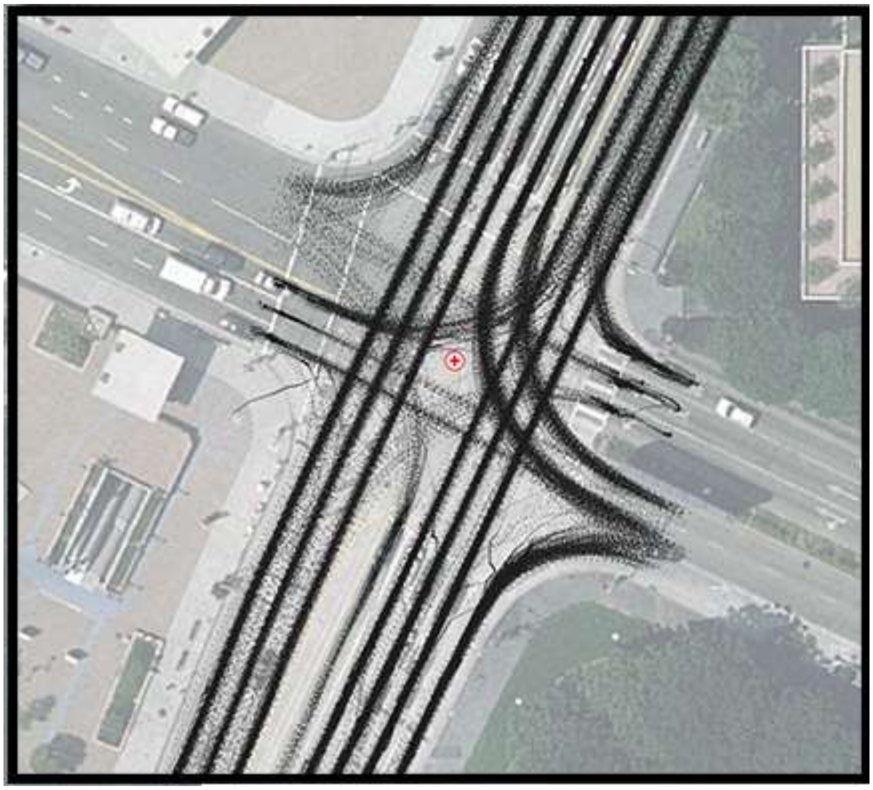
Evaluation of Methods for Modeling Vehicle Activity at Signalized Intersections for Air Quality Hot-Spot Analyses

Final Report



Original Aerial Photo: NGSIM dataset (4)

October 2020

Publication No. FHWA-HEP-21-008

This report covers work undertaken in both Phases 1 and 2 of the subject project

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

This report summarizes an evaluation undertaken to compare methods of representing vehicle activity at signalized intersections for use in project scale air quality analysis. This evaluation is intended to advance the state of the practice for emissions and dispersion analysis at signalized intersections, which will improve the accuracy of pollutant concentration estimates. The Next Generation Simulation (NGSIM) Lankershim Blvd. dataset was the basis for a detailed baseline that was compared to other methods that are more practical to implement. This final report includes information on data inputs, modeling, method comparison, results, and recommendations based on two intersections of NGSIM data in Los Angeles, CA, and covers both phases 1 and 2 of the subject project. The target audience is transportation agency technical staff undertaking project-level air quality analyses.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-HEP-21-008		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
Evaluation of Methods for Modeling Vehicle Activity at Signalized Intersections for Air Quality Hot-Spot Analyses, Final Report	5. Report Date: October 2020 6. Performing Organization Code
7. Author(s) Brian Naess, Catherine Seppanen, and Saravanan Arunachalam, PhD, Institute for the Environment, The University of North Carolina at Chapel Hill; Richard G. Dowling, PhD, PE, Zifeng Wu, PhD, Kittelson & Associates, Inc.; Damon Fordham, The Cadmus Group LLC; Nagui M. Rouphail, PhD, North Carolina State University; John Zamurs, PhD, ZAMURS AND ASSOCIATES, LLC	**8. Performing Organization Report No.**
9. Performing Organization Name and Address The Cadmus Group LLC 100 Fifth Avenue, Suite 100 Waltham, MA 02451	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** DTFH6117D00007L, order no. 693JJ318F000339
12. Sponsoring Agency Name and Address Federal Highway Administration, Office of Natural Environment 1200 New Jersey Avenue, SE Washington, D.C. 20590	**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code** HEP

15. Supplementary Notes

FHWA Review Team: David Kall (COTR), Cecilia Ho, Michael Claggett, George Noel

16. Abstract

This report summarizes an evaluation undertaken to compare methods of representing vehicle activity at signalized intersections for use in project scale air quality analysis. This evaluation is intended to advance the state of the practice for emissions and dispersion analysis at signalized intersections, which will improve the accuracy of pollutant concentration estimates. The Next Generation Simulation (NGSIM) Lankershim Blvd. dataset was the basis for a detailed baseline that was compared to other methods that are more practical to implement. This Phase 2 report includes information on data inputs, modeling, method comparison, results, and recommendations based on two intersections of NGSIM data in Los Angeles, CA. The target audience is transportation agency technical staff undertaking project-level air quality analyses.

17. Key Words	18. Distribution Statement
Signalized intersections, drive cycles, vehicle trajectories, operating mode distributions, modes of vehicle activity, MOVES, CAL3QHC, emissions modeling, dispersion modeling, NGSIM	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	41 (49 incl. front matter)	N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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List of Abbreviations and Symbols

Full	**Abbreviation / Acronym**	**Full**	**Abbreviation / Acronym**
Approaching	App	Meter	m
At Grade	AG	Meters per second	mps
Boulevard	Blvd	Micrograms per cubic meter	ug/m3 or $\mu g/m^3$
Carbon Monoxide	CO	Miles per hour	mph
Centimeter	cm	MOtor Vehicle Emission Simulator	MOVES
Computer-Aided Design	CAD	Next Generation Simulation	NGSIM
Correlation Coefficient	CORR	Normalized Mean Square Error	NMSE
Departing	Dep	Northbound	NB
Digital Elevation Model	DEM	Operating Mode	Opmode
Eastbound	EB	Parts per million	ppm
Environmental Protection Agency	EPA	Particulate Matter	PM
Federal Highway Administration	FHWA	Particulate Matter with diameter < 2.5 microns	$PM_{2.5}$
Foot or Feet	ft	Particulate Matter with diameter < 10 microns	PM_{10}
Fraction of Predictions Within a Factor of Two of Observations	FAC2	Right Turn	RT
Fractional Bias	FB	Second	sec
Free Flow	FF	Southbound	SB
Geographic Information System	GIS	Sport Utility Vehicle	SUV
Green Times Per Cycle	g/C	State Implementation Plan	SIP
Highway Capacity Manual (edition not specified)	HCM	Thru	TH
Highway Capacity Manual Sixth Edition	HCM6	U.S. Geological Survey	USGS
Highway Capacity Software	HCS	Vehicles	veh
Identifier	ID	Vehicle Specific Power	VSP
Idle	Id	Volume/Capacity	V/C
Left Turn	LT	Westbound	WB

1 INTRODUCTION

Characterizing the modal operation of vehicles for emissions modeling purposes is complicated for signalized intersections due to the four major modes of vehicle activity: cruise, idling, acceleration, and deceleration. The CAL3QHC[1, 2] and CAL3QHCR[3] dispersion models, which have been available since the 1990s, use cruise links and have a queueing algorithm available that uses idle links to account for the spatial distribution of two of the four modes of vehicle activity at signalized intersections. The introduction of the MOtor Vehicle Emission Simulator (MOVES)[a] model in 2010 expanded choices for modeling vehicle activity through advanced model options associated with the modal nature of the underlying emission rates. The advanced options include the use of link drive schedules (second-by-second speed traces) or operating mode distributions (distribution of vehicle activity over bins based on vehicle specific power (VSP)).

This study uses Next Generation Simulation (NGSIM) video recordings that captured 100% of vehicles passing through several intersections paired with processing algorithms to produce real world vehicle traces (second-by-second speeds) for the inputs to the advanced MOVES options. These trajectory data were used to create a detailed baseline for comparing against other methods that are more practical to implement for each project-level air quality analysis. While it is often not practical to collect all the data required to execute the advanced options in MOVES for every project-level air quality analysis, the availability of this data presents an opportunity to evaluate and improve the CAL3QHC queueing algorithm, refine traffic parameter inputs, and compare different methodologies used by practitioners for intersection-scale air quality analysis.

This study used the NGSIM dataset to compare CO, $PM_{2.5}$, and PM_{10} emissions and pollutant concentration results from eight different modeling methodologies (see Table 1 for a description of each Method) at two intersections on Lankershim Boulevard in Los Angeles, California, the Lankershim Boulevard / Universal Hollywood Drive intersection (labeled by NGSIM as Intersection #2) and the Lankershim Boulevard / Main Street intersection (labeled by NGSIM as Intersection #3) (see Figure 1 for a map of the domain).

For more information about how the inputs were prepared, we refer the reader to the Task 7.2 technical report. For more information about how the models were set up and run, we refer the reader to the Task 7.3 technical report. For a detailed discussion of the modeling results, we refer the reader to the Task 7.4 technical report. For a detailed discussion of how the CAL3QHC queueing algorithm compares to the current methodology contained in the current Highway Capacity Manual (HCM6), consult the Task 5 memorandum and its appendices. These reports and associated files are available upon request from the FHWA Transportation and Air Quality Conformity Team at taqc@dot.gov.

This final report highlights the important details, results, and findings presented in those earlier technical reports, and further applies insights learned over the course of the project to provide recommendations to practitioners to improve running emissions inputs for air quality analyses at signalized intersections.

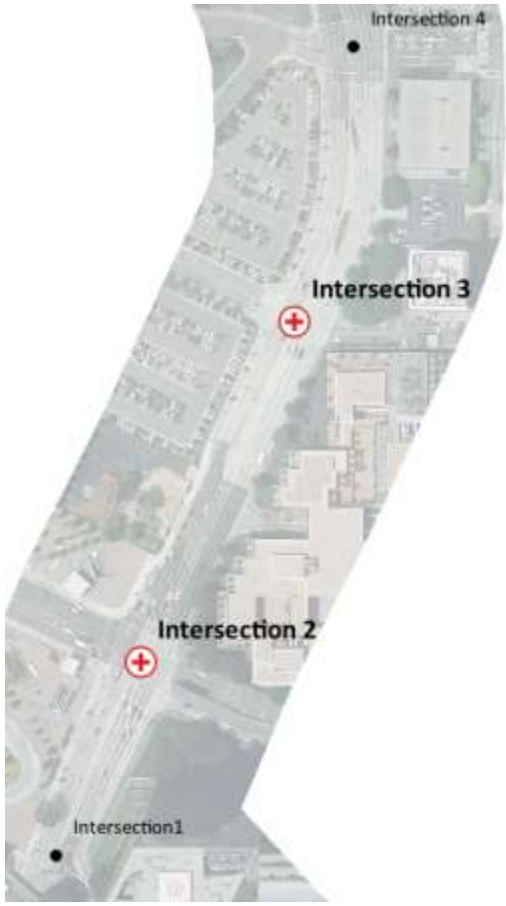
[a] https://www.epa.gov/moves

Table 1. Description of methods used in the study.

Method	Description
Method 1[b] (baseline)	• Uses filtered trajectory data as the basis for operating mode distributions for input in MOVES • Uses a link network consisting of very short links (5-10 meters long) representing each lane of traffic to capture vehicle activity in and around each intersection • Used as the basis of comparison for the other methods
Method 2	• Uses the current queueing algorithm in CAL3QHC on a simplified link network with long, central links to capture all vehicle activity traveling in a given direction
Method 3	• Same inputs as Method 2 with idle removed from MOVES default drive cycles for cruise links
Method 4[c]	• Four types of overlapping links instead of two (deceleration, queue, acceleration, and cruise)
Method 6	• Three types of non-overlapping links (queue, acceleration, and cruise) • Links use average speed to consider all the vehicle activity that travels over that link during the entire cycle of the traffic signal (red, yellow, and green phases)
Method 7	• Same inputs as Method 6 with idle removed from MOVES default drive cycles for cruise and acceleration links
Method 8	• Same inputs as Method 2, but it uses Highway Capacity Software (HCS7) to calculate queue length
Method 9	• Same inputs as Method 6 but uses an adjusted operating mode distribution to reallocate activity associated with vehicle speeds higher than 50 mph to corresponding bins associated with speeds between 25 – 50 mph

[b] One important distinction to note is that in this report, the baseline is labeled as Method 1 throughout. However, in the Task 7.2, 7.3, and 7.4 reports, several different baseline versions were considered (e.g., Method 1 and Method 1C). When comparing between this report and previous technical reports, Method 1 in this report corresponds to Method 1C in the previous technical reports.

[c] Note that a Method 5 was initially considered, but over the course of the study, it was determined to be redundant and was not modeled.



Original Aerial Photo: NGSIM dataset (4)

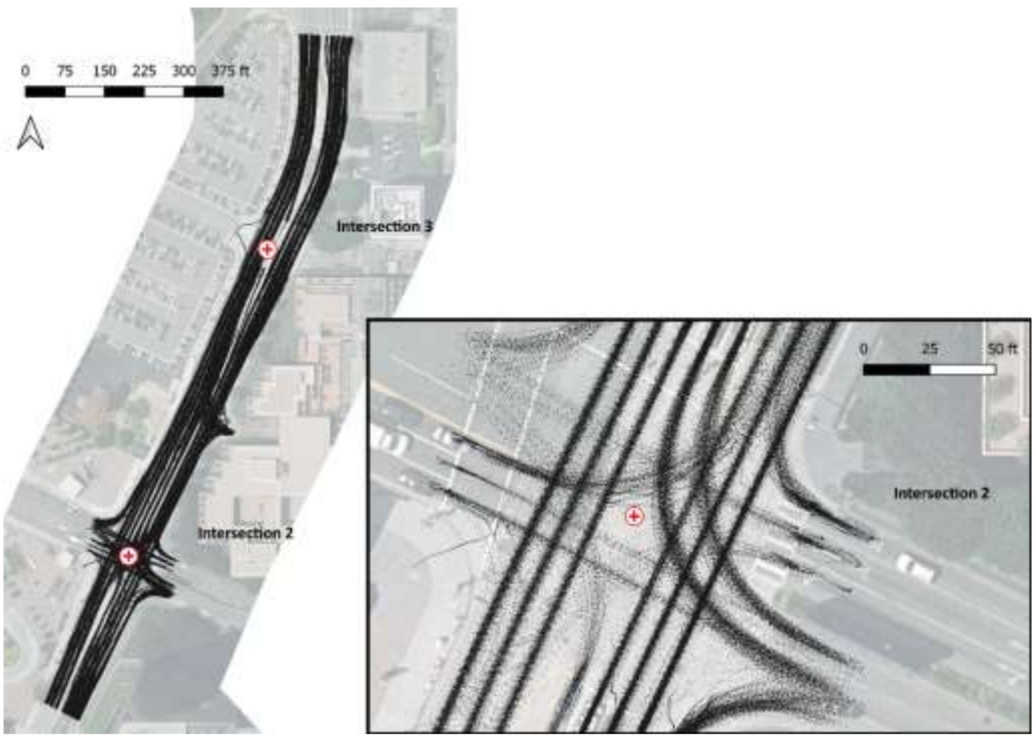
Figure 1. Map. Map of NGSIM domain with labels for each of the numbered intersections with a focus on Intersection 2 and Intersection 3.

2 DATA AND MODELING

In this chapter, we present an overview of the NGSIM data and how the data were processed for use in the eight different modeling methods. We also present an overview of the two intersections that were modeled, the air quality models that were used, and we highlight key facets of each method and how they differentiate from one another.

2.1 Next Generation Simulation (NGSIM) Data

The NGSIM program researchers collected detailed vehicle trajectory data on Lankershim Boulevard in the Universal City neighborhood of Los Angeles, CA, on June 16, 2005. These data were collected using five video cameras mounted on the roof of a 36-story building, and a customized software application developed for the NGSIM program transcribed the vehicle trajectory data from the video. This vehicle trajectory data provided the precise location of each vehicle within the study area every one-tenth of a second, resulting in detailed lane positions and locations relative to other vehicles (Figure 2).[4, 5] The trajectory data focused on the flow of traffic on Lankershim Blvd., and, as such, data on cross streets, like Universal Hollywood Dr., was limited to within 100 feet from the intersection centers.



Original Aerial Photo: NGSIM dataset [4]

Figure 2. Map. Trajectory data from NGSIM for Intersection 2 and Intersection 3 showing vehicle locations every 1/10th second.

2.2 Overview of Domain

Lankershim Blvd. is a three to four lane arterial bisecting the area between Hollywood Freeway to the south and Ventura Freeway to the north. Figure 3 shows the NGSIM domain including intersection numbers, section numbers, and origin/destination codes. The numbers in pink refer to origin/destination codes. In the NGSIM study location, much of the east side of the domain is associated with Universal Studios, while much of the west side is devoted to on-street parking. As such, the volume of traffic on the cross streets is significantly lower than the volume traveling north and south on Lankershim Blvd. Between 8:30 AM and 9:00 AM, the volume traveling northbound that crossed through Intersection 2 or Intersection 3 ranged from 700 – 800 vehicles, while the volume traveling southbound that crossed through Intersection 2 or Intersection 3 ranged from 1100 – 1200 vehicles. At Intersection 2, the volume traveling eastbound or westbound ranged from 60 – 286 vehicles, with the bulk of the vehicles departing eastbound, having turned left off of southbound Lankershim Blvd. At Intersection 3, there were a total of 142 vehicles that either originated or departed in an eastbound or westbound direction. The sparse availability of cross street data points, combined with the low volume of vehicles traveling in the eastbound and westbound direction, led to some uncertainty in some of the input parameters required for MOVES and precluded modeling emissions associated with eastbound and westbound traffic at Intersection 3.

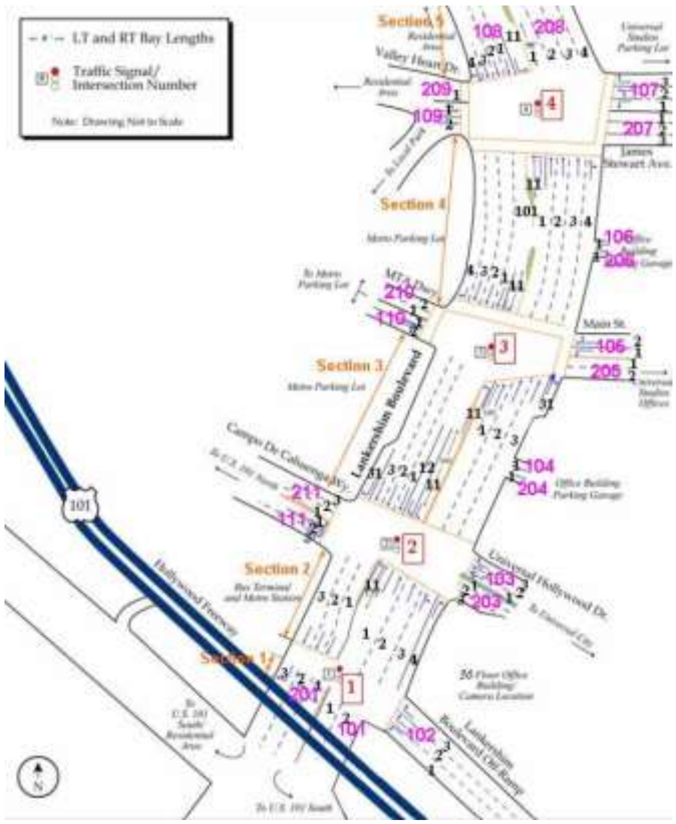


Figure 3. Map. NGSIM Domain with lane numbers (in black), Section IDs (in orange), and Intersection IDs (in red boxes).[d]

Despite their close proximity, there were some important differences in the signal timing characteristics of Intersection 2 and Intersection 3. There was not much queueing on Lankershim Blvd. at Intersection 3, with a red light only 16% of the cycle time, while Intersection 2 was more balanced in terms of major to side-street green light cycles. At Intersection 2, southbound through traffic had a red light 48% of the time, while northbound through traffic had a red light 64% of the time. Left turning southbound traffic

[d] Adapted from Figure 4 of the NGSIM Lankershim Data Analysis Summary Report prepared for FHWA by Cambridge Systematics, Inc. [(6)]

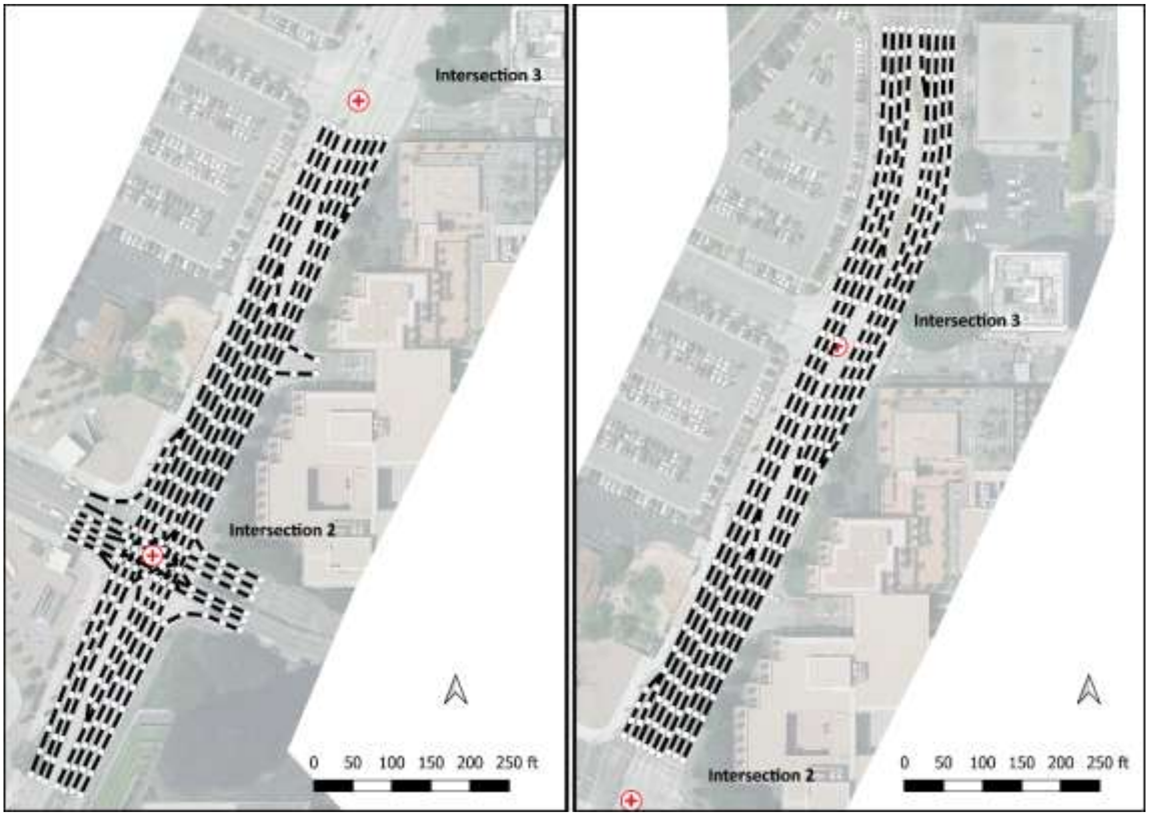
experienced a red light 75% of the time, causing long queues in the two left turn lanes. The signal timing differences, combined with the number of vehicles traveling on the cross streets, motivated the Team to model Intersection 3 differently from Intersection 2. For Intersection 2, all four directions of travel were modeled, like a typical intersection, while at Intersection 3, the Team ignored eastbound and westbound traffic to focus on northbound and southbound traffic.

In addition to the signalized intersections there are also major parking garages located on the east side of Lankershim Blvd., and turning traffic associated with these parking garages had an impact on our modeling results. Gate 5 of Universal Studios, located in Section 3 and labeled with the origin/destination codes of 104/204, impacted northbound traffic leaving Intersection 2, while a parking garage in Section 4, labeled with the origin/destination codes of 106/206, impacted northbound traffic leaving Intersection 3. While not mentioned in the CAL3QHC or MOVES documentation, parking garages and other situations that may impede the flow of traffic, can have noticeable impacts on emissions and air quality, and deserve consideration when setting up air quality modeling simulations.

2.3 Baseline Network

Since CAL3QHC is a line-source model, and NGSIM did not provide a shapefile representing the center lines of our domain, it was necessary to create a road network from scratch. There are two important features of the baseline (Method 1) network that warrant mention. First, the baseline network consists of very short links, with most links around 30 feet long but no shorter than 20 feet. The link networks for the other methods have longer links, with the exception of queue links representing left turn lanes. The short baseline links capture in high resolution some of the unpredictability in average speed and acceleration associated with real-world driving. Second, the baseline network has links representing each lane of traffic, and, in the case of Intersection 2, the network includes links representing turning traffic within the intersection. The link networks used by the other methods have a single link with a width value representative of all lanes traveling in a single direction. The presence of links representing individual lanes in the baseline network captures differences in average speed and acceleration that can result from turning traffic. In summary, the baseline network was designed to provide as much detail as possible about running emissions from vehicles driving in the domain. Figure 4 shows the baseline link network for Intersection 2 modeling (left) and Intersection 3 (right), where the end points are represented with white circles and the links are represented with black lines.

It is important to note that all of the other methods use baseline links as their building blocks. For example, a single Method 6 cruise link might be comprised of seven connected baseline links from the middle lane, though its geometry would only contain the starting coordinates of one link and the ending coordinates of another link. This baseline link building block approach allows for direct comparison of emissions between the baseline and the other methods.



Original Aerial Photo: NGSIM dataset [(4)]

Figure 4. Map. The baseline link networks for Intersection 2 (left panel) and Intersection 3 (right panel).

2.4 MOVES Modeling to Calculate Emissions

Once the baseline road networks were created, NGSIM trajectory data points were assigned to the corresponding baseline links, so the Team could apportion activity onto each link and calculate emissions. The Team used the latest version of the MOVES model (2014b) in project-level mode to calculate link-based emissions of CO, $PM_{2.5}$, and PM_{10} for each method.[(6)] For intersection level modeling, the focus is on running exhaust emissions, crankcase exhaust emissions, and emissions from tire wear and brake wear. MOVES calculates emissions on each link based on the volume, types of vehicles traveling on the link (fleet mix), and their operating mode distributions. An operating mode distribution represents the fraction of activity that vehicles spend in different operating modes, like braking, accelerating, and idling, and operating modes are defined by specific speed and vehicle specific power (VSP) ranges, which, in turn, are influenced by the road grade or elevation change. Table 2 lists the operating modes by operating mode ID.

Table 2. Operating modes by operating mode ID.

opModeID	opModeName
0	Braking
1	Idling
11	Low Speed Coasting; VSP<0; 1<=Speed<25
12	Cruise/Acceleration; 0<=VSP<3; 1<=Speed<25
13	Cruise/Acceleration; 3<=VSP<6; 1<=Speed<25
14	Cruise/Acceleration; 6<=VSP<9; 1<=Speed<25
15	Cruise/Acceleration; 9<=VSP<12; 1<=Speed<25
16	Cruise/Acceleration; 12<=VSP; 1<=Speed<25
21	Moderate Speed Coasting; VSP<0; 25<=Speed<50
22	Cruise/Acceleration; 0<=VSP<3; 25<=Speed<50
23	Cruise/Acceleration; 3<=VSP<6; 25<=Speed<50
24	Cruise/Acceleration; 6<=VSP<9; 25<=Speed<50
25	Cruise/Acceleration; 9<=VSP<12; 25<=Speed<50
27	Cruise/Acceleration; 12<=VSP<18; 25<=Speed<50
28	Cruise/Acceleration; 18<=VSP<24; 25<=Speed<50
29	Cruise/Acceleration; 24<=VSP<30; 25<=Speed<50
30	Cruise/Acceleration; 30<=VSP; 25<=Speed<50
33	Cruise/Acceleration; VSP<6; 50<=Speed
35	Cruise/Acceleration; 6<=VSP<12; 50<=Speed
37	Cruise/Acceleration; 12<=VSP<18; 50<=Speed
38	Cruise/Acceleration; 18<=VSP<24; 50<=Speed
39	Cruise/Acceleration; 24<=VSP<30; 50<=Speed
40	Cruise/Acceleration; 30<=VSP; 50<=Speed
501	Brakewear; Speed=0

The equation to calculate VSP is shown in Equation 1 and is taken from the MOVES 2004 Energy and Emission Inputs Draft Report, Equation A-1.[7]

$$VSP = \frac{(A \times Speed + B \times Speed^2 + C \times Speed^3 + Mass \times Speed \times Accel)}{Mass} \quad (1)$$

where:

VSP is in KW/Metric Ton,

Speed is in meters/second (mps,

Accel is in meters/second^2,

A is rolling resistance term in KW / mps,

B is friction term in KW / mps2,

C is aerodynamic drag term in KW / mps3,

Mass is in metric tons (1000 kg).

The baseline method used filtered NGSIM trajectory speed and acceleration data averaged into one second intervals to construct operating mode distributions. Rather than rely on the built-in drive cycle approach in MOVES, we developed a Python script to read in trajectory data for multiple vehicles on the same link, calculate VSP, determine the appropriate operating mode for each second of the trajectory data, and construct operating mode distributions for each link and vehicle type. This approach differed from the other methods in that the other methods relied predominantly on the average speed approach built into MOVES, where MOVES selects an appropriate operating mode distribution based on default drive cycles.

The Team determined that the NGSIM data contained unrealistic acceleration values, and these extreme acceleration values would inflate baseline emissions estimates. There is consensus in the literature that for the "average" passenger car, the maximum vehicle acceleration is inversely proportional to speed. The acceleration values presented in Table 3 are consistent with recommendations found in the Institute of Transportation Engineers (ITE) Traffic Engineering Handbook, 5th Ed.[8] However, the literature did not provide a consensus deceleration maximum to use. Comfortable deceleration rates are implicitly included in design controls such as stopping and decision-sight distance. The American Association of State Highway Transportation Officials (AASHTO) Green Book specifies that most drivers when confronted with an unexpected object may decelerate at a rate greater than 4.5 meters/sec/sec (m/s/s) or which is approximately 10 miles per hour/sec (mph/s).[8] Those rates are higher than the ones adopted in designing the clearance interval at signals, which is about 7 mph/s. The Team therefore recommended the use of 10 mph/s as the highest feasible deceleration rate for this study.

Table 3. Speed and acceleration filtering criteria for removing NGSIM points from the analysis for the baseline method.

Speeds (mph)	Acceleration (mph/s)
0 – 15	5.5 and higher
15 – 25	5.0 and higher
25 – 35	4.7 and higher
Over 35	4.4 and higher
Any	-10.0 and lower

All NGSIM points with a speed in the left column and an acceleration value in the right column were excluded in the speed or acceleration averages used to calculate operating mode distributions and vehicle specific power. The Team decided to filter out points rather than replace acceleration values with capped values to ensure that the study used original, NGSIM acceleration values rather than modified values.

2.5 CAL3QHC

CAL3QHC is an air quality modeling software that uses a line-source based dispersion algorithm (CALINE-3), combined with a queue length algorithm based on recommendations from the 1985 Highway Capacity Model, to predict pollutant concentrations near roadways and intersections. CAL3QHC estimates the length of the vehicle queue during traffic signal red time based on several inputs dealing with the vehicular traffic and traffic signal timing. Queue links, which are referred to as idle links in the CAL3QHC documentation, represent a straight segment of roadway on which vehicles are idling for a specified period of time. MOVES2014b, in its Operating Mode Definitions for Running Exhaust, defines idling as when a vehicle's speed is less than 1 mph. CAL3QHC uses idle links to represent the red phase on top of free flow links[e] to represent the green phase at the approach to an intersection. Therefore, the links represent different points in time over the course of the traffic signal phasing cycle. CAL3QHC calculates pollutant concentrations at up to 60 locations called receptors. Receptors are typically located close to the roadway (ten feet from the edge) throughout the domain to capture in detail concentration hot-spots that may result from queueing, deceleration, or acceleration. This study provided an opportunity to evaluate the built-in queue length algorithm in CAL3QHC and compare the results to queue lengths derived from the newer Highway Capacity Software (HCS7)[(9)] alongside of other modeling approaches, like the approach recommended in the U.S. EPA's "Transportation Conformity Guidance for Quantitative Hot-spot Analyses in $PM_{2.5}$ and PM_{10} Nonattainment and Maintenance Areas."[(10)]

2.6 Highway Capacity Software (HCS7)

HCS7™ (Release 7.8.5) includes updated modules to implement the Highway Capacity Manual 6th Edition (HCM6) procedures for signalized intersections, urban streets, alternative intersections, roundabouts, freeway facilities, basic freeway segments, freeway weaving segments, freeway merge and diverge segments, and multilane highways, as well as methodologies for two-way stop control and all-way stop control that are unchanged from the previous version.[(9)] HCS7 employs the nine-step procedure documented in the Highway Capacity Manual, which uses a queue accumulation polygon and the possible arrival departure polygon types to compute the back of queue, the maximum number of fully stopped vehicles per cycle. Stochastic fluctuations in vehicle arrivals resulting in cycle failures (where demand arriving in a single signal cycle temporarily exceeds the per cycle discharge capacity of the signal

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[e] In order to maintain consistency in terminology between different models, this report refers to idle links as queue links and free flow links as cruise links.

approach) within the analysis hour are accounted for. The procedure applies to both under saturated and over saturated conditions. The method is sensitive to arrival rates, signal timing, phasing, arrivals on green and red, and saturation flow rates. HCS7 predicts delays and queues for demands that persist for a 15-minute analysis period within the peak hour. The method is adjustable to full hour analysis, if desired. As part of the first phase of this project, the Team compared HCS7 queue results with the queue results from CAL3QHC, and some of the findings from this analysis are presented in Chapter 4.

2.7 Method 2, Method 3, and Method 8

Method 2, Method 3, and Method 8 all used a link network consisting of overlapping queue and cruise links. They differed from each other in the following ways:

- Method 2 modeled the queueing algorithm provided in CAL3QHC.
- Method 3 used the same inputs as Method 2, except that it removed idle from the MOVES default drive cycles for cruise links to address potential double counting of idle emissions, since MOVES default drive cycles have some amount of idle activity built into them.
- Method 8 used the same inputs as Method 2, but it used the results from the HCS7 to calculate queue length.

A cruise link is defined in the CAL3QHC User's Guide(1) as a straight segment of roadway having a constant width, height, travel volume, travel speed, and vehicle emission factor.(2) A new link must be coded when there is a change in width, traffic volume, travel speed, or vehicle emission factor. A single cruise link is meant to represent multiple lanes of traffic by simply setting the width of the link to equal the number of lanes times the width of each lane plus a buffer of 3 meters on each side.

A speed of 35 mph for northbound and southbound vehicles and a speed of 25 mph for eastbound and westbound vehicles for the Intersection 2 modeling was used on cruise links, and these speeds were verified based on queries of the vehicle velocity over one second time periods in the NGSIM trajectory data. Every cruise and queue link were assigned a volume based on the link's purpose, i.e., through traffic or left turn, and volumes were calculated from querying the origin and destination codes provided in the NGSIM data.

Queue links were prepared as input into CAL3QHC for Method 2, Method 3, Method 4, and Method 8, but the model only uses the queue links to determine the direction of queueing. Once the model has run, the user can export the results of the queueing algorithm to verify the queue length that was used in the dispersion modeling.

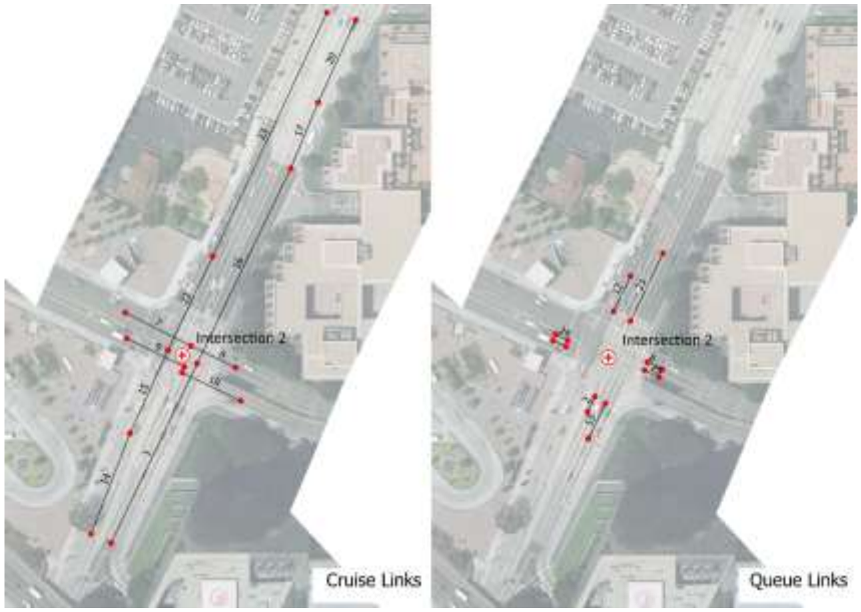
Table 4 presents the queue length estimates (in feet) for Intersection 2, and Table 5 presents the queue length estimates (in feet) for Intersection 3. The CAL3QHC queue length estimates were used in Method 2, Method 3, and Method 4, while the HCS7 queue length estimates were used in Method 8. Figure 5 shows the link network with link ID for Intersection 2, while Figure 6 shows the link network with link ID for Intersection 3. Note that in Figure 5 and Figure 6 queue link lengths are estimates and are only used by CAL3QHC to determine the direction of the queue.

Table 4. Queue length estimates (feet) from CAL3QHC and HCS7 for Intersection 2.

Link	**CAL3QHC**	**HCS7**
NB LT	25.6	33.5
NB TH+RT	137.9	193.4
EB LT	67	93.8
EB TH+RT	27.6	35.5
SB LT	224.6	246.5
SB TH+RT	104.4	180
WB LT	19.7	31.2
WB TH+RT	51.2	29

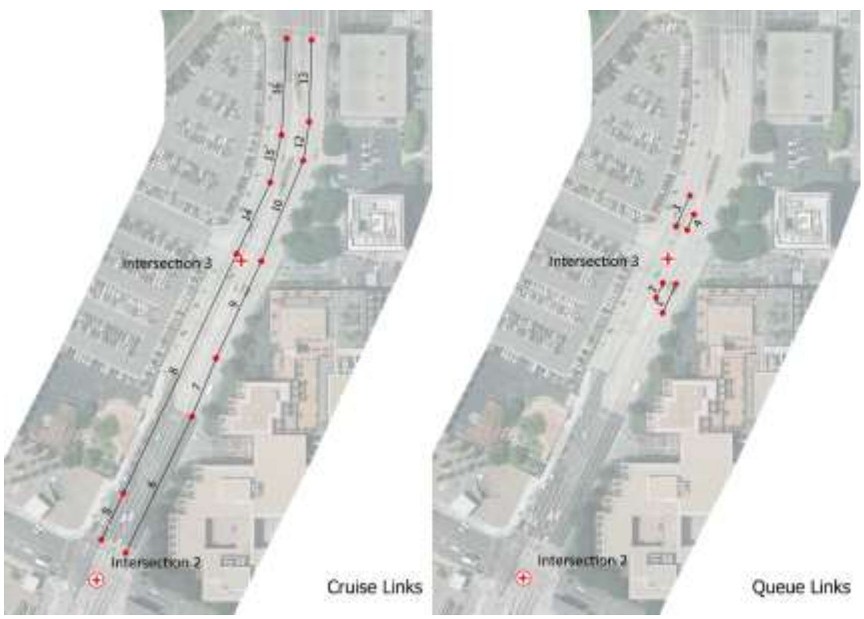
Table 5. Queue length estimates (feet) from CAL3QHC and HCS7 for Intersection 3.

Link	**CAL3QHC**	**HCS7**
NB LT	2	7.3
NB TH+RT	31.52	44.5
SB LT	3.94	10.8
SB TH+RT	51.22	138.2



Original Aerial Photo: NGSIM dataset [(4)]

Figure 5. Map. Cruise and queue links with link ID numbers for Methods 2, 3, and 8 at Intersection 2.



Original Aerial Photo: NGSIM dataset [(4)]

Figure 6. Map. Cruise and queue links with link ID numbers for Methods 2, 3, and 8 at Intersection 3.

2.8 Method 4

Method 4 built upon the existing CAL3QHC queueing algorithm by providing four types of overlapping links instead of two. These four types of links represent the four types of vehicle activity at signalized intersections: deceleration, queue, acceleration, and cruise. Method 4 used the same queue and cruise links from Methods 2, 3, and 8. However, in places where the cruise links overlap with the acceleration or deceleration links, the cruise links were split using GIS, to allow for more precise volume calculations (to avoid double-counting).

The robust NGSIM dataset allowed for a thorough analysis of appropriate acceleration and deceleration rates to use. One way to calculate acceleration depends on the change in speed and the distance necessary to go from the initial speed to the final speed (see Equation 2 below), and it can also describe the minimum deceleration rate required to stop over a given distance. Therefore, a meaningful acceleration rate can be used to inform the creation of acceleration and deceleration links by calculating distance or the length of the link.

$$A = \frac{V_f^2 - V_i^2}{2 * D} \qquad (2)$$

where:

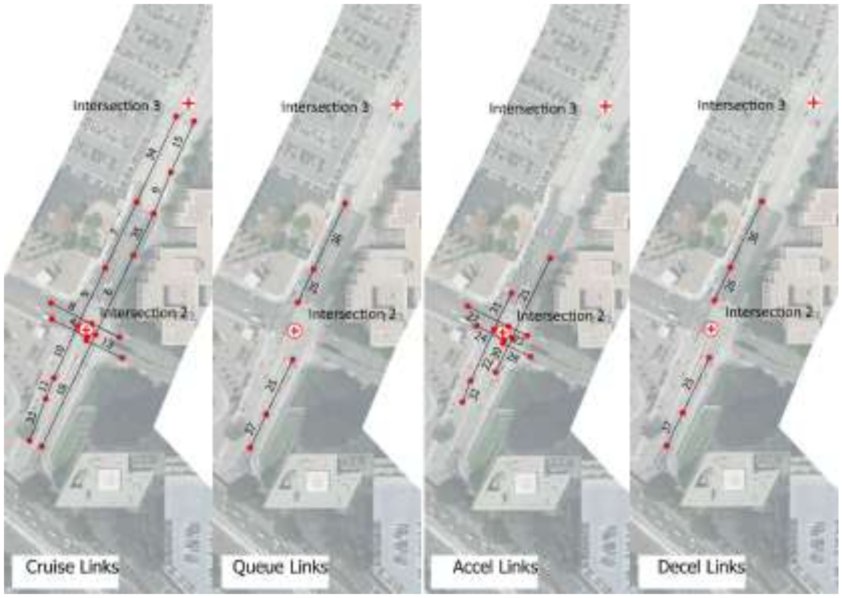
A = Acceleration (ft/s^2),

V_f = Final Velocity (ft/s),

V_i = Initial Velocity (ft/s),

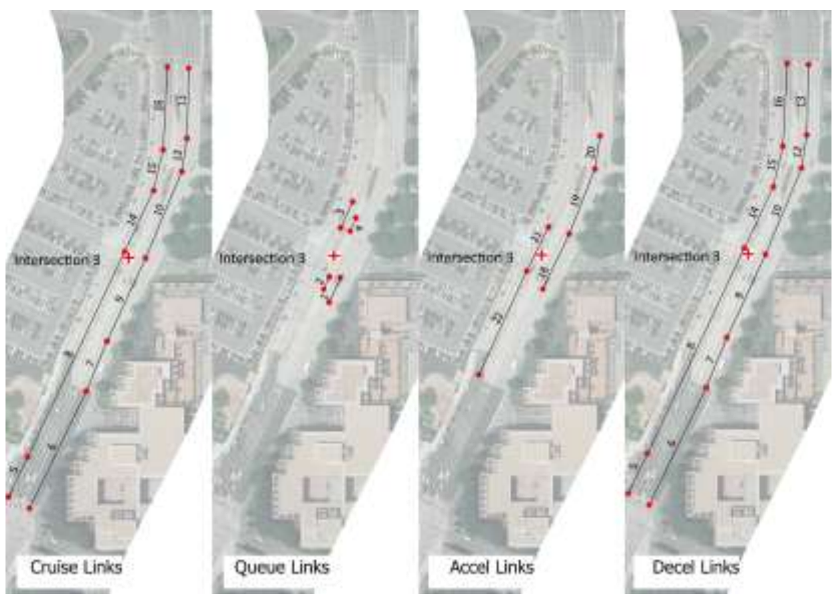
D = Distance (ft).

Based on an analysis of the NGSIM data, a deceleration rate of -3.2 mph/s and an acceleration rate of 2.9 mph/s for both southbound and northbound vehicles were used in the Intersection 2 modeling. For Intersection 3, deceleration and acceleration rates differed between northbound and southbound lanes, with deceleration rates ranging from -4.0 mph/s to -5.1 mph/s, while acceleration rates ranged from 2.3 mph/s to 3.3 mph/s. Deceleration links for eastbound and westbound travel at Intersection 2 were ignored due to a lack of data on Universal Hollywood Drive. Acceleration links were started at the midpoint of the queue link where possible, i.e., in situations where the queue links were longer than one baseline link. A single speed for acceleration and deceleration links was calculated based on the average of the initial speed and the final speed, and custom operating mode distributions were constructed based on the initial speed, final speed, and link length. Volume was calculated from querying the origin and destination codes provided in the NGSIM data. Figure 7 and Figure 8 show the Method 4 link network for Intersection 2 and Intersection 3, respectively. Note that in Figure 7 and Figure 8 queue link lengths are estimates and are only used by CAL3QHC to determine the direction of the queue.



Original Aerial Photo: NGSIM dataset [4]

Figure 7. Map. Cruise, queue, acceleration, and deceleration links with link ID numbers for Method 4 at Intersection 2.



Original Aerial Photo: NGSIM dataset [4]

Figure 8. Map. Cruise, queue, acceleration, and deceleration links with link ID numbers for Method 4 at Intersection 3.

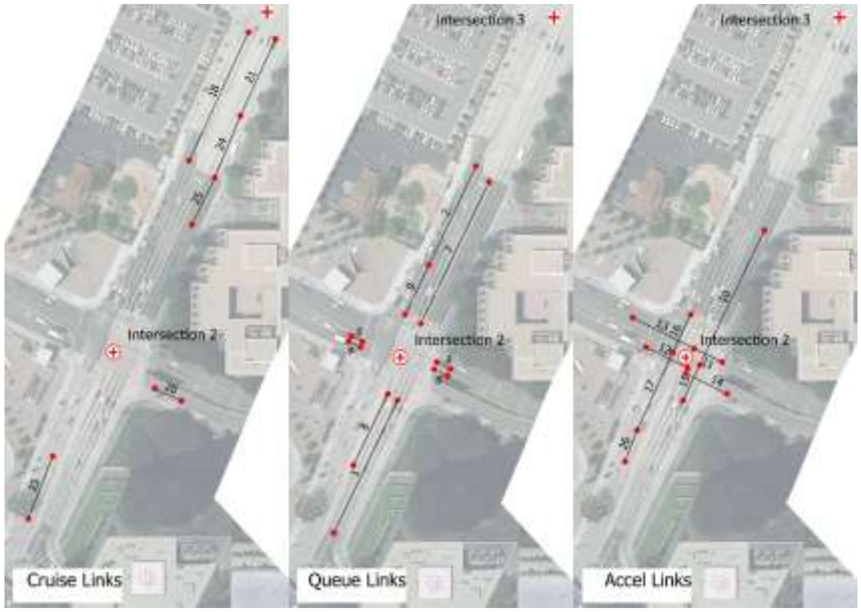
2.9 Method 6, Method 7, and Method 9

Methods 6, 7, and 9 follow the EPA's PM Hot-Spot Guidance by using average speed with non-overlapping cruise, acceleration, and queue links.[10] Unlike previous methods, queue links for Methods 6, 7, and 9 include deceleration as well as idling. They differed from each other in the following ways:

- Method 6 followed the standard hot-spot analysis approach.
- Method 7 removed idle from the MOVES default drive cycles.
- Method 9 used an adjusted operating mode distribution to reallocate activity associated with vehicle speeds higher than 50 mph to corresponding bins associated with speeds between 25 – 50 mph.

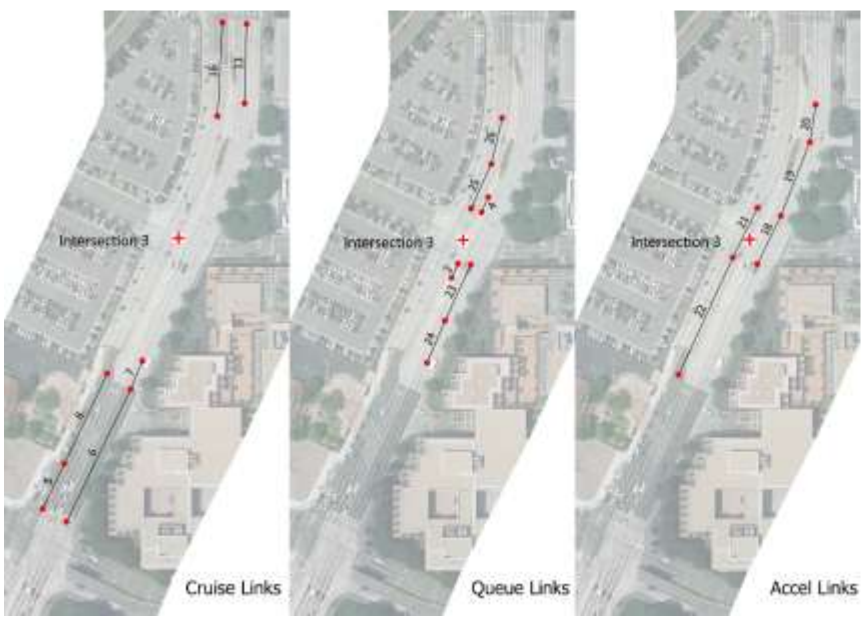
A hot-spot analysis is required for transportation projects that anticipate a significant contribution from diesel vehicles, and hot-spot analyses must use the EPA-approved emissions models, MOVES, and approved dispersion models like AERMOD or CAL3QHC. The EPA Guidance recommends that the study domain be split into different links to provide adequate resolution of different driving behavior.

An average speed is assigned to each link that considers all the vehicle activity on that link during the entire cycle of the traffic signal (red, yellow, and green phases). Average speeds for acceleration and queue links were calculated directly from the NGSIM data. There are no deceleration links, but because queue links in these methods are meant to represent idling and decelerating vehicles, the Method 4 deceleration links were used for the queue links. Acceleration links also mimicked those found in Method 4, except that some links were adjusted to start at the "stop bar". Cruise links were then added to represent the remainder of the domain. Rather than use average speeds for the cruise links, the same speeds (35 mph for northbound and southbound vehicles, 25 mph for eastbound and westbound vehicles) were used to be consistent with the results from Methods 2, 3, 4, and 8. Volume was calculated from querying the origin and destination codes provided in the NGSIM data. Figure 9 and Figure 10 show the link networks for Methods 6, 7, and 9 for Intersection 2 and Intersection 3, respectively.



Original Aerial Photo: NGSIM dataset (4)

Figure 9. Map. Cruise, queue, and acceleration links with link ID numbers for Methods 6, 7, and 9 at Intersection 2.



Original Aerial Photo: NGSIM dataset (4)

Figure 10. Map. Cruise, queue, and acceleration links with link ID numbers for Methods 6, 7, and 9 at Intersection 3.

3 MODELING RESULTS

In this chapter, we present key results from our emissions modeling with MOVES as well as pollutant concentrations as calculated by CAL3QHC.

3.1 Emissions

As mentioned previously, emissions are directly related to:

- Volume, i.e., how many vehicles were traveling on the link.
- Fleet mix, i.e., what vehicle types were traveling on the link.
- Road grade, i.e. the slope of the road, since engines work harder when traveling uphill.
- Activity, i.e., what were the vehicles doing on the link (queueing, accelerating, cruising, etc.).

Since the baseline network was much more refined than the link networks for the other methods, there were differences in all of the important emissions characteristics listed above when compared to the other methods. In the baseline method, each link represented the actual vehicles traveling that link throughout the NGSIM study period, so each link had its own volume, fleet mix, and activity profile. The other methods used aggregate volume counts based on origin and destination and a domain-wide fleet mix consisting of 97% cars, 2.8% trucks, and 0.2% motorcycles. Furthermore, there are slight differences in road grade values, as the grade depends on the start and end coordinate elevations. Despite these differences, the Team made every effort to ensure as much consistency as possible between the inputs used for the baseline and the inputs used for the other methods.

3.1.1 Operating Mode Distributions

The baseline method used filtered NGSIM trajectory speed and acceleration data averaged into one second intervals to construct operating mode distributions. The baseline method emissions results represented, as much as possible, actual driving behavior and activity. The other methods rely on MOVES to calculate emissions based on speed, where MOVES selected an appropriate operating mode distribution based on default drive cycles. Figure 11 shows the operating mode distributions for cars for all eight methods at Intersection 2, while Figure 12 shows the operating mode distributions for cars at Intersection 3. For reference, Table 2 provides a listing of what each operating mode stands for. One important takeaway from the operating mode distribution plots is that the baseline method has a higher percentage of braking (operating mode 0) than any of the other methods. This could be an artifact of excluding high acceleration values in the baseline method. However, the Team also noticed that, at least for these two intersections, there was more actual braking present in the NGSIM data than is represented in the drive cycles used by MOVES to create operating mode distributions for the other methods.

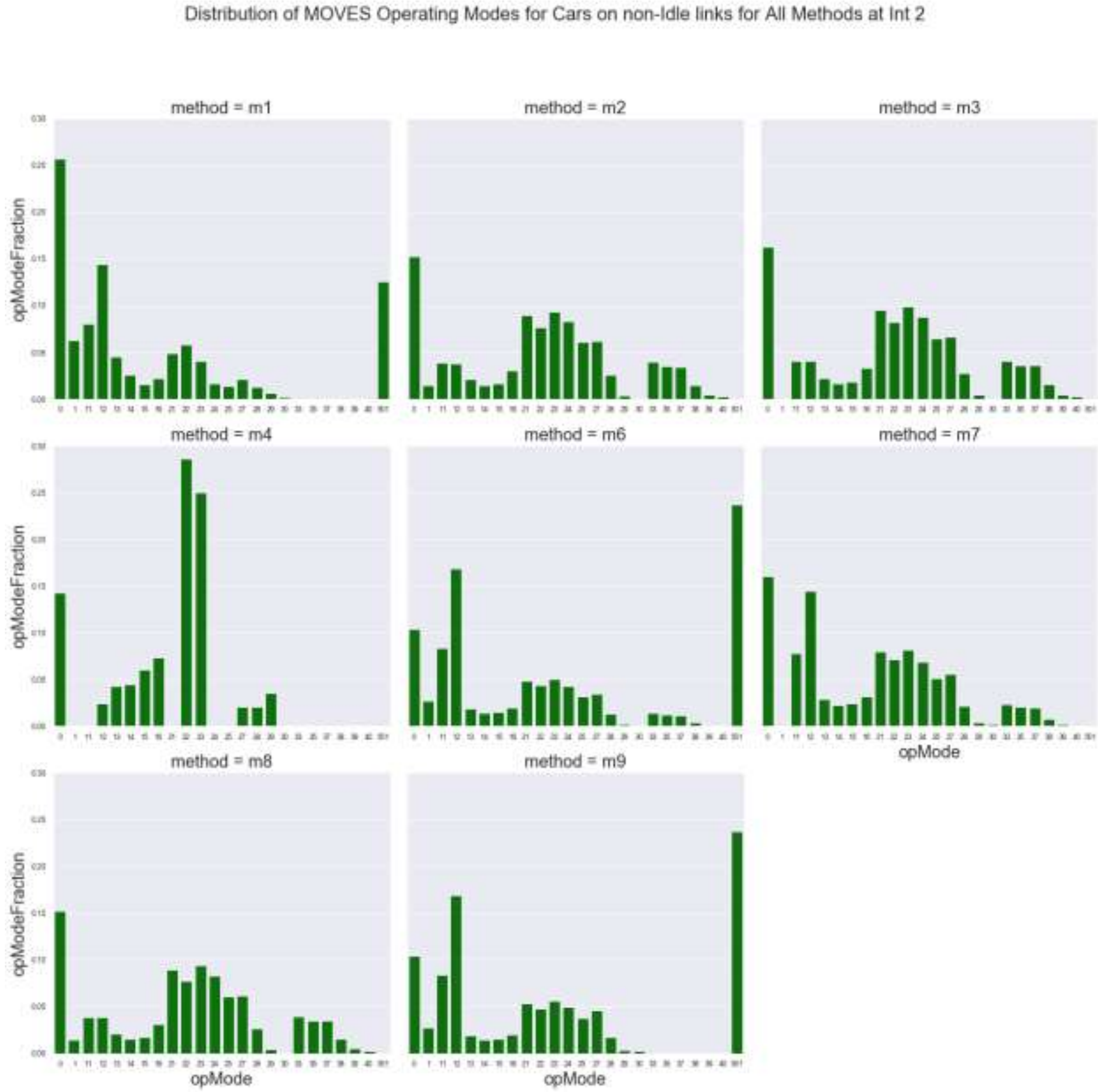


Figure 11. Chart. Distribution of MOVES operating modes for cars on non-idle links for all Methods for Intersection 2.

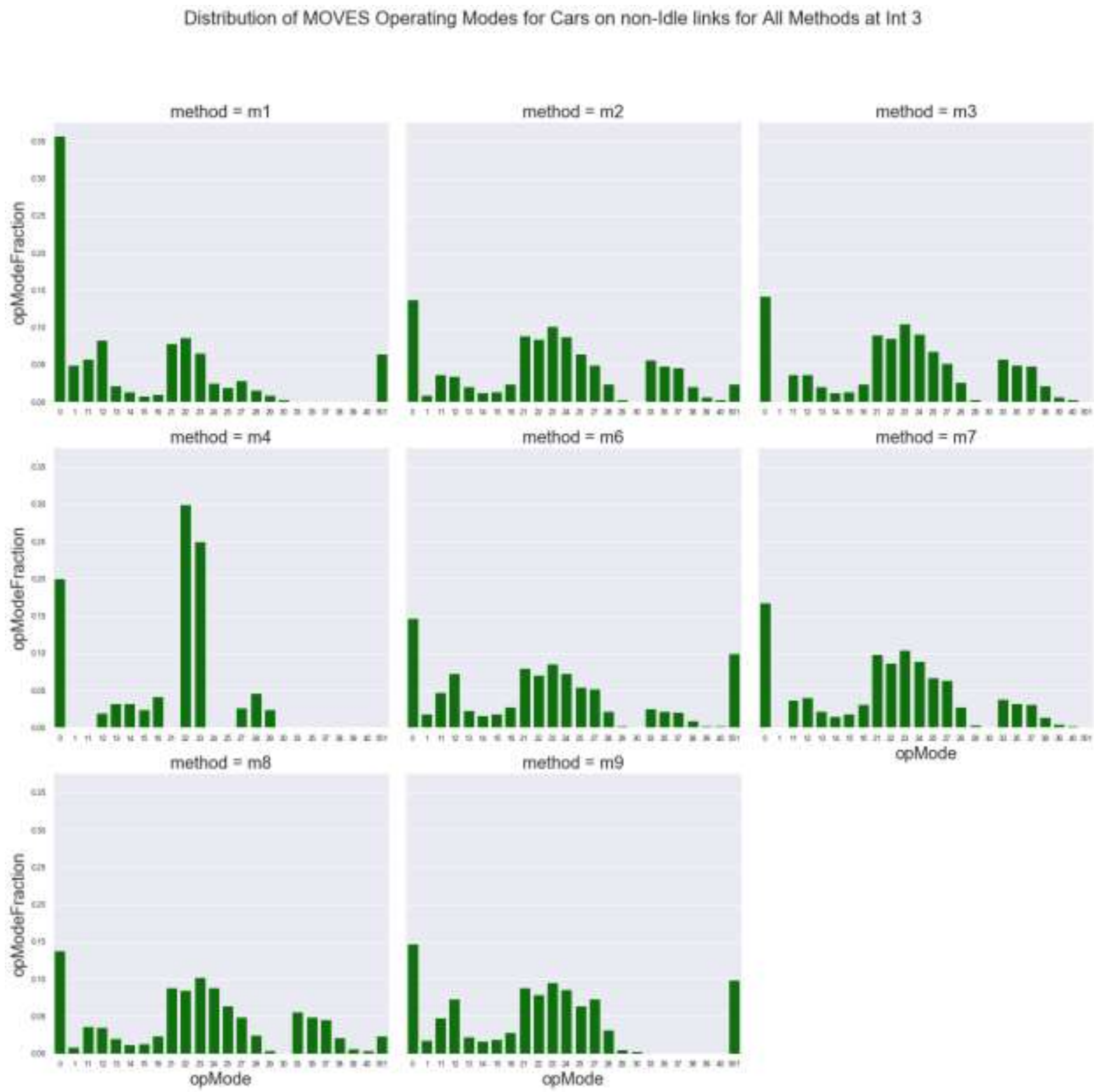


Figure 12. Chart. Distribution of MOVES operating modes for cars on non-idle links for all Methods for Intersection 3.

3.1.2 Total Emissions

After the MOVES modeling runs were completed, the Team calculated the total emissions for the baseline and each of the methods for both intersections. Figure 13 and Table 6 show total emissions for all three pollutants for Intersection 2, while Figure 14 and Table 7 show total emissions for Intersection 3. There were lower overall emissions for all pollutants associated with Intersection 3 than with Intersection 2; but this was expected, since Intersection 2 included eastbound and westbound links. PM_{10} was underpredicted by all methods at both intersections compared to the baseline, likely the result of underpredicting brakewear. The differences in total emission estimates between methods that use overlapping queue links (Methods 2, 3, 4, and 8) and those that use an average speed on non-overlapping links (Methods 6, 7, and 9) are greater in Intersection 2 than in Intersection 3 due to the signal timing at the intersections. As mentioned previously, the percentage of red time is higher at Intersection 2 than at Intersection 3, resulting in longer queue links and higher emissions. Method 8 has the same emissions as Method 2 since the only difference between the two methods is the length of the queue, i.e., the physical distance the queueing vehicles take up. The number of vehicles queuing per hour was not changed between Method 2 and Method 8. CAL3QHC separates out the calculation of the queue length and the calculation of the total number of vehicles queued, and queue emissions are based on the number of vehicles in the queue, so queue length only factors in when dispersing those emissions to calculate pollutant concentrations.

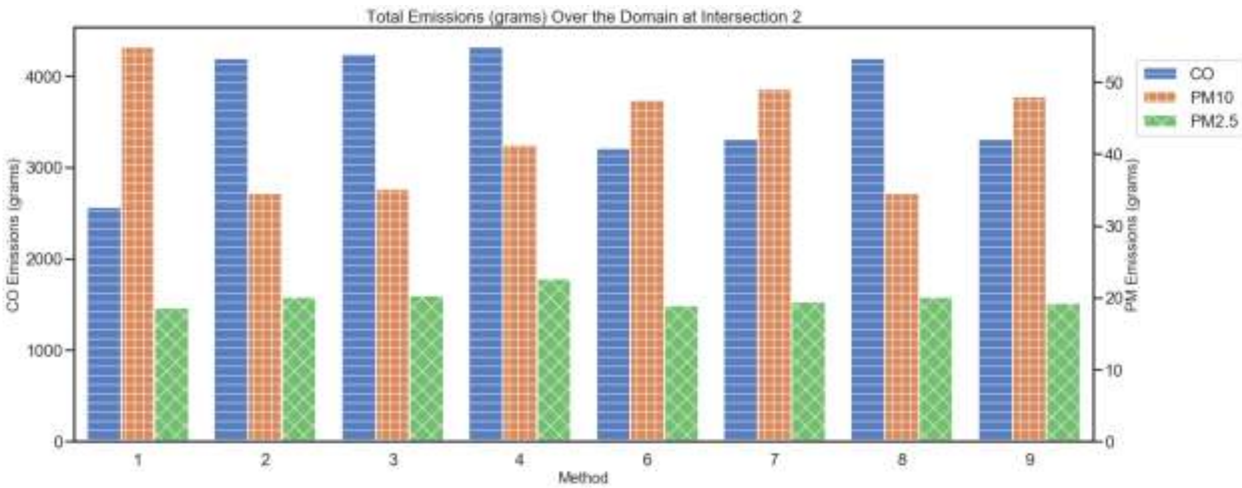


Figure 13. Graph. Total emissions (grams) over the domain for Intersection 2.

Table 6. Total emissions for all pollutants for Intersection 2.

Method	CO (grams)	PM_{10} (grams)	$PM_{2.5}$ (grams)
1 (Baseline)	2,566.2	54.9	18.6
2	4,191.2	34.6	20.1
3	4,246.2	35.1	20.3
4	4,321.2	41.4	22.7
6	3,206.8	47.5	18.9
7	3,306.6	49.1	19.4
8	4,191.2	34.6	20.1
9	3,308.4	48.0	19.2

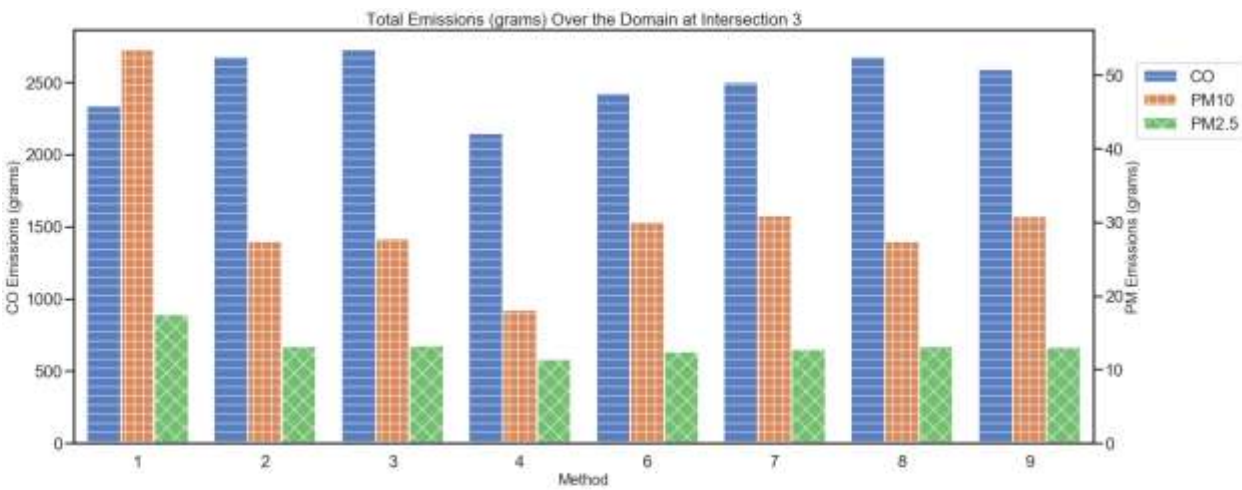


Figure 14. Graph. Total emissions (grams) over the domain for Intersection 3.

Table 7. Total emissions for all pollutants for Intersection 3.

Method	CO (grams)	PM_{10} (grams)	$PM_{2.5}$ (grams)
1 (Baseline)	2334.8	53.5	17.4
2	2678.7	27.4	13.2
3	2729.0	27.9	13.3
4	2149.0	18.1	11.3
6	2427.3	30.0	12.4
7	2502.5	30.9	12.8
8	2678.7	27.4	13.2
9	2592.0	30.8	13.2

One interesting finding from comparing Method 6 with Method 7 is that Method 7, which removes idling from the operating mode distribution and redistributes that activity across the other bins associated with moving vehicles, results in modestly higher (~2 – 3%) emissions for all pollutants. Since this is the only difference between Method 6 and Method 7, this suggests that for domains that are dominated by cars, emissions from idling are smaller than emissions associated with moving. It is likely that for a domain with a higher concentration of trucks, especially diesel trucks, where a hot-spot analysis would be required, emissions associated with idling would be higher.

Table 8 and Table 9 summarize model performance for a variety of emissions-related metrics when compared to baseline values for Intersection 2 and Intersection 3, respectively. The values shown are the percent difference from the baseline method. The performance is indicated by either positive or negative numbers, which correspond to the percent difference in each metric when comparing each method against the baseline. Positive values indicate overprediction, while negative values indicate underprediction. The smallest percent change in total emissions is highlighted in **bold** for each pollutant.

Based on the emissions-oriented metrics for Intersection 3, Methods 6, 7, and 9 have a slight edge over the other simplified methods for CO. None of the simplified methods performed well with total PM_{10} emissions, though Method 4 was clearly the worst performer. Method 4 was also the worst performer for $PM_{2.5}$, while Methods 2, 3, 6, 7, 8, and 9 showed similar underpredictions for total $PM_{2.5}$ emissions. For Intersection 2, all of the simplified methods overpredicted total CO emissions while underpredicting total PM_{10} emissions. The simplified methods performed well compared to the baseline method for $PM_{2.5}$. For Intersection 2, Method 4 was once again the worst performer, while Methods 6, 7, and 9 performed fairly well. ***Method 6 performed the best for CO and performed comparatively well for $PM_{2.5}$ and PM_{10}.***

Table 8. A comparison of various emissions-related metrics across the different methods for Intersection 2.

Pollutant	Method	Total Emissions	Brakewear Emissions	Crankcase Exhaust Emissions	Running Exhaust Emissions	Tirewear Emissions
CO	2	+63.0	+0.0	+54.0	+63.0	+0.0
CO	3	+65.0	+0.0	+56.0	+65.0	+0.0
CO	4	+68.0	+0.0	+62.0	+68.0	+0.0
CO	6	**+25.0**	+0.0	+21.0	+25.0	+0.0
CO	7	+29.0	+0.0	+24.0	+29.0	+0.0
CO	8	+63.0	+0.0	+54.0	+63.0	+0.0
CO	9	+29.0	+0.0	+24.0	+29.0	+0.0
PM_{10}	2	-37.0	-69.0	+42.0	+34.0	-18.0
PM_{10}	3	-36.0	-68.0	+43.0	+35.0	-18.0
PM_{10}	4	-30.0	-58.0	+42.0	+26.0	-9.0
PM_{10}	6	-25.0	-58.0	+65.0	+47.0	-9.0
PM_{10}	7	**-11.0**	-22.0	+36.0	+8.0	+0.0
PM_{10}	8	-37.0	-69.0	+42.0	+34.0	-18.0
PM_{10}	9	-13.0	-25.0	+34.0	+8.0	+0.0
$PM_{2.5}$	2	+8.0	-69.0	+42.0	+34.0	-18.0
$PM_{2.5}$	3	+9.0	-68.0	+43.0	+35.0	-18.0
$PM_{2.5}$	4	+22.0	-58.0	+65.0	+46.0	-9.0
$PM_{2.5}$	6	**+2.0**	-25.0	+33.0	+6.0	+0.0
$PM_{2.5}$	7	+4.0	-22.0	+36.0	+8.0	+0.0
$PM_{2.5}$	8	+8.0	-69.0	+42.0	+34.0	-18.0
$PM_{2.5}$	9	+3.0	-25.0	+34.0	+8.0	+0.0

Table 9. A comparison of various emissions-related metrics across the different methods for Intersection 3.

Pollutant	Method	Total Emissions	Brakewear Emissions	Crankcase Exhaust Emissions	Running Exhaust Emissions	Tirewear Emissions
CO	2	+15.0	+0.0	+8.0	+15.0	+0.0
CO	3	+17.0	+0.0	+10.0	+17.0	+0.0
CO	4	-8.0	+0.0	-9.0	-8.0	+0.0
CO	6	**+4.0**	+0.0	-2.0	+4.0	+0.0
CO	7	+7.0	+0.0	+1.0	+7.0	+0.0
CO	8	+15.0	+0.0	+8.0	+15.0	+0.0
CO	9	+11.0	+0.0	+4.0	+11.0	+0.0
PM_{10}	2	-49.0	-68.0	-3.0	-11.0	-14.0
PM_{10}	3	-48.0	-67.0	-3.0	-10.0	-14.0
PM_{10}	4	-66.0	-91.0	+17.0	-23.0	-18.0
PM_{10}	6	-44.0	-58.0	-14.0	-20.0	-7.0
PM_{10}	7	**-42.0**	-56.0	-12.0	-18.0	-7.0
PM_{10}	8	-49.0	-68.0	-3.0	-11.0	-14.0
PM_{10}	9	**-42.0**	-58.0	-12.0	-15.0	-7.0
$PM_{2.5}$	2	**-24.0**	-68.0	-3.0	-11.0	-14.0
$PM_{2.5}$	3	**-24.0**	-67.0	-3.0	-10.0	-14.0
$PM_{2.5}$	4	-35.0	-91.0	+17.0	-23.0	-18.0
$PM_{2.5}$	6	-29.0	-58.0	-14.0	-20.0	-7.0
$PM_{2.5}$	7	-26.0	-56.0	-12.0	-18.0	-7.0
$PM_{2.5}$	8	**-24.0**	-68.0	-3.0	-11.0	-14.0
$PM_{2.5}$	9	**-24.0**	-58.0	-12.0	-15.0	-7.0

3.2 Concentrations

CAL3QHC model results for all three pollutants are presented below in box-and-whisker style plots (Figure 15) that show statistical quartiles. [11] In these plots, the boxes represent the 25^{th} – 75^{th} percentiles, while the whiskers extend to show the 0 – 25^{th} and 75^{th} – 99^{th} percentiles. The line through each colored box represents the median concentration. These figures provide some context on the range of concentrations predicted by CAL3QHC from each method, and they show that the maximum concentrations could often be considered statistical outliers. Table 10 lists the maximum concentration values for all pollutants for Intersection 2, while Table 11 lists the maximum concentration values for Intersection 3.

As was the case with total emissions, maximum concentrations are higher (about double) at Intersection 2 than at Intersection 3 for all pollutants. Interestingly, though baseline PM_{10} emissions were higher than the other methods at both intersections, several methods resulted in higher maximum PM_{10} concentrations at Intersection 2. The queueing algorithm in HCS7 that was modeled in Method 8 resulted in higher maximum concentrations and lower median concentrations for all pollutants at both intersections when compared to the CAL3QHC queueing algorithm used in Method 2. For maximum CO and $PM_{2.5}$ concentrations, Method 8 performed worse compared to the baseline than Method 2, but for maximum PM_{10} concentrations, Method 8 performed better than Method 2. Method 3 resulted in almost identical receptor concentrations when compared with Method 2 for all pollutants at both intersections, but Method 7 resulted in consistently higher maximum concentrations than Method 6 at both intersections.

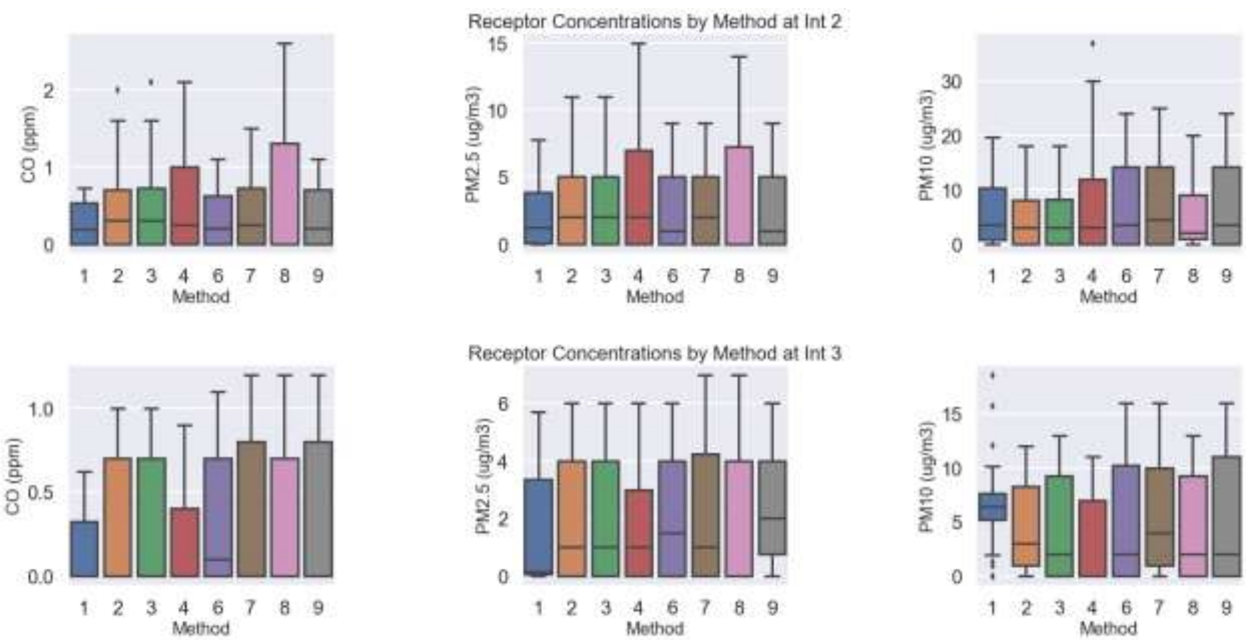


Figure 15. Chart. Box-and-whisker plots of receptor concentrations for all three pollutants by method at both Intersection 2 and Intersection 3.

Table 10. Maximum receptor concentrations for all methods for Intersection 2.

Method	**CO (ppm)**	**$PM_{2.5}$ (μg/m³)**	**PM_{10} (μg/m³)**
1 (Baseline)	0.7	7.8	19.7
2	2	11	18
3	2.1	11	18
4	2.2	15	37
6	1.3	10	26
7	1.5	10	27
8	2.6	14	20
9	1.3	10	26

Table 11. Maximum receptor concentrations for all methods for Intersection 3.

Method	**CO (ppm)**	**$PM_{2.5}$ (μg/m³)**	**PM_{10} (μg/m³)**
1 (Baseline)	0.6	5.7	18.6
2	1	6	12
3	1	6	13
4	0.9	6	11
6	1.1	6	16
7	1.2	7	16
8	1.2	7	13
9	1.2	6	16

Table 12 summarizes model performance for predicting maximum concentrations for all pollutants when compared to baseline values for Intersection 2 and Intersection 3. The values shown are the percent difference from the baseline method. The performance is indicated by either positive or negative numbers, which correspond to the percent difference in each metric when comparing each method against the baseline. Positive values indicate overprediction, while negative values indicate underprediction. The smallest average percent change in maximum concentrations is highlighted in **bold** for each pollutant.

Overall, Method 6 performed best in terms of predicting maximum concentration for all pollutants at both intersections.

Table 12. A comparison of maximum concentration values predicted for Intersection 2 and Intersection 3.

Pollutant	**Method**	**Intersection 3 Max Conc.**	**Intersection 2 Max Conc.**	**Average**
CO	2	+60.0	+178.0	+119.0
CO	3	+60.0	+192.0	+126.0
CO	4	+44.0	+206.0	+125.0
CO	6	+76.0	+81.0	**+78.5**
CO	7	+92.0	+108.0	+100.0
CO	8	+92.0	+261.0	+176.5
CO	9	+92.0	+81.0	+86.5
PM_{10}	2	+5.0	+42.0	+23.5
PM_{10}	3	+5.0	+42.0	+23.5
PM_{10}	4	+5.0	+94.0	+49.5
PM_{10}	6	+5.0	+29.0	**+17.0**
PM_{10}	7	+23.0	+29.0	+26.0
PM_{10}	8	+23.0	+81.0	+52.0
PM_{10}	9	+5.0	+29.0	**+17.0**
$PM_{2.5}$	2	-35.0	-9.0	-22.0
$PM_{2.5}$	3	-30.0	-9.0	-19.5
$PM_{2.5}$	4	-41.0	+88.0	+23.5
$PM_{2.5}$	6	-14.0	+32.0	**+9.0**
$PM_{2.5}$	7	-14.0	+37.0	+11.5
$PM_{2.5}$	8	-30.0	+2.0	-14.0
$PM_{2.5}$	9	-14.0	+32.0	**+9.0**

4 KEY FINDINGS

This section presents some of the key findings from the modeling of Intersection 2 and Intersection 3. Key findings include results from intercomparison of emissions and concentration results by method, as well as important takeaways from this research that may be applicable to practitioners conducting similar analyses.

4.1 Emissions

The following represent key findings from this analysis related to emissions. These key findings are related to comparisons between the simplified methods and the baseline.

1. Methods 2 – 9 generally overpredict total CO emissions and underpredict total PM_{10} emissions.
2. Underpredictions for PM_{10} emissions are strongly influenced by the amount of braking in all baseline links, not just the links close to the intersection. Methods 2, 3, 4, and 8 do not account for braking far from the intersection, because braking was removed from the operating mode distributions for cruise links.
3. The adjustments to the operating mode bins in Method 9 increased emissions slightly compared to Method 6, because emissions from all pollutants from operating mode bins 21 – 30 are slightly larger than operating mode bins 31 – 40.
4. For queue links in Methods 2, 3, 4, and 8, queue link speeds are set to 0 mph. This forces MOVES to put all braking activity into operating mode bin 501, which does not produce any brakewear or tirewear emissions. This could be avoided if the speed on the queue link was set to 1 mph.
5. For Methods 6, 7, and 9, speed on cruise links was set to 35 mph to be consistent with cruise links in Methods 2, 3, 4, and 8. It is possible that these methods would have performed better when compared to the baseline if an average speed was used instead, because the emission profiles from acceleration links matched up better with the emission profiles from the sum of the baseline links.
6. Data associated with the baseline method showed that speed and acceleration values on links representing the far-right lane were affected by vehicles turning in and out of the parking garages located on the northbound side between Intersection 2 and Intersection 3 and between Intersection 3 and Intersection 4. Braking and subsequent acceleration in these links was higher than nearby links that were not affected, which led to increased emissions.

4.2 Concentrations

1. Underpredicting total emissions does not necessarily mean that the models will underpredict maximum concentrations. For PM_{10}, most of the simplified models underpredicted PM_{10} emissions but overpredicted maximum concentrations of PM_{10} for both intersections, with overpredictions ranging from 5% – 94%.
2. Overprediction of total CO emissions did universally correspond with an overprediction of maximum CO concentrations, in some cases overestimating by over 200%.
3. Even though activity and emissions from eastbound and westbound traffic were minimal for Intersection 2, it was enough to cause some maximum concentrations to occur at receptors located close to the intersection.
4. For intersections with short red cycle durations, like Intersection 3, maximum concentrations are most likely to occur near links with the highest emissions, even when those links are distant from the center of the intersection.

4.3 Important Takeaways

4.3.1 Queue Length Estimation

For queue length estimation, the queue algorithm in CAL3QHC is 35 years old, and it ignores all the idling at the back of the queue during the initial green period from the front of the queue. CAL3QHC is unable to model directly shared left-through lane approaches, which tend to be prevalent in older downtown settings, or right turn lane approaches, which tend to be prevalent on higher volume arterials in newer suburbs. The Team found that CAL3QHC significantly underestimates queues (as compared to HCS7) when the volume/capacity (V/C) ratio falls in the range of 0.80 to 1.00. When V/Cs are above 1.10, the situation is reversed with CAL3QHC predicting significantly greater queues than HCS7. This is due to a change in the formula in the queue length estimation from the 1985 HCM method currently in CAL3QHC and the most recent 2016 HCM6 method. The Team also found that the use of the default 1600 pc/hr/lane saturation flow rate input for CAL3QHC may result in underestimating (in most cases) or overestimating (in some cases) the capacity of an intersection movement which can critically impact the predicted delay and queues. For practitioners who need to estimate queue length, the Team recommends the method in HCM6 and implemented in HCS7 software over CAL3QHC.

4.3.2 Preferred Method

There was little evidence in this study to support a recommendation for using a simplified method with overlapping links, i.e., Methods 2, 3, 4, or 8. While the Team had serious reservations about the acceleration and deceleration values in the NGSIM data, it was apparent that Methods 2, 3, 4, and 8 underestimated the amount of braking that happened throughout the domain. This issue was exacerbated by the close spacing of the intersections, because an analysis focused on a single intersection cannot ignore the braking associated with the surrounding intersections. Methods 6, 7, and 9 generally did a better job of predicting emissions than Methods 2, 3, 4, and 8, though it must be said that these methods also consistently underpredicted PM_{10} emissions, if only by a smaller amount. They also did better in terms of predicting maximum pollutant concentrations. These methods rely on using MOVES to find the best drive schedule based on road type and average speed.

Model performance may not be the sole factor in determining which method to use. Deviations from current practice, especially something that complicates the process, should be carefully evaluated. Methods 3, 7, and 9 require two MOVES runs; one to get the default operating mode distributions from MOVES, and a second run to use the modified distributions. The research Team developed scripts to perform the operating mode calculations needed for this analysis, but that type of scripting requires experienced programmers and may represent an extra layer of difficulty for someone running the models. Method 4 requires a determination of meaningful acceleration and deceleration rates. While default rates can certainly be used, the best approach would be to analyze data at the intersection of interest or another nearby, comparable intersection to calculate appropriate rates. Finally, each method requires the preparation of a link network for the prospective intersection. While the Method 2 link network does not have deceleration or acceleration zones, it does still contain overlapping links. The Method 6 link network does not have any overlapping links.

Two limitations for any recommendations came up repeatedly in Team discussion:

- A single method should be used for all pollutants, as the Team is cognizant of the need for simplicity for practitioners.
- A method that does not require any extra MOVES runs, which add additional technical and time burdens on practitioners, should be used.

Based on the MOVES, HCM6/HCS7, and CAL3QHC modeling performed for this study and the associated comparison of the statistical measures of performance as identified in the project workplan, **the Team recommends Method 6**.

5 RECOMMENDATIONS FOR PRACTITIONERS

This section provides tips and recommendations to practitioners for calculating emissions from running processes when conducting transportation-related, project-level air quality analyses. These recommendations are intended to complement guidelines and best practices described in the EPA's Hot-Spot Guidance,[10] particularly in Appendix D: Characterizing Intersection Projects for MOVES. Since these recommendations are focused on emissions, they are focused on MOVES and can be used to prepare emissions inputs for AERMOD or CAL3QHC or any other applicable dispersion model.

In most build versus no-build situations, practitioners will have the benefit of having data from traffic simulations. Likely, this dataset will provide links with volume and speed, often broken out into subsets representing different vehicle types and different periods of the day. However, there are times when this data may not be available, or the data is insufficient for the task at hand. In the absence of better data, like drive schedules or operating mode distributions, the Team recommends the user follow the steps outlined in Option 1 in Appendix D, "Characterizing Intersection Projects for MOVES,"[10] which relies on meaningful average speeds for each link in your network. The following recommendations are provided to allow a practitioner to generate reasonable data for characterizing emissions from running processes at intersections.

5.1 Link Network Design

The creation of a link network to represent all of the activity at an intersection is a critical first step to calculating running emissions. Each link must provide MOVES with enough information to estimate emissions. Key pieces of data include spatial information, like start and end coordinates, as well as road grade, and traffic-related information, like fleet mix (which can be link-specific or a project-wide value applied to all links), total volume per link, and average speed. Rather than rely solely on approach and departure links, the Team recommends that the domain be split into queue links, acceleration links, and cruise links. Each link should represent the middle of the direction of travel, and each link should have a width that corresponds to the number of lanes represented. Different dispersion models may also require additional width added to each link, e.g., CAL3QHC recommends adding 3 meters to cruise links to account for the plume generated by moving vehicles.[1] In cases where the road bends or lanes are added or removed, a separate link should be used to represent the network properly.

5.1.1 Queue Links

Queue links should represent the spatial extent of approaching traffic that decelerates and then queues at the stop bar. While not all traffic will need to decelerate or stop at the intersection, the queue link should represent spatially the part of the domain where traffic does decelerate or stop. The end point of the queue link should be located on the stop bar, and the start point should represent the point at which vehicles begin to decelerate to ensure that road grade is calculated properly.

If the practitioner is modeling a new intersection or if there are questions about when vehicles begin to decelerate, there are several options for estimating the length of the queue link, which includes the length of the vehicle queue and the deceleration distance. The HCM includes formulas for calculating the queue length as well as deceleration length in Chapter 31. Practitioners should consult the HCM for a full explanation, but we provide a synopsis of the calculations below. There are several steps to the process. The first step is to estimate the back of the stopped queue, N_f, beginning with a calculation of d_a, the average acceleration and deceleration delay combined (Equation 3).

$$d_a = \frac{[1.47(S_a - S_s)]^2}{2(1.47S_a)}\left(\frac{1}{r_a} + \frac{1}{r_d}\right) \quad (3)$$

where:

d_a = acceleration-deceleration delay (s),

S_a = average speed on the intersection approach (mph),

S_s = threshold speed defining a stopped vehicle, usually between 0 mph – 5 mph (mph),

r_a = acceleration rate (ft/s^2),

r_d = deceleration rate (ft/s^2)

Then, an intermediate term, t_f, or time to back of stopped queue, is calculated (Equation 4).

$$t_f = \left(\frac{v(r - d_a)}{(s - v)}\right) \quad (4)$$

where:

t_f = time to back of stopped queue (s),

v = lane volume (veh/s),

r = red time (s),

d_a = acceleration-deceleration delay (s),

s = saturation flow rate per lane (veh/s)

N_f is then calculated using Equation 5.

$$N_f = s \times t_f \quad (5)$$

where:

N_f, = back of the stopped queue (veh),

s = saturation flow rate per lane (veh/s),

t_f = time to reach the back of stopped queue (s)

The deceleration distance, *Dd*, can be calculated using Equation 6. Equation 6 is merely another form of Equation 2 (refer to Section 2.8), but it is rewritten to solve for *Dd*. Note that the constant of 1.47 is necessary to ensure proper unit conversion.

$$D_d = \frac{(1.47 \times S_a)^2}{(2 \times r_d)} \quad (6)$$

where:

D_d = Deceleration distance (ft),

S_a = average speed on the intersection approach (mph),

r_d = deceleration rate (ft/s^2)

Finally, the total distance required to decelerate and stop, Q_l, can be calculated using Equation 7.

$$Q_l = (N_f * L_v) + D_d \quad (7)$$

where:

Q_l = Queue link length (ft),

N_f, = back of the stopped queue (veh),

Lv = length per vehicle (ft/veh)

D_d = Deceleration distance (ft)

Equations 3 – 5 can be employed to estimate N_f for isolated intersections with protected phasing for all movements. For more complex situations (such as permitted left turns, a close upstream signal, coordinated signals, etc.) the analyst is advised to use a highway capacity analysis software package to perform the more complex queue accumulation computations needed to estimate N_f. Once the value of N_f has been obtained, then the practitioner can use Equations 6 and 7 to calculate Q_l.

While the Team had difficulty finding published deceleration rates (r_d) to use, the Team did find average deceleration rates for vehicles that stopped at the stop bar ranging from -3 mph/sec to -5 mph/sec in the NGSIM data. Using Equation 5, Table 13 provides deceleration length estimates based on different starting speeds and deceleration rates, as well as values provided by California Department of Transportation (CALTRANS) in the seventh edition of their Highway Design Manual in section 405.2 Left Turn Channelization, Table 405.2B.[12] The practitioner can then combine a deceleration length with an estimate of queue link length to calculate the total queue link length, Q_l.

Table 13. Rounded deceleration length estimates (feet) based on an initial vehicle speed and a final vehicle speed of 0 mph.

Initial Vehicle Speed (mph)	**Deceleration –3 mph/sec**	**Deceleration –4 mph/sec**	**Deceleration –5 mph/sec**	**CALTRANS Highway Design Manual**
20	98	74	59	*
25	153	115	92	*
30	221	165	132	235
35	300	225	180	*
40	392	294	235	315
45	496	372	298	*
50	613	459	368	435

Note on Table 13. Rounded deceleration length estimates (feet) based on an initial vehicle speed and a final vehicle speed of 0 mph. An asterisk (*) denotes that no value was provided by CALTRANS for that vehicle speed.

5.1.2 Acceleration Links

Acceleration links represent the spatial extent of departing vehicles accelerating out of queue links to a cruising speed. The start point of the acceleration link should match the end point of the queue link, and the end point of the acceleration link should represent the point at which a majority of vehicles have reached a cruising speed. Any acceleration that occurs from vehicles stopped in the queue will be captured in the operating mode distribution of the queue link. Due to differing driving behavior, some vehicles accelerate quickly, while other vehicles accelerate at a slower rate. The acceleration link should try to capture the majority of vehicles' acceleration. Equation 2 (refer to Section 2.8) in tandem with an acceleration rate can be used to estimate the length of the acceleration link.

There are many published references containing reasonable acceleration rates. Table 3 provided guidance on maximum reasonable acceleration rates, while in NCHRP Web-Only Document 210 Example No. 3 – Project-Level Analysis, Table 5.6, the authors calculated an acceleration rate of 7 ft/sec/sec or about 4.7 mph/sec for an example acceleration link with an average speed of 25.6 mph and a cruise speed of 38.4 mph.[13] For a detailed analysis of vehicle acceleration rates, please review the paper by Long, 2000.[14]

The Team found average acceleration rates ranging from 2.3 mph/sec to 3.3 mph/sec for vehicles that stopped at the stop bar in the NGSIM data, but based on published values, the Team recommends acceleration rates between 2.5 mph/sec and 4.0 mph/sec. Table 14 provides acceleration link length estimates (feet) based on different cruising speeds and acceleration rates shown in the table.

Table 14. Rounded acceleration link length estimates (feet) based on an initial vehicle speed of 0 mph and a final vehicle speed.

Final Vehicle Speed (mph)	Acceleration 2.5 mph/sec	Acceleration 3 mph/sec	Acceleration 3.5 mph/sec	Acceleration 4 mph/sec
20	117	98	84	73
25	183	153	131	115
30	264	220	189	165
35	359	299	257	225
40	469	391	335	293
45	594	495	424	371
50	733	611	524	458

5.1.3 Cruise Links

Cruise links represent the spatial extent of vehicles traveling at cruising speed. Cruise links are likely to occur far away from intersection centers or other potential traffic-influencing factors like parking garages and should start at the endpoint of the acceleration links. For project-scale modeling, cruise links may be used to “fill in” the rest of the domain. However, as mentioned later in this document, care should be taken not to extend cruise links past potential queue link start points at nearby intersections.

5.2 Link Speed

The speed on the link should be set to the average speed and represent all of the disparate activity on the link, including queueing, acceleration, and free flow travel. The speed limit on the link may not be representative of the average speed, even for cruise links. In a detailed analysis of model results, the Team found that emissions estimates on links using average speed in Method 6, like queue links and acceleration links, were closer to baseline emissions estimates than emissions estimates from cruise links, which used the speed limit of the link. Furthermore, queue link speeds should not be set to zero, because that results in MOVES allocating too much activity to operating mode bin 501, braking while stopped.

5.2.1 Sources for Speed

Most practitioners will have access to traffic analysis tools that are either macroscopic (e.g., HCS7 which faithfully implements the HCM6 methodologies) or microscopic, both of which can produce link speed estimates. In addition, there are many other good sources of speed data available for existing roadways. Probe data can provide great insight into average speeds, as the practitioner can pull data for different times of the day on varying days in varying seasons. Vendors such as Waze[15], INRIX[16], and HERE[17] all offer traffic-related data that could be used in project-level air quality modeling, though the data may require some processing before it can be used. For instance, Waze traffic incident data refers to its own link network, so it is likely that some geospatial processing will be necessary to map the incident data from the Waze network to the practitioner’s network. The North Carolina Department of Transportation (NCDOT) contracts with HERE to access probe data on their freeways and major arterials, and subscribers can download those data from the Regional Integrated Transportation Information System (RITIS) at the University of Maryland Center for Advanced Transportation Technology (CATT) lab. The NCHRP Web-Only Document 210 mentioned in their Example Number 3, Project Level Analysis, at the intersection of two fictional major arterials, the speed on acceleration links could be half that of cruise links and queue link speed can be set to 5.9 mph. [13]

5.3 Other Considerations

This study included intersections that were spaced relatively close to each other. The center of Intersection 1 is only about 360 feet away from the center of Intersection 2, Intersection 3 is about 600 feet from Intersection 2, and Intersection 4 is less than 500 feet from Intersection 3. Closely spaced intersections like this inevitably mean that queues in one intersection can impact traffic leaving another intersection. As such, the Team recommends that the link network design considers surrounding intersections.

The modeling work done for this project focused on one intersection at a time, and cruise links extended from the endpoints of the acceleration links to the stop bar of the adjacent intersections. Recall that cruise link speeds were set at 35 mph uniformly across all of the simplified methods instead of using an average speed. Since the baseline method included all vehicle activity, including the expected slowdowns and queueing related to vehicles approaching the other intersections, the other methods often performed poorly in estimating emissions far from the intersection center, because those simplified links did not account for adjacent intersections with a representative average speed. In projects with closely spaced intersections, the Team recommends creating queue links for adjacent intersections and ending cruise links at the start points of those queue links. These queue links should use an average speed.

This study also included two major parking garages, one in Section 3 and one in Section 4. NGSIM data and baseline modeling revealed that traffic entering and exiting the parking garages affected through traffic, especially in the right lanes. Through traffic entering the parking garages decelerated to turn, and vehicles exiting the parking garages accelerated out onto Lankershim Blvd. The other methods did not account for these activities and their associated emissions, as the location of the parking garages corresponded with cruise links. The Team recommends, in cases where there is an area that may slow down traffic flow, like a parking garage, that coincides with the spatial extent of cruise links, that the practitioner create a separate link that encompasses both the deceleration of vehicles entering the parking garage and the acceleration of vehicles leaving the parking garage. The link should have a lower average speed than the surrounding links, especially if the surrounding links are cruise links.

6 FUTURE RESEARCH NEEDS

This section highlights recommendations that the Team has for future research or modifications to CAL3QHC.

6.1 Models and Tools

To facilitate incorporation of the results of this study, it is recommended that the programming within CAL3QHC be revised to allow inclusion of Method 6 directly into the program. The intent is to allow practitioners to use the model as they have been with a minimum of a learning curve and change in practice. Most microsimulation models as well as some macroscopic tools now have integrated emissions estimation modules using simulated trajectories, though those modules have not been rigorously tested against empirical measures or MOVES predictions. Their advantage is that they provide a fully integrated activity-emissions estimation in a single model. The HCM6 signalized intersection analysis method can be used for estimating queue length, the sum of the back of queue, and deceleration distance to a stop. Since CAL3QHC does not have these calculations, they need to be made using external software, or by hand as shown in Section 5.1.1, but only under the stated conditions. Integrating the back of queue logic into CAL3QHC would allow the practitioner to use a single model for hot-spot analyses.

Ideally, the integration of the HCM6 signalized intersection analysis method into CAL3HQC would also allow for modeling under various signal control conditions, like stop signs or roundabouts. Roundabouts are touted as superior to signals from an emissions perspective because of the smoother trajectories due to the yield control at the approaches. Further additions to CAL3QHC could include:

- Ability to model shared right and through lanes, and shared left and through lanes.
- Ability to deal with new forms of alternative intersections (Superstreets; Reduced Conflict Intersections; Diverging Diamond Interchanges, etc.).
- Ability to account for levels of signal coordination on queues.
- Ability to vary the saturation flow rate to account for geometric conditions (grades and curvatures), vehicle classes and turning movements.
- Ability to estimate a stochastic back of queue estimate.
- Ability to model the effect of stop and yield control such as roundabouts.
- Ability to model vehicle spillback due to short pockets and effects on queues (SIDRA model accounts for this effect).

One downside of the HCM6 method is that it does not give an average speed for the approach, which is needed under existing and new project scenarios. Therefore, practitioners will still need to rely on other data inputs to assign proper speeds.

If CAL3QHC was updated with the addition of the HCM6 methodologies, some additional guidance and an updated User's Guide would likely be necessary, particularly related to identifying and setting the cruise, acceleration, and queue links. Revised model input guidance would likely be needed as well as revised output formats.

In the event that CAL3QHC cannot be updated with HCM6 methodologies, another option could be a separate spreadsheet tool that uses Equations 3 – 7 to calculate queue link length and Equation 2 to calculate acceleration link length. Additional equations to account for other signal control conditions could also be included. The link lengths from the spreadsheet tool could then be used as inputs to the current CALINE-3 model (CAL3QHC without the queueing algorithm) or other dispersion models. A spreadsheet tool would be fairly trivial to develop, yet it would simplify the preparation of data inputs for practitioners when compared to calculating queue link length by hand.

6.2 Follow-Up Studies

Below are additional input datasets that could be used for follow-up studies or to test recommendations made in this report. This research identified several features of Intersections 2 and 3 that presented some complications. To demonstrate the reliability of the findings from this study and to enhance its adoption, the basics of this study could be repeated at a new intersection, completely independent of the Lankershim Blvd. sites. This new intersection could be an isolated intersection or within an urban area with nearby intersections but with adequate intersecting street coverage and free of situations such as parking garages or other impacts to traffic flow. Should Method 6 result in being found as the best method for replicating “ground truth” at this new site as well, it would greatly increase the confidence for adopting Method 6 as the best method to improve vehicle activity inputs for the project-level air quality analysis process.

These additional datasets include:

- There is another NGSIM dataset captured on Peachtree Street in Atlanta. Its structure is similar to the Lankershim Blvd. site, including 5 intersections spaced on average 500 ft apart, and contains over 2,300 vehicle trajectories over a period of 30 minutes.
- Wei and Frey (2020) [(18)] have compiled a detailed 1 Hz trajectory database of 214 vehicles on specific routes in the Raleigh area traveling both on surface streets and freeway links. Concurrent emissions were measured for each vehicle trip using a PEMS device, and a vehicle specific power (VSP) modal model and the MOVES Operating Mode (OpMode) model have been used to evaluate and quantify the fuel use and emission rates (FUERs) for on-road vehicles.
- Under the auspices of the “Safety Pilot Model Deployment” program, a dataset with access to high resolution vehicle data traveling on the Ann Arbor, MI, network contains trajectories of vehicles using in-vehicle devices. Data are available for download from the U.S. DOT website [f]. This dataset collected in 2012 – 2013 is more recent than that of NGSIM.

In relation to data needs, one missing element of the methods described here is the effect of signal coordination. This requires tying the trajectories to their arrival rate at the stop bar in the cycle, so that the higher number of arrivals in the green phase, the lower the projected emissions. The basic assumption in the queue calculations thus far has been a uniform arrival rate of vehicles throughout the cycle. Under excellent progression, the queue length could be cut in half or more, while under poor progression it could easily double. And finally, we reiterate that other types of control, such as stop or yield control are not present in NGSIM data and must be analyzed in a different setting.

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9 APPENDIX

The following memoranda are available on request from FHWA:

- Task 5 Memorandum with detailed discussion of how the CAL3QHC queueing algorithm compares to the current methodology contained in the current Highway Capacity Manual (HCM6)
- Task 7.2 Memorandum on Compiling Data for Intersection 3
- Task 7.3 Memorandum on Running MOVES and CAL3QHC for the Intersection 3
- Task 7.4 Memorandum on Performing Inter-comparison between Various Methods for Intersection 2 and Intersection 3

These reports and associated files are available upon request from the FHWA Transportation and Air Quality Conformity Team at taqc@dot.gov.