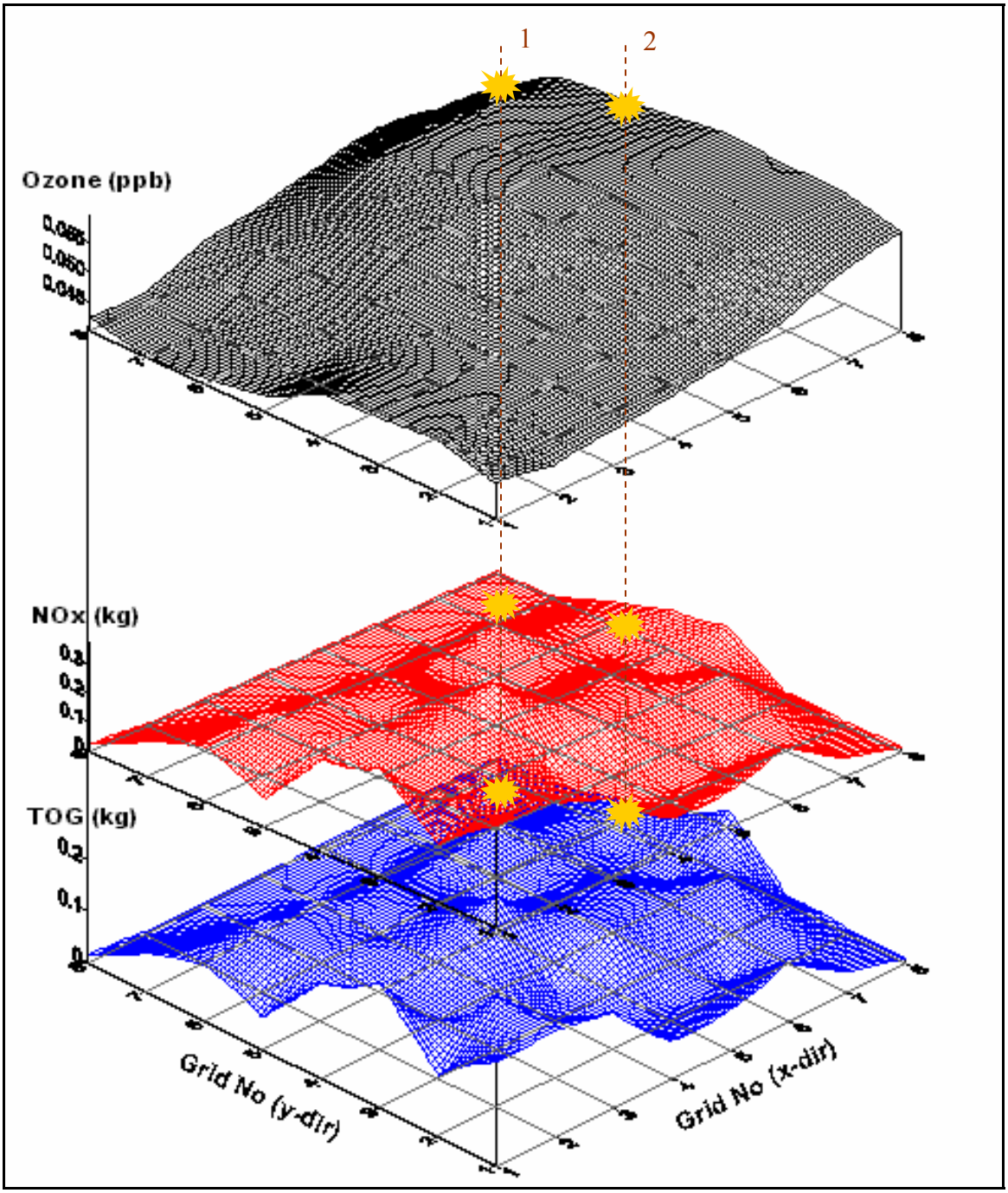

Figure 12. Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 2p

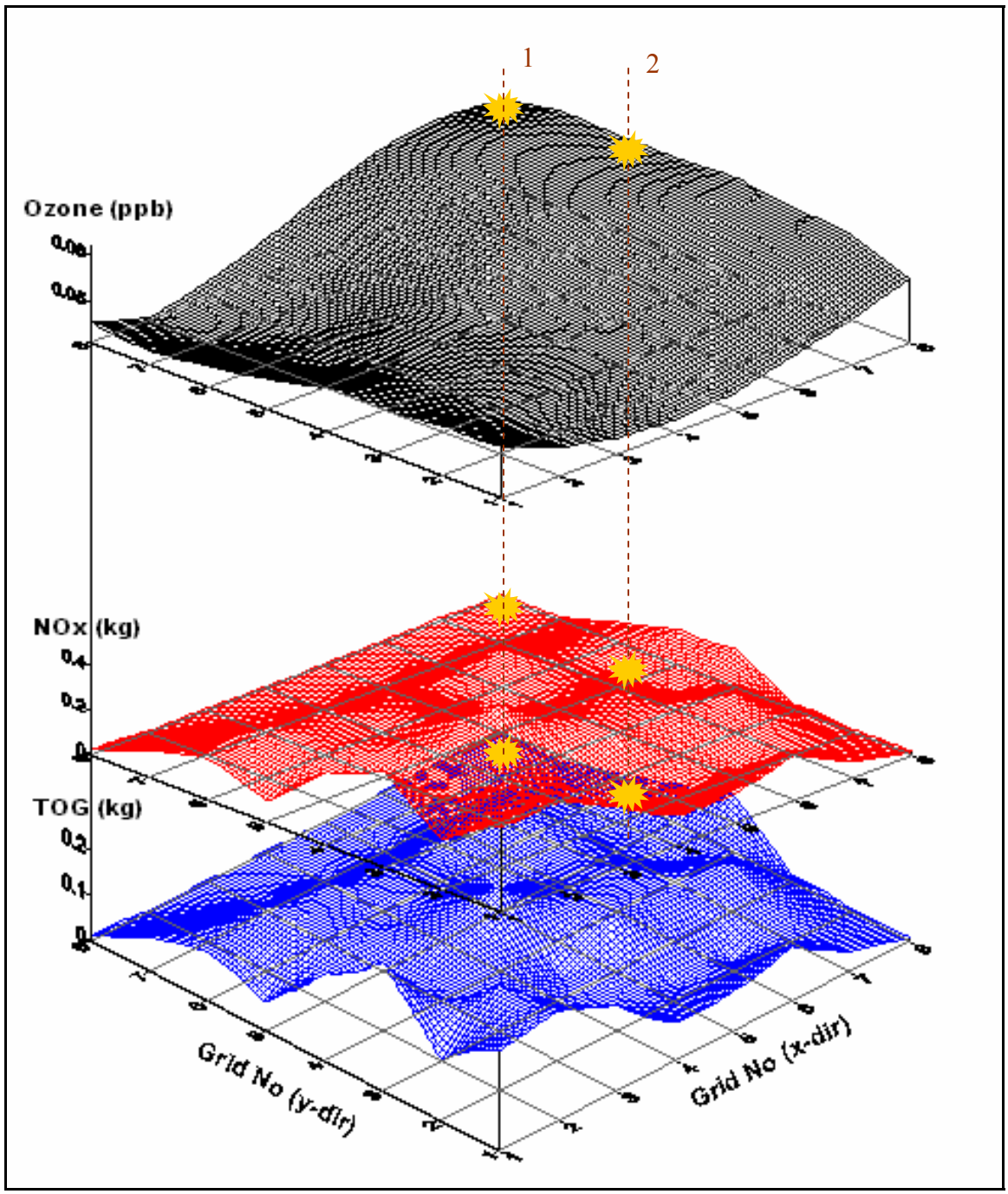

Figure 13. Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 3p

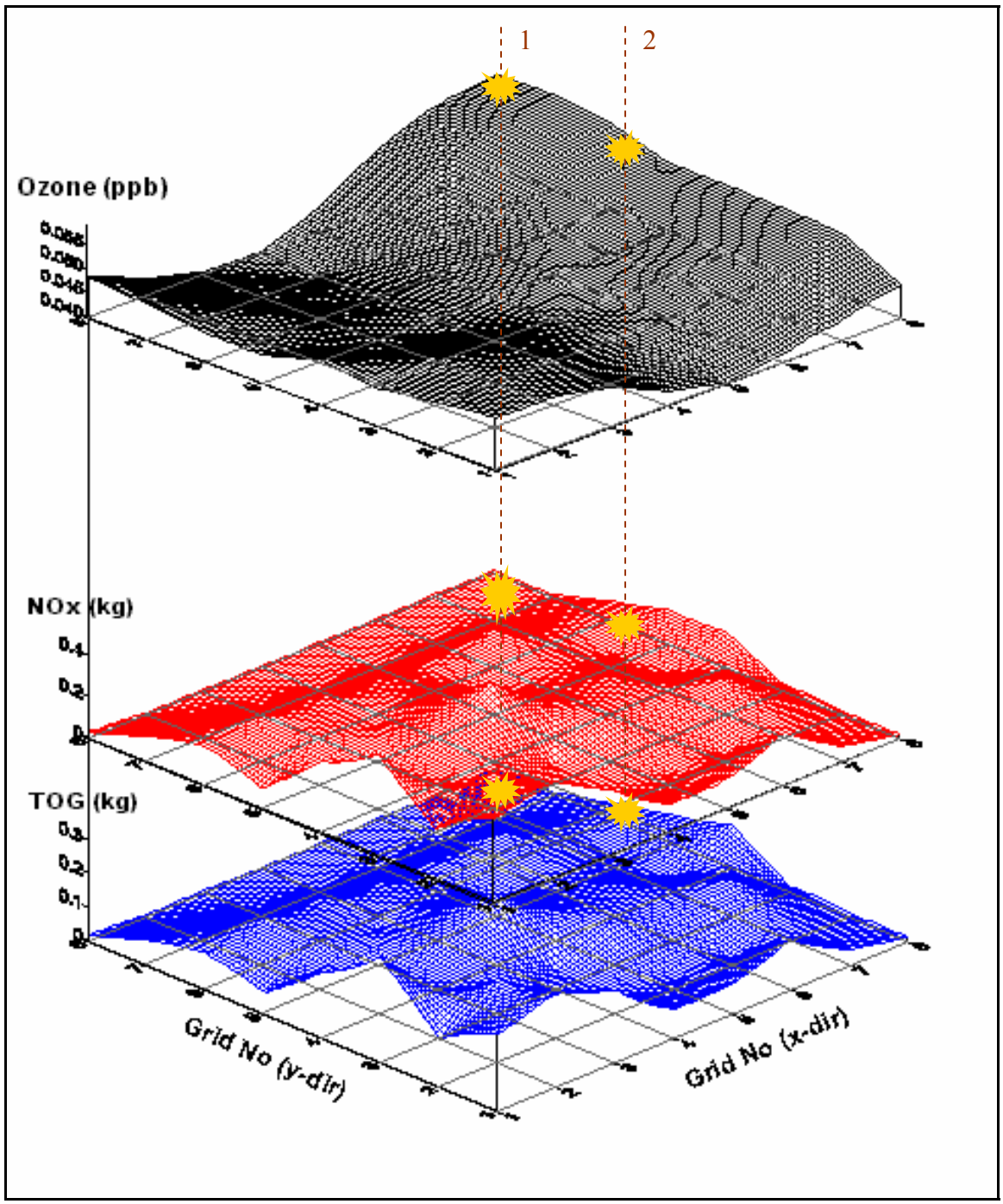

Figure 14. Mobile Source TOG and NO_x Emissions (kg) and Estimated O_3 Concentrations (ppb) for Central LA, 4p

Discussion of Results

In our previous studies we found that the hourly link running stabilized emissions increased as much as ~ 3.0% and ~ 18.0%, and decreased as low as -1.5% and -20.0% when 15-minute link average and hourly lane average speeds were used for estimation, respectively (Sogutlugil and Niemeier, 2004a; Sogutlugil and Niemeier, 2004b). Although the differences in hourly link running stabilized emissions were significantly higher in magnitude when hourly lane average speeds are used compared to the magnitudes of the differences when 15-minute link average speeds are used, we have shown in the previous section of this article that the resulting impact of differences in emissions on estimated O_3 and $PM_{2.5}$ concentrations are not that different across scenarios (Figures 3, 4, 6 and 7).

In fact, the differences in estimated O_3 and $PM_{2.5}$ concentrations are quite similar across the two scenarios because only 26% of the regional travel occurs on freeways in the region (Sierra Research, 1997) and the freeway emissions for which we could utilize real-world variable average speeds for estimation is around 70% of the total emissions from freeways. Therefore, only 18% of the total travel activity data used to estimate the mobile source emissions is based on real-world data, that is, the variable speeds for 15-minute periods and across lanes could be used for only 18% of the regional travel activity for mobile source emissions estimation. Taking the emissions from area and point sources (which are constant across scenarios) into consideration as well, the magnitudes of the daily total emissions inputs change very little across scenarios. Table 3 presents the total (from all sources) and mobile source emissions

values for a section in the modeling domain for which the differences in gridded O_3 and $PM_{2.5}$ concentrations have higher magnitudes when compared to the other locations in the region (Figures 3, 4, 6 and 7). The section is the part of the domain covering Central LA between 400 m and 440 m in the x-direction and 3750 m and 3790 m in the y-direction in the UTM coordinate system. Even in Central LA, where the differences in estimated pollutant concentrations are somewhat higher, the differences in daily total emissions inputs are very low for the three scenarios we examined.

Table 3. Emissions from All Sources (AS)[5] and Mobile Sources (MS) Used as Input for Photochemical Modeling – Central Los Angeles (tons/day)

		TOG	NMOG	NO_x	CO	SO_x	TSP	PM_{10}	$PM_{2.5}$	$PM_{0.1}$
Base Case	**AS**	296.74	165.67	119.08	966.96	3.53	27.12	15.05	6.42	1.0
	MS	80.98	76.91	67.36	753.46	0.53	2.63	1.75	1.62	0.29
When 15-minute Link Average Speeds are Used	**AS**	295.57	165.67	118.06	966.96	3.51	27.09	15.02	6.40	.99
	MS	79.81	75.79	66.35	741.75	0.51	2.60	1.72	1.59	0.28
When Hourly Lane Average Speeds are Used	**AS**	296.60	165.53	118.08	960.71	3.52	27.12	15.04	6.41	1.0
	MS	80.83	76.77	66.31	747.21	0.52	2.63	1.74	1.61	0.28

[5] 'All sources' means all emissions producing sources, that is, area-, point and mobile sources.

Daily total and daily mobile source emissions values were also estimated for other sections and the differences in estimated emissions either do not exist or are very negligible for all of those sections.

It should be noted that, in addition to the fact that the contribution of freeway travel (for which we could use variable 15-minute link and hourly lane average speeds for emissions estimation) to the total emissions produced in the region is only 18%, using 15-minute link and hourly lane average speeds for estimation resulted in both increases and decreases in estimated emissions values for facility links (Sogutlugil and Niemeier, 2004a; Sogutlugil and Niemeier, 2004b). Therefore, the absolute values of the differences in daily mobile source emissions (estimated by summing up mobile source emissions estimated for each hour of the day) become low. Given that emissions from other sources do not differ across scenarios, the differences in daily total emissions (estimated by summing up mobile source emissions and emissions from other sources) do not exist or are very negligible. Next, we focused on exploring the factors which result in, although in low magnitude, differences in pollutant concentrations.

Given that changing the resolution of average speeds for emissions estimation did not substantially change the daily total emissions values across the scenarios, the differences in concentration estimates result from the differences in the allocation of mobile source emissions throughout the day to each hourly period. In other words, allocation of daily mobile source emissions to each hour of the day is the only major difference among the photochemical air quality model inputs which in fact resulted

from using hourly link average, 15-minute link average and hourly lane average speeds are used for emissions estimation[6].

To present the effects of using different resolution average speeds, which change the allocation of emissions to each hourly period during the day, on pollutant concentrations, we examined the differences in O_3 and $PM_{2.5}$ concentrations for another alternative case. For this case, we used the daily mobile source emissions values estimated for the base case, however, substituted constant allocation factors provided in UCDrive in contrast to utilizing the allocation factors we estimated using real-world hourly link average speeds (Hicks and Niemeier, 2001; Niemeier, Zheng et al., 2004). While mobile source emissions are estimated, these constant allocation factors are used to partition the travel activity estimated for multi-hour periods in the travel demand models to each hourly period (Ortuzar and Willumsen, 1994; Niemeier, Zheng et al., 2004). Therefore, for this new scenario, all the input data sets for the photochemistry modeling including the daily mobile source emissions are identical for the base and the alternative cases except for the allocation of emissions to hourly periods. Figure 15 and 16 present the differences in estimated O_3 and $PM_{2.5}$ concentrations. Although we used the same daily base case total daily emissions as input data for the alternative case, the differences in concentrations for both pollutants are higher than the differences resulting from using 15-minute link and hourly lane average speeds (Figures 3, 4, 6 ,7, 15 and 16).

[6] The commonly-used approach is to allocate daily estimated emissions (or travel activity) to each hourly period using region-wide allocation factors. In this study, we first estimated hourly emissions and then estimated hourly allocation factors by dividing hourly emissions by daily total emissions.

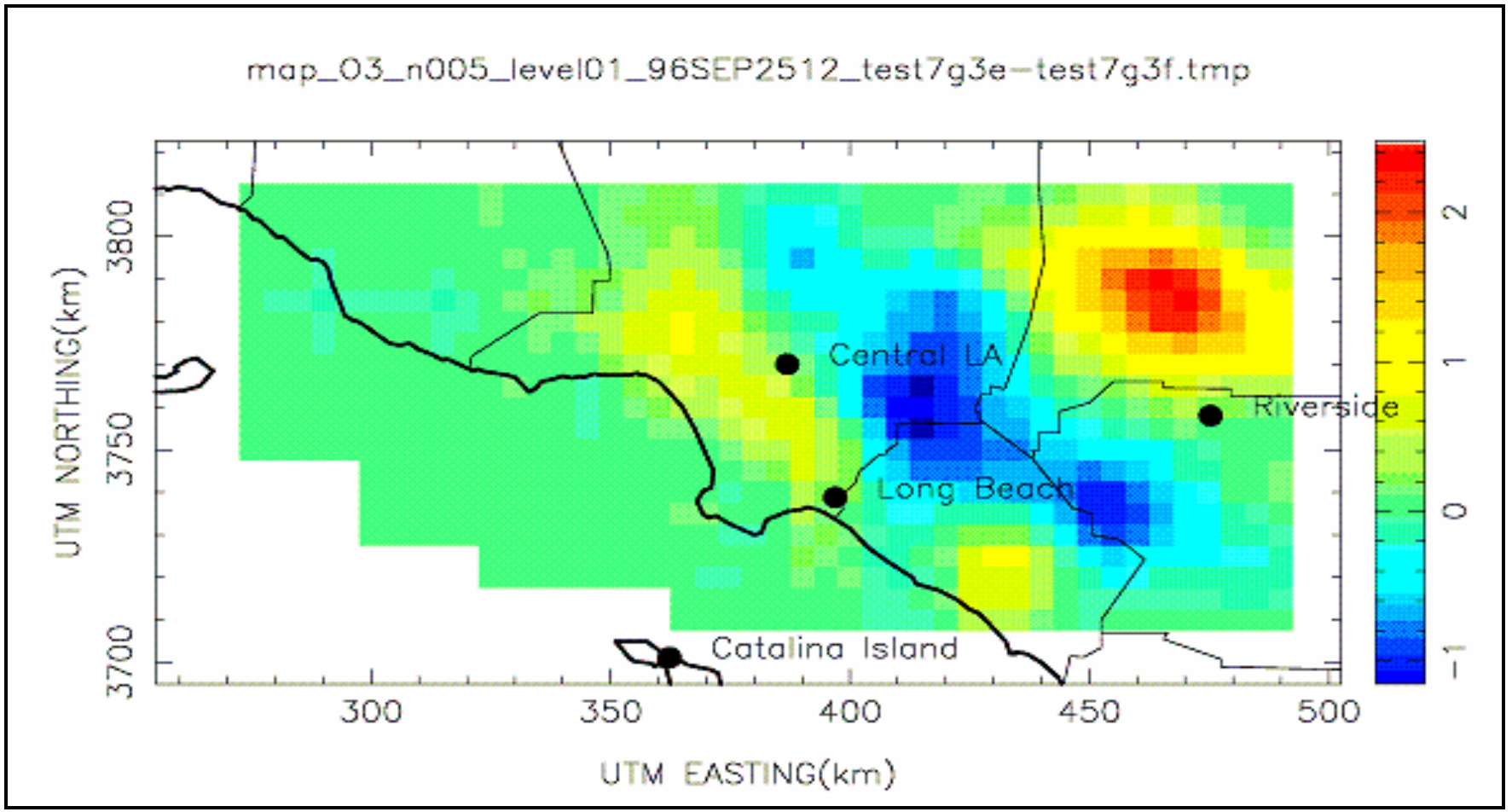

Figure 15. Estimated Differences in Hourly O_3 Concentrations for 12p (ppb) when Constant Allocation Factors versus Base Case Allocation Factors are Used (Holding Total Emissions Constant and Equal to Base Case Total Emissions)

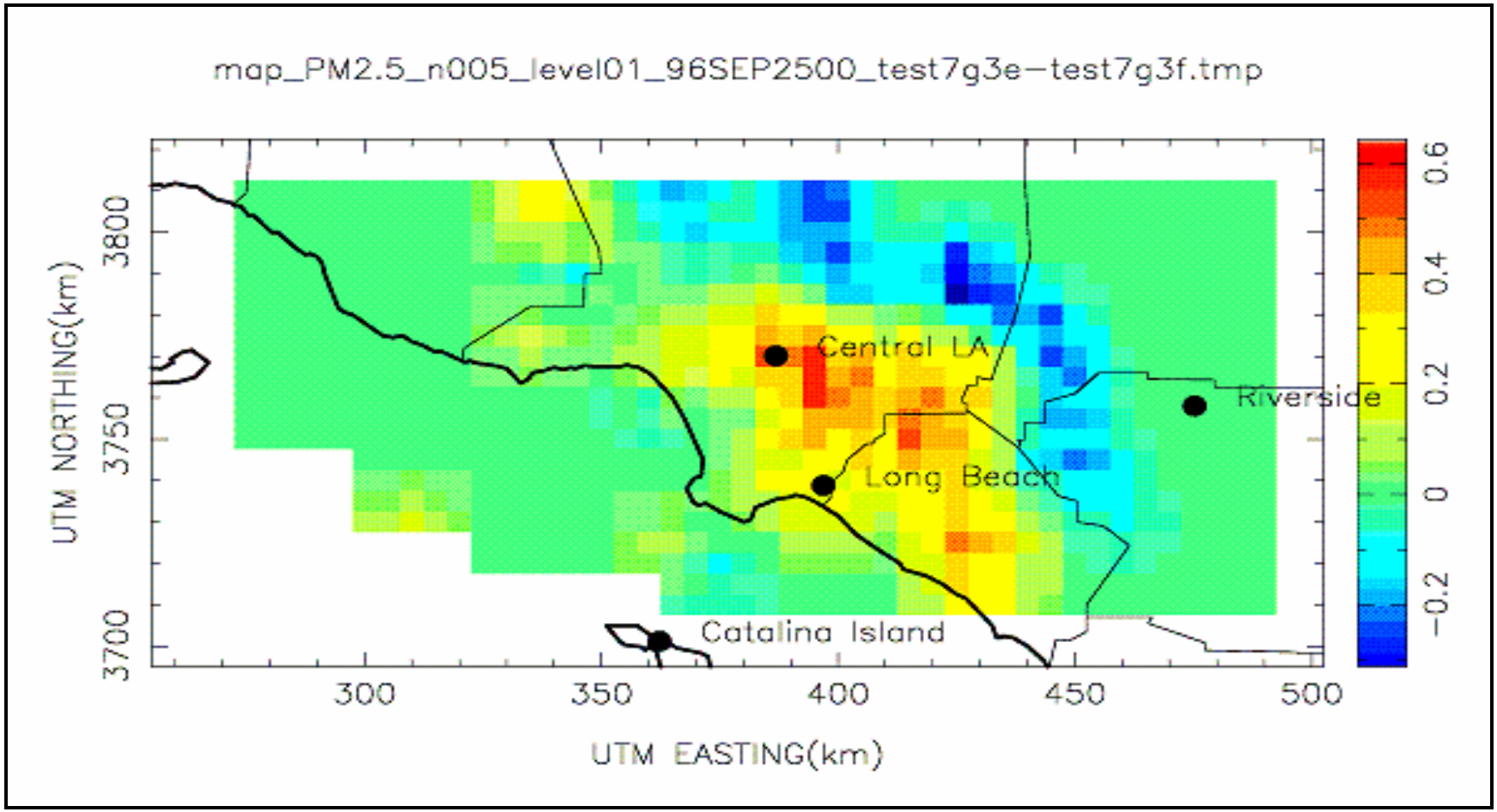

Figure 16. Estimated Differences in 24-hour average $PM_{2.5}$ Concentrations ($\mu g/m^3$) when Constant Allocation Factors versus Base Case Allocation Factors are Used (Holding Total Emissions Constant and Equal to Base Case Total Emissions)

The differences in gridded concentration estimates in Figures 15 and 16 are the result of using different allocation factors. Moreover, for a given set of emissions (such as when mobile source emissions were estimated using hourly link speeds), the allocation of mobile source emissions to each hourly period also differs across grid cells in a section. Figure 17 demonstrates the hourly distributions of mobile source emissions when hourly link, 15-minute link and hourly lane average speeds are used, alongside the constant allocation factors used in UCDrive, for the section for which we estimated quite similar daily total emissions values in Table 3. The section (domain covering Central LA between 400 m and 440 m in the x-direction and 3750 m and 3790 m in the y-direction in the UTM coordinate system) includes 64 5 km$\times$5 km grid cells. The figure shows that the hourly distribution of daily mobile source emissions is not constant. The average values for the hourly allocation factors for each set of mobile source emissions are presented with their standard deviations to demonstrate the variations of allocation factors across the 64 grid cells of the section.

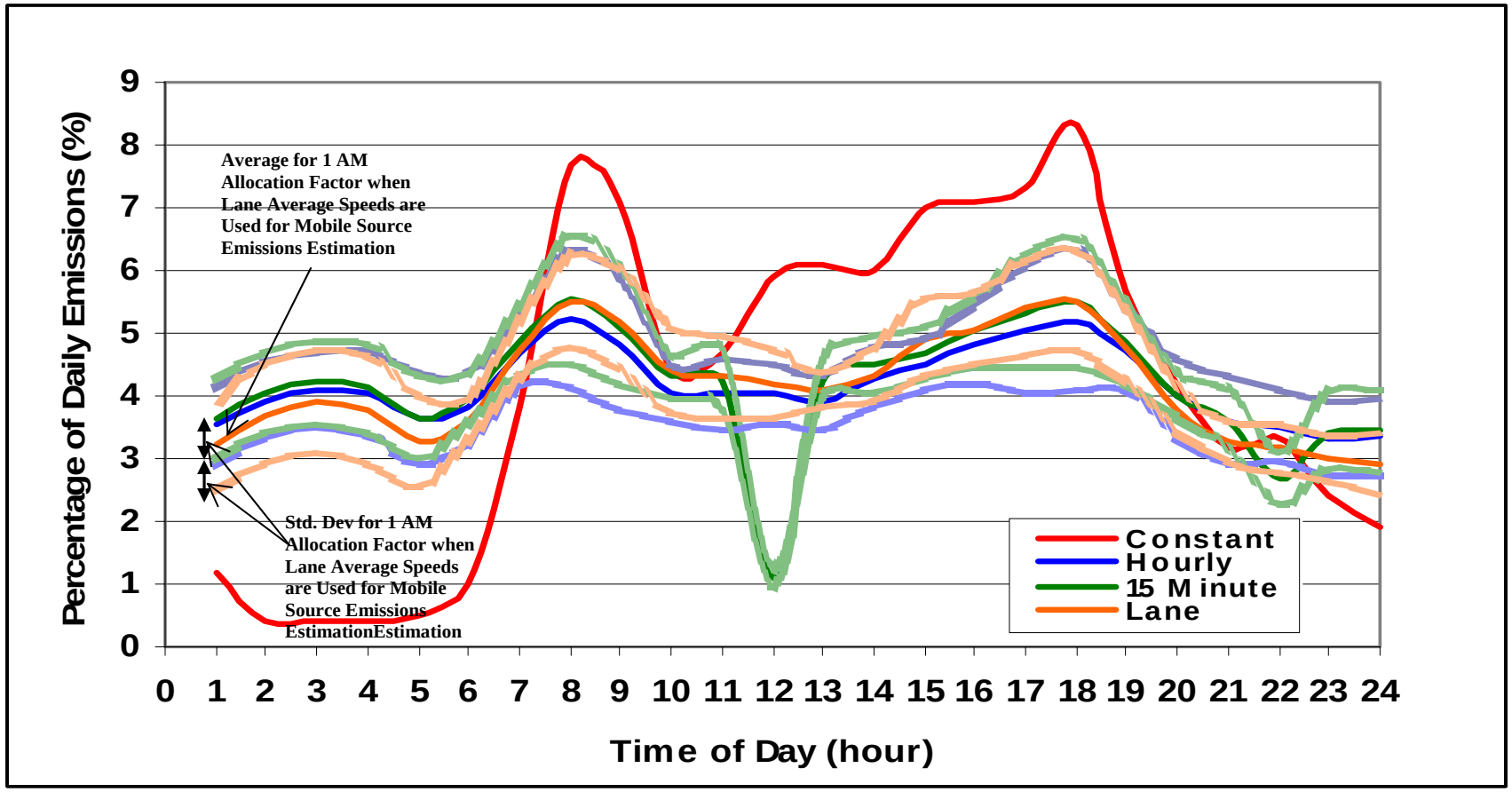

Figure 17. Hourly Allocation Factors for Mobile Source Emissions when a) Hourly Link, b) 15-Minute Link, c) Hourly Lane Average Speeds are Used for Emissions Estimation

Conclusion and Further Research

There are two major findings from this study. First, along with the findings from our previous studies (Sogutlugil and Niemeier, 2004a; Sogutlugil and Niemeier, 2004b), analyzing the effects of using higher resolution average speeds on estimated emissions is not adequate to interpret the resulting effects on estimated pollutant concentrations. Second, even if the daily total emissions values differ only slightly when different resolution average speeds are used, allocation of these emissions to each hour differs when variable average speeds are used and this produces differences in estimated pollutant concentrations.

The second finding also indicates that using constant allocation factors for all the locations in a region to distribute daily total emissions by hour is misleading. There is need for more spatially and temporally resolved travel activity data to overcome uncertainties in emissions estimation and eventually photochemistry modeling.

Based on these findings, further research should focus on the effects of using higher resolution average speeds (e.g., 15-minute lane average speeds or speeds averaged for periods lower than 15 minutes)`on the distribution of daily emissions by hour and their effects on estimated pollutant concentrations. However, it should be noted that, to perform more advanced analyses to address the uncertainties related to variability in average speeds, there is need to collect travel activity data from all facilities so that variable speeds for all facility types can be utilized for emissions estimation. The authors of this study should note that, given that average speeds and variability in average speeds differ for different types of roadway facilities, the differences in total

emissions and pollutant concentrations can show different characteristics if real-world data from other facilities are utilized.

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CHAPTER 7. CONCLUSIONS AND FURTHER RESEARCH

It has been acknowledged that there is uncertainty in the regional mobile source emissions estimates resulting from using travel activity input data that misrepresents the real-world travel conditions. One set of travel activity input data includes the average speeds on facility links of the transportation networks. The accuracy of average speeds estimated in the transportation demand models and passed to regional mobile source emissions models has been identified as a source of uncertainty, examined and improved in various studies (e.g., Chatterjee, Miller et al., 1997).

The major finding of this study is that, in addition to the previously examined uncertainties related to the inaccuracy of the average speeds for a given period of time and multi-lane link, variability in these speeds for shorter periods and across lanes also results in uncertainties in estimated running stabilized emissions. Moreover, these differences in running stabilized emissions estimates result in differences in estimated gridded O_3 and $PM_{2.5}$ concentrations.

In this study, we focused on the effects of 15-minute link average and hourly lane average speed variability on estimated hourly link running stabilized emissions. The magnitudes of the differences in link running stabilized emissions are higher when lane average speeds are used compared to the magnitudes of the differences when 15-minute link average speeds are used. We found that the percentage differences in running stabilized emissions from links are only loosely correlated to the congestion level on the facility link when 15-minute link average speeds are used. Moreover, for differences in

running stabilized emissions when hourly lane average speeds are used, even a loose correlation does not exist between hourly percentage differences and the congestion level.

When both 15-minute link and hourly lane average speeds are used, the differences in running stabilized emissions are significantly different across the days of the week and hourly periods of the day for most of the links in the region. This shows that the speed variability patterns across the days and hourly periods are sufficiently distinct to result in significant differences. The differences resulting from using 15-minute link average speeds are likely to be significant for facility links where traffic flow is interrupted (e.g., when signalization is present, etc). On the other hand, differences are significantly different across the days of the week and hourly periods of the day for almost all the links when hourly lane average speeds are used, independent from the interruptions to the traffic flow.

The gridded O_3 and $PM_{2.5}$ concentrations estimated when 15-minute link and hourly lane average speeds are used for mobile source emissions estimation show that explaining the effects of variability in average speeds on running stabilized emissions estimates does not describe the resulting uncertainties in secondary pollutant concentration estimates.

Further research should focus on analyzing the uncertainties in estimated mobile source emissions and secondary pollutant concentrations using real-world highly resolved average speeds from facilities other than freeways. The differences in running stabilized emissions and pollutant concentrations might show different characteristics given that very different traffic flow characteristics are observed and traffic control strategies are implemented on other types of facilities (e.g., Chatterjee, Miller et al., 1997). It will also

be valuable to utilize different resolution average speeds, that is use higher time resolutions for link and lane average speeds, to analyze the uncertainties in running stabilized emissions estimates resulting from assuming the average speeds are constant for hourly periods and across lanes for a link. In other words, the sensitivity analyses presented in this study should be extended to acknowledge the effects of using higher resolution speeds on regional mobile source emissions estimates.

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