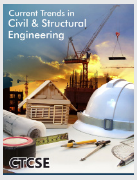

ISSN: 2643-6876

DOI: 10.33552/CTCSE.2022.08.000691

Current Trends in Civil & Structural Engineering

Iris Publishers

Review Article

High-Resolution Modelling of Carbon Dioxide Emissions Before and After the Implementation of a Designated Truck Lane

Edward Tang[1], Hatem Abou-Senna[2]*, Anurag Pande[1] and Robert L Bertini[3]

[1]*California Polytechnic State University, USA*

[2]*University of Central Florida, USA*

[3]*University of South Florida, USA*

***Corresponding author:** Hatem Abou-Senna, University of Central Florida, USA.

Received Date: **January 19, 2022**

Published Date: **March 04, 2022**

Abstract

This work seeks to assess the impact of adding a lane for slower trucks on a divided multilane highway on CO_2 emissions. A portion of the U.S. 101 highway in San Luis Obispo County in California consists of the Cuesta Grade which is a 2.75-mile segment with a 7% grade. A microsimulation software, VISSIM, was used in conjunction with the Environmental Protection Agency's emissions model, MOVES, to estimate CO_2 emissions on the corridor before and after the construction of the third lane. It was found that CO2 emissions decreased between 1998 (before) and 2012 (after the 2003 lane addition), but the effect of the truck lane was shown to be different for the northbound (uphill) and southbound (downhill) directions. The truck lane in the northbound direction exhibited a 9.5% decrease in volume with 10.7% decrease in emissions, and the southbound direction experienced a 20.3% increase in volume but 7.4% decrease in emissions. For the northbound (uphill) direction, emissions seemed to correlate more closely with traffic volumes while a sensitivity analysis revealed travel speeds had a more profound effect on southbound (downhill) emission rates. In the conclusion section, ideas to further validate the emissions estimate are discussed. Emissions seemed to correlate more closely with traffic volumes (uphill) while travel speeds had a more profound effect on southbound (downhill) emission rates. One factor to be accounted for is the change in volume which seems to play a much larger role in emissions than roadway features or topography.

Keywords: Emissions, traffic simulation, VISSIM, MOVES

Introduction

Greenhouse gas (GHG) emissions and other pollutants have long impacted the climate, public health, and the economy. Quantifying these emissions is a critical step towards addressing these impacts. The transportation sector is a major source of carbon dioxide (CO_2) emissions, being second only to the electric utility sector [1]. In the transportation sector, emissions vary based on the type of vehicle among other traffic-related factors [2], and simulation is a tool that can help quantify the impact of these sources. Microscopic traffic simulation is a relatively low-cost and effective tool commonly used to create models to evaluate traffic systems under a variety of circumstances. Microsimulation modeling and resulting data frequently have been used to estimate emissions [3-5]. Over various iterations of calibration, models can be improved over time to generate more accurate results. This study attempts to quantify the change in emissions resulting from the addition of a truck climbing lane on a rural segment, namely Cuesta Grade, of

a 'freeway' corridor in the Central Coast of California. While the segment under consideration is technically not a freeway; the traffic patterns are consistent with that of a rural freeway since ut is barrier-separated and the at-grade intersections on the corridor under consideration have low traffic volumes on the side roads. The U.S. 101 corridor passes through San Luis Obispo (SLO) County and handles significant regional freight demand in addition to the local commuter traffic. The flow of commuter traffic is Southbound (SB; towards the city of SLO) and Northbound (NB; towards North SLO County).

Objectives

With a valid simulation model that accurately reflects factors such as highway capacity, grades, meteorological conditions, vehicle volumes, and speeds, it is possible to estimate GHG emissions. The objectives of this study were:

1. To create a properly calibrated and validated traffic simulation model in VISSIM that reflects PM peak traffic conditions on the Cuesta Grade of U.S. 101, including volumes, speeds, and vehicle composition. VISSIM wsa chosen for its high level of detail and functionality.
2. To compute detailed surface CO_2 emissions generated by vehicles during this time period using MOVES. Data gathered from VISSIM will be used as inputs for MOVES using VISSIM MOVES Integration software (VIMIS) (2, 3).
3. To compare CO_2 emissions before-and-after the construction of a third traffic lane, to determine any impacts.

Literature Review

Estimating aggregate vehicle emissions using simulation models

A detailed microscopic traffic simulation model has previously been developed for Interstate 4 in Orlando, Florida during the PM Peak Hour [2,3]. Using the EPA's mobile source emissions model, MOVES, they estimated CO, NOx, PM2.5, PM10, and atmospheric CO_2 based on a variety of inputs. MOVES is capable of emissions modeling at a great level of detail – vehicle trajectory data, traffic volumes, average speeds, meteorological conditions, vehicle age, vehicle composition, and fuel type are just some examples of inputs that MOVES can use to generate emissions values. MOVES also generates results on a second-by-second basis. Abou-Senna et al. [2,3] found previously that emissions rates were highly sensitive to acceleration at low-speeds (i.e., congestion involving frequent braking and acceleration).

Chamberlin et al. discussed best practices when conducting project-level analyses using EPA's MOVES software [5]. A project-level analysis with MOVES requires interfacing with a traffic microsimulation model and an air dispersion model. The advantage of microsimulation is that it can capture a higher resolution of detail and dynamic behaviors of individual vehicles. Chamberlin et al. [5] discuss the significance of location (specific coordinates) defined in the model for estimating emissions because of inherent variability resulting from network elements such as intersections. A test-bed emissions analysis (PM2.5) of an intersection before and after signal optimization was conducted to determine the impacts on emissions. Chamberlin et al. [5] found that using average speed and operating mode distribution (based on VSP) show emissions reductions and both approaches have similar estimates for fuel consumption. However, the operating mode distribution's results showed greater variability closer to the intersection, more accurately representing variances in acceleration and speed.

Estimating individual vehicle emissions using simulation models

Barth et al. gathered data from the University of California, Riverside mobile emissions research laboratory to develop a model for estimating heavy-duty diesel (HDD) vehicle emissions [6]. While emissions models for light-duty vehicles (LDV) have been extensively researched and developed, fewer efforts have been made to develop HDD vehicle emissions models even though HDD vehicles can represent a significant portion of emissions. Barth et al. [6] used a test fleet of 11 vehicles using various procedures to capture real-world emissions data. Test procedures included the California Air Resources Board (CARB) HDD test, dynamometer testing, real-world driving, and customized modal emission cycles developed by the team. Validation consists of data obtained from the dynamometer testing. Of particular interest is that the model can be adapted to test the presence of grades and truck lanes since the Cuesta Grade involves both of these scenarios. Nam et al. equipped a test vehicle with a Portable Emissions Measurements System (PEMS) developed by Ford to measure the impact of driver behavior on vehicle emissions [7]. The test vehicle was driven on an 8.5-mile segment consisting of 17 traffic signals in Oakland County, Michigan. The researchers drove the vehicle "normally" and "aggressively" to capture different emissions data sets. For the modeled emissions, the researchers used VISSIM and CMEM with a complex network consisting of a 4 x 5-mile grid. CMEM was calibrated using dynamometer data. Calibrating VISSIM involved creating a virtual vehicle that ran on the same route as the real-world test vehicle. Results showed that while travel times were similar for both normal and aggressive driving styles, fuel consumption and emissions were higher for the latter. The VISSIM and CMEM model compared favorably in its generated emissions values, but the authors note that its ability to predict emissions from a low-emitting vehicle was limited. Chamberlin et al. compared two popular emissions simulators, MOVES and CMEM, by analyzing the emissions estimates based on a test-bed analysis of changing a 3-leg signalized intersection to a roundabout [8]. While the research does not definitively state which emissions estimator is more accurate or preferred, the authors describe in detail the greater capability of MOVES over CMEM. MOVES is capable of incorporating meteorological data and fuel type, and it relies on data from 62,500 dynamometer test vehicles as opposed to CMEM's 343 vehicles. MOVES can also model more pollutant processes than CMEM and

Citation: Edward Tang, Hatem Abou-Senna, Anurag Pande, Robert L Bertini. High-Resolution Modelling of Carbon Dioxide Emissions Before and After the Implementation of a Designated Truck Lane. Cur Trends Civil & Struct Eng. 8(4): 2022. CTCSE. MS.ID.000691. DOI: 10.33552/CTCSE.2022.08.000691.

uses statistical modeling of emissions using vehicle specific power and speed. CMEM only uses analytical modeling of the physical processes involving combustion, but it is well understood that fuel consumption and emissions are greatly affected by driver behavior. One limitation of the study is that neither the data from MOVES or CMEM was validated against real-world data.

Roadway environment and vehicle emissions

Chu and Meyer describe a methodology for estimating emissions reductions of truck only toll lanes [9]. Using the U.S. EPA's MOBILE6.2 emissions model (precursor to MOVES), they measured HC, CO, NOX, and CO_2 for gasoline and diesel trucks. The software was limited in that it was unable to use speed as an input for estimating CO_2 emissions. The authors used an equation to correlate fuel consumption with CO_2 emissions for more accurate results. Chu and Meyer found that voluntary and mandatory use of truck only toll lanes reduced CO_2 emissions on freeways by around 62%. Boriboonsomsin and Barth researched emissions trends for light-duty vehicles when traveling on a grade [10]. The authors gathered CO_2 emissions data by driving a test vehicle, measuring its fuel consumption, and using an empirical formula to determine the emissions generated. The route consisted of a 15-mile segment with average road grade of 4%. Boriboonsomsin and Barth used CMEM to estimate CO_2 emissions. The results showed that fuel economy for light-duty vehicles on flat roads is 15% to 20% better than for the particular segment tested. One limitation acknowledged by the study is that only light-duty vehicles were tested and modeled. Emissions of heavy-duty vehicles, which have a lower power-to-weight ratio, may be more impacted by the presence of grades. Conversely, it is unclear what the effects on hybrid vehicles are.

Liu et al. [11] explored how grade impacts vehicle operations, emissions, and pollutant exposures along freeways using VT-Micro. The study confirmed that integrating road grade may be critical for transportation conformity and PM2.5 hotspot analysis [11]. Llopis-Castelló et al. [12] aimed to evaluate the impact of road horizontal alignment on CO_2 emissions produced by passenger cars using a new methodology based on naturalistic data collection. The analysis concluded that CO_2 emission rates increase with the Curvature Change Rate [12]. Llopis-Castelló et al. [13] also studied the influence of the geometric design consistency on vehicle CO_2 emissions on 47 homogeneous road segments by means of Global Positioning System devices. Vehicle CO_2 emissions were estimated by applying the VT-micro model. They concluded that vehicle CO_2 emissions decreases as the consistency level of a homogeneous road segment increases [13].

Modeling traffic emissions based on vehicle type and driver behavior

Ahn et al. estimated fuel consumption and emissions (CO, HC, and NOx) of light-duty vehicles and light-duty trucks using hybrid regression models [4]. The motivation for the study stemmed from the limitations of existing urban models that only used average link speeds, whereas variances in acceleration and speed have a significant effect on fuel consumption and emissions. At the time, EPA's MOBILE6 software did not account for driver-related behaviors on emissions. The researchers collected speed and acceleration data from test vehicles at the Oak Ridge National Laboratory (ORNL). Emissions data obtained from the models were validated against real-world emissions data obtained from EPA's Automotive Testing Laboratories and National Vehicle and Fuels Emission Laboratory. Ahn et al. found that the model was consistent with real-world data with a coefficient of determination over 90 percent. Papson et al. [14] used MOVES to predict nitrogen oxides (NOx) and particulate matter (PM) emissions at congested and uncongested signalized intersections [14]. The researchers used a time-in-mode analysis combining emissions factors for an activity mode (acceleration, deceleration, cruise, idle) with time spent in each mode. The emissions analysis paired MOVES with Synchro to conduct the traffic simulation. Results showed that acceleration was responsible for 46% to 55% of emissions, and cruising accounted for 28 to 47% of emissions. The authors concluded that uniform traffic flow is less sensitive to congestion than expected. In congested uniform traffic flow scenarios, cruise emissions were shown to increase while idling and acceleration emissions decreased. Managing control delay to minimize acceleration is important in reducing vehicle emissions. One limitation acknowledged by the study is the lack of validation for the emissions factors. Perugu et al. [15] presented successful application of data-driven, Spatial Regression and output optimization Truck model (SPARE-Truck) to develop truck-related activity inputs for the mobile emission model, and eventually to produce truck specific gridded emissions. They concluded that it is easy to segregate gridded emission inventory by truck type since currently there is no reliable method to test different truck-category specific travel-demand management strategies for air pollution control [15].

Validation of microscopic traffic simulation models with real traffic data

Calibration and validation of models is an important final step to ensuring that the simulation model performs as expected and can generate reasonable data. Punzo & Simonelli [16] tested four models of varying complexity against four test vehicles equipped with GPS receivers that recorded position at one tenth second intervals [16]. Validation involved comparison of model results with test vehicle results using the same inputs. Punzo & Simonelli [16] calibrated their results in which they attempted to reproduce a trajectory from vehicles 2, 3, and 4 by using parameters calibrated on the leader vehicle 1. One limitation is that the leading vehicle has no knowledge of the preceding vehicle's trajectory. Punzo & Simonelli [16] found that cross validations showed real world data to perform better using a Root Mean Square Percentage Error (RMSPe) when compared to data collected from a test track. When collecting real traffic data using a test vehicle, it is important to understand that validation may produce different errors even with

Citation: Edward Tang, Hatem Abou-Senna, Anurag Pande, Robert L Bertini. High-Resolution Modelling of Carbon Dioxide Emissions Before and After the Implementation of a Designated Truck Lane. Cur Trends Civil & Struct Eng. 8(4): 2022. CTCSE. MS.ID.000691. DOI: 10.33552/CTCSE.2022.08.000691.

the same driver. The authors suggest studying driver behavior over a long period of time to recognize how road and traffic characteristics can affect the driver, altering any perceived notions of a controlled study. Statistical measures for comparing results including root mean square error, root mean square percentage error, and Theil's Indicator were used as error testing for both calibration and validation. Conclusions highlighted the importance of real-world data for validation. Mahesh et al. [17] measured real-world emissions of gaseous pollutants (CO, HC, and NO) from twenty trucks of different sizes and emission standards in Chennai, India using AVL Ditest gas 1000. They found that considerable reductions in emission factors were observed from lower to higher emission control standards for all the pollutants [17].

Much research exists to estimate vehicle emissions on the aggregate and/or individual level using microsimulation software in conjunction with emissions modeling software for heavy duty trucks or roadway environment. However, very few research exists that studied the effect of both roadway grade and land use travel patterns in a designated truck lane on emissions especially in a before and after study. This paper benefits from the available research in that individual vehicle characteristics are being modeled to determine aggregate emissions on a corridor. The research shows that topography and roadway characteristics affect emissions. A 4% grade can increase light-duty vehicle emissions by 15-20% [10]. Acceleration may account for as much as half of emissions while cruising may account for as little as a third [14]. Between the two major emissions models, MOVES and CMEM, MOVES has greater capability and relies on a larger library of test data than CMEM (62,500 vehicles vs. 343 vehicles). Therefore, in this study, we chose to use MOVES as the emissions estimator.

Simulation Model for U.S. 101

Area of study

The study area includes the Cuesta Grade of U.S. 101 in SLO County (See Figure 1). The northbound portion extends from the Monterey Street on-ramp (milepost 29.985) in SLO to the Junction 58 East (JCT 58) off-ramp (milepost 37.863) in Santa Margarita. The southbound portion extends from the JCT 58 on-ramp to the Monterey Street off-ramp. The simulation models created in this study include the Monterey Street and JCT 58 ramps and all at grade stop-controlled intersections in between.

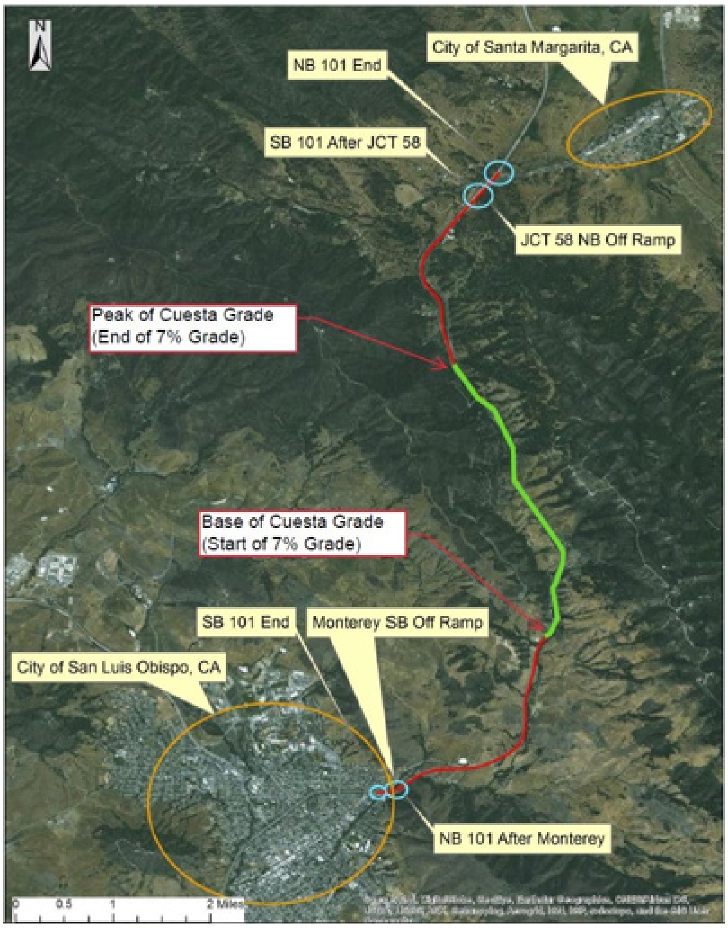

Figure 1: Locations of data collection measurement points.

Citation: Edward Tang, Hatem Abou-Senna, Anurag Pande, Robert L Bertini. High-Resolution Modelling of Carbon Dioxide Emissions Before and After the Implementation of a Designated Truck Lane. Cur Trends Civil & Struct Eng. 8(4): 2022. CTCSE. MS.ID.000691. DOI: 10.33552/CTCSE.2022.08.000691.

U.S. Route 101 and cuesta grade

U.S. 101 is a north-south highway that runs along the West Coast of the United States from California to Washington. It passes through several communities and cities in the Central Coast region of California. U.S. 101 varies in geometry but is generally two to three lanes in each direction. In California, the route connects the Central Coast region with the metropolitan regions of the San Francisco Bay Area and Los Angeles. The Cuesta Grade is a portion of the U.S. 101 extending beyond the northern city limits of San Luis Obispo, CA to Santa Margarita, CA. It is a 4-lane highway with a posted speed limit of 65 mph for cars and light trucks, and a 6-lane limited-access highway with a 35-mph reduced speed limit for heavy goods vehicles (HGV) on the nearly 3-mile steep southbound downgrade section. Historically, the highway was four lanes throughout the entire Cuesta Grade section (~3- mile segment in the middle of the corridor shown in Figure 1) but was widened to six lanes in 2003. The purpose was to improve safety and increase capacity as slow-moving heavy vehicles on the steep grade often caused congestion [18]. Trucks are required to use these lanes and are restricted to a speed limit of 35 mph in the southbound (downhill) direction, but cars may also use these lanes and have no speed restrictions. This widening was expected to reduce sudden acceleration potentially resulting in lower vehicle emissions. The corridor has varying grades with a maximum elevation of 1,522 feet. There are six intersecting roads in the northbound direction and five intersecting roads in the southbound direction. Additionally, there are two egress only roads in the southbound direction. Operation on the Cuesta Grade is similar to a freeway, even though it is technically a multilane highway, due to very low volumes from these intersecting roads and barrier separation. Also, as noted earlier, the PM peak direction is the northbound (uphill) direction.

Creating the network

Before-and-after comparison

To analyze the emissions impact of widening from four to six lanes, two separate networks were created to represent the past and present conditions. Each network has unique volumes, link geometry, and speed distributions. The first network (Network 1) uses data from 1998 to simulate conditions before the widening of the Cuesta Grade began construction in 1999. The second network (Network 2) uses data from 2012 to essentially represent current conditions which are the most complete data available at the time from Caltrans [19].

Road network

VISSIM includes satellite imagery from Microsoft's Bing Maps which was used as a basis for tracing the network. Links were created in segments along U.S. 101 with different grades assigned to each link. All links were assigned the standard lane width of 12 feet, and the HGV vehicle class is restricted to travel in lane 1. Network 1 uses a 4-lane network throughout the Cuesta Grade, and Network 2 represents the 6-lane portion from milepost 32.545 to 35.255. Road grades were collected in the field starting at Reservoir Canyon Road and 3.35 miles northbound. The remaining grades were collected using Google Earth's elevation profile. Each of these grades were assigned to individual links. The complete network consists of 190 links and 199 connectors for a total of 389 links and connectors. The Cuesta Grade section of U.S. 101 involves several, albeit low-volume, at-grade stop-controlled intersection. Stop signs and conflict areas were assigned to these intersecting roads.

Traffic data

To create an accurate emissions model, the number of vehicles and its distribution are needed. Directional volumes from 1998 and 2012 were obtained from Caltrans. For some of the low- volume ramps, Caltrans only provided the ADT. The ADT values were converted to peak hour using Equation 1, where ADT is the average daily traffic volume, and the K-Factor is the peak factor.

$$Peak\ Hour\ Volume = (ADT) * (K\ Factor) \quad (1)$$

Traffic volumes for the network were determined by studying ramp and highway volumes from Caltrans. A summary of the volume inputs for Networks 1 and 2 are shown in Table 1.

Table 1: Volume Inputs (Vehicles Per Hour).

Road Link	Network 1 (4-lane)	Network 2 (6-lane)
Northbound		
Monterey Street	325	340
NB 101 Network Origin point	2,620	2,179
Fox Hollow Road	5	10
Reservoir Canyon Road	5	10
Vista Del Ciudad Road	5	10
Cuesta Springs Road	5	10
Tassajara Creek Road	15	20
Old Stagecoach Road	5	27
Southbound		
Junction 58 East	190	230

Citation: Edward Tang, Hatem Abou-Senna, Anurag Pande, Robert L Bertini. High-Resolution Modelling of Carbon Dioxide Emissions Before and After the Implementation of a Designated Truck Lane. Cur Trends Civil & Struct Eng. 8(4): 2022. CTCSE. MS.ID.000691. DOI: 10.33552/CTCSE.2022.08.000691.

SB 101 Network Origin Point	1,600	1,865
Tassajara Creek Road	20	20
Cuesta Springs Road	10	15
TV Road	15	15
Old Stagecoach Road	13	13
Hawk Hill Road	11	11

Vehicle compositions varied depending on the year of analysis. Caltrans reported 8% and 9% heavy trucks in 1998 and 2012, respectively, at milepost 30.360 [19].

VISSIM requires speed distributions to be defined for all vehicle classes. Posted speed limit was used to determine speed distributions for the corridor. Three distributions were created to model the varying speeds of three different vehicle classes:

1. Cars and light trucks – Minimum speed of 55 mph, maximum speed of 75 mph, 15th percentile speed of 60 mph, and 85th percentile speed of 70 mph.
2. HGV – Minimum speed of 50 mph, maximum speed of 65 mph, 15th percentile speed of 55 mph, and 85th percentile speed of 60 mph.
3. HGV (Reduced Speed Area) – Minimum speed of 25 mph, maximum speed of 40 mph, 15th percentile speed of 30 mph, and 85th percentile speed of 35 mph in the southbound direction (no truck only speed restriction in northbound direction due to the steep upgrade).

Data collection points

In VISSIM, data collectors were placed at strategic locations to collect speed, acceleration, and volumes for both vehicle classes. Data collection points were first placed on each link (in the case of two lanes, one for each lane), and data collection measurements were further defined by specifying the data collection points. For example, the "NB 101 After Monterey" data collection measurement collected data from data collection points 7 and 8 (one for each lane). Figure 1 illustrates each data collection measurement location. These data collection locations were included to ensure that requisite data for emissions estimation (through MOVES) were available.

Emissions modeling

As mentioned earlier, emissions were estimated by exporting the simulation results from VISSIM and importing into MOVES software using VIMIS [2,3]. The data inputs for MOVES include link length, grade, vehicle composition, volume, and vehicle trajectory data which include speed, and acceleration on a link-by-link basis. Vehicle composition was obtained from Caltrans and simulated in VISSIM. All other inputs (volume, speed, and acceleration) were separated by vehicle type. All data were then aggregated into 3 sections: upstream of the truck lane, at the truck lane, and downstream of the truck lane to compare the effects at each section in 1998 and 2012.

Assumptions

Real-world traffic conditions are intricate systems and very difficult to perfectly replicate in the simulation. Not all data can be reasonably collected for use in a simulation model. Models and the resulting calibration/validation rely on assumptions to fill these gaps. The VISSIM model being developed for this study relies on the following assumptions:

1. Area of Study is limited to the Cuesta Grade on U.S. 101 (milepost 29.985 to milepost 37.863) and intersecting roads that do not dead-end to small properties which may not have notable traffic volumes.
2. Time of Study is limited to the PM peak period (5:00 – 6:00 PM).
3. Time of Simulation is limited to 70 minutes. A 10-minute time period is used as a warm-up for the simulation.
4. Vehicle Composition is limited to cars, light trucks, and HGV. Vehicles were not further sub-classified within their vehicle type (i.e. sedans and SUVs are considered to be the cars and light trucks type, respectively). Motorcyclists and regional transit were not included in the model due to their negligible percentages in the traffic fleet.
5. Traffic Inputs have several key assumptions:
6. Peak hour volumes may not have been collected during the mid-week (Tuesday –Thursday) due to lack of available data.
7. D Factors were adjusted to match the same peak hour of data collection (60% for 1998, 55% for 2012).
8. Ramp volumes are provided in ADT and converted to peak hour volume using an assumed K Factor of 10%.
9. Traffic volumes were not available for the stop-controlled intersections along the Cuesta Grade corridor. These values were assumed to be between 5-30 vehicles per hour.
10. Speed Distributions were assumed to be a range based on the posted speed limit and varied between vehicle classes.
11. Unless otherwise specified, VISSIM's default parameters are assumed.

Citation: Edward Tang, Hatem Abou-Senna, Anurag Pande, Robert L Bertini. High-Resolution Modelling of Carbon Dioxide Emissions Before and After the Implementation of a Designated Truck Lane. Cur Trends Civil & Struct Eng. 8(4): 2022. CTCSE. MS.ID.000691. DOI: 10.33552/CTCSE.2022.08.000691.

Data Analysis and Results

Simulation model validation

Calibration and validation are important steps to ensure the accuracy of the model. The origin-destination matrix was calibrated several times until validation showed acceptable levels of discrepancy between real and simulated volumes as measured by validation measures. These measures include the GEH statistic, Root Mean Squared Error (RMSE), and Theil's Indicator.

GEH statistic: The GEH Statistic is a formula commonly used to compare two sets of hourly traffic volumes. It was derived empirically by Geoffrey E. Havers (hence the name GEH) in the 1970s and is defined by Equation 2, where M is the traffic model count and C is the real-world count.

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}} \qquad (2)$$

It is generally accepted that values less than 5 to have a low chance of error, between 5 and 10 medium chances of error, and greater than 10 high chances of error [20].

Root mean squared error

The root means squared error represents the distance of a data point from a fitted line. In this case, the fitted line would be the real-world data, and the data point would be the simulation count. RMSE is bounded between 0 – 1 with 0 representing no error. It is defined by Equation 3, where yi is the traffic model count, ŷi is the real-world count, and n is the number of observations.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \qquad (3)$$

Theil's indicator

Theil's Indicator is used as a measure of forecast accuracy bounded between 0 – 1 with 0 representing perfect forecast [21]. It is defined by Equation 4, where n is the number of observations, Ai represents the actual observations (here real-world traffic counts), and Pi represents the predictions (i.e., simulated traffic counts).

$$U = \frac{\left[\frac{1}{n}\sum_{i=1}^{n}(A_i - P_i)^2\right]^{\frac{1}{2}}}{\left[\frac{1}{n}\sum_{i=1}^{n}A_i^2\right]^{\frac{1}{2}} + \left[\frac{1}{n}\sum_{i=1}^{n}P_i^2\right]^{\frac{1}{2}}} \qquad (4)$$

Traffic Volumes

These validation measures were computed using simulated counts from five runs averaged together. The results of the simulation are shown in Table 2 and Table 3. Validation measures revealed acceptable numbers for all data points.

Table 2: Network 1 (4-lane; from 1998) Traffic Volume Results.

	NB 101 After Monterey	JCT 58 NB Off Ramp	NB 101 End	SB 101 After JCT 58	Monterey SB Off Ramp	SB 101 End
Expected Counts	2,940	190	2,385	1,795	325	1470
Simulation Counts	2,919	196	2,384	1,785	323	1,429
GEH Statistic	0.4	0.43	0.03	0.23	0.11	1.07
Theil's Indicator	0	0.04	0.01	0.02	0.03	0.02
RMSE	0.01	0.08	0.02	0.03	0.06	0.04

Table 3: Network 2 (6-lane; from 2012) Traffic Volume Results.

	NB 101 After Monterey	JCT 58 NB Off Ramp	NB 101 End	SB 101 After JCT 58	Monterey SB Off Ramp	SB 101 End
Expected Counts	2,475	189	2,386	2,151	336	1,815
Simulation Counts	2,500	182	2,358	2,098	335	1,779
GEH Statistic	0.51	0.48	0.58	1.15	0.07	0.85
Theil's Indicator	0.01	0.03	0.01	0.02	0.02	0.02
RMSE	0.01	0.06	0.03	0.03	0.05	0.03

Emissions Results

From averaging the five simulation runs in VISSIM, the aggregated data used as MOVES inputs are shown in Table 4, and emissions results are shown in Table 5. Overall, PM peak hour CO_2 emissions decreased by 6.8% across the whole corridor. Across the whole corridor, results show that between 1998 and 2012 total CO_2 emissions decreased in the northbound direction for 2012 and increased for the southbound direction. The only exception to this was the 2.75-mile southbound segment with the third truck lane which showed a 7.4% decrease in emissions.

Citation: Edward Tang, Hatem Abou-Senna, Anurag Pande, Robert L Bertini. High-Resolution Modelling of Carbon Dioxide Emissions Before and After the Implementation of a Designated Truck Lane. Cur Trends Civil & Struct Eng. 8(4): 2022. CTCSE. MS.ID.000691. DOI: 10.33552/CTCSE.2022.08.000691.

Table 4: Inputs for Moves Emissions Modeling.

	Network 1 (4-lane): 1998 Data					Network 2 (6-lane): 2012 Data				
Direction	**Section**	**Total Volume**	**Average Speed (mph)**		**Truck Percentage**	**Section**	**Total Volume**	**Average Speed (mph)**		**Truck Percentage**
			Cars	**Trucks**				**Cars**	**Trucks**	
Northbound	Upstream of Truck Lane	2,919	60.06	51.24	8.7	Upstream of Truck Lane	2,500	61.12	52.06	8.92
	Truck Lane	2,770	46.31	21.23	8.74	Truck Lane	2,530	60.96	21.39	8.93
	Downstream of Truck Lane	2,384	60.26	54.17	8.1	Downstream of Truck Lane	2,330	60.19	54.81	8.71
Southbound	Upstream of Truck Lane	1,785	63.37	56.17	8.29	Upstream Truck Lane	2,098	63.2	55.61	9.01
	Truck Lane	1,761	61.67	30.58	8.18	Truck Lane	2,118	63.27	30.35	8.97
	Downstream of Truck Lane	1,429	63.12	55.95	8.05	Downstream of Truck Lane	1,779	62.44	55.8	8.66

Table 5: Moves Emissions Estimates.

	Network 1 (4-lane): 1998 Data			Network 2 (6-lane): 2012 Data			% Change	
Direction	**Section**	**Length (mi)**	**CO_2 (kg)**	**Section**	**Length (mi)**	**CO_2 (kg)**	**Emissions**	**Volume**
Northbound (Uphill)	Upstream of Truck Lane	2.6	5,485	Upstream of Truck Lane	2.6		-17	-16.8
	Truck Lane	2.75	8,445	Truck Lane	2.75	7,627	-10.7	-9.5
	Downstream of Truck Lane	2.47	3,110	Downstream of Truck Lane	2.47	3,021	-2.9	-2.3
	Total	7.82	17,040	Total CO_2	7.82	15,337	-11.1	--
Southbound (Downhill)	Upstream of Truck Lane	2.47	3,647	Upstream of Truck Lane	2.47	3,750	+2.8	17.5
	Truck Lane	2.75	3,635	Truck Lane	2.75	3,386	-7.4	20.3
	Downstream of Truck Lane	2.6	2,128	Downstream of Truck Lane	2.6	2,301	+8.1	24.5
	Total	7.82	9,410	Total CO_2	7.82	9,437	+0.3	--
	Total Corridor CO_2		26,450	Total Corridor CO_2		24,774	-6.8	--

Discussion

Considering only the designated truck lane portion, northbound (uphill) emissions decreased by 10.7%, and volumes decreased by 9.5%; while southbound (downhill) emissions decreased by 7.4%, although volumes increased by 20.3% in the same section. The decrease in peak hour volume in the northbound direction and increases in the southbound direction may seem surprising but is consistent with the changes in travel patterns of the Central Coast region. In 2003, the city of SLO was the major employment center while Northern SLO County cities were the residential communities. Hence, the PM peak hour in the NB direction was quite pronounced. While the NB remains the peak direction even today, the directional split has become more balanced. Employment growth in the northern SLO County due to the rise of Paso Robles wine country may have contributed to this trend.

At the corridor level, results showed overall increased emissions in the southbound direction and decreased emissions in the northbound direction. It is important to note that other factors (besides the addition of the third lane in both directions) may have influenced the results which included mixed effects between volume and grade. Examination of general correlations between volume and emissions on the corridor revealed that the correlation was less pronounced in the southbound direction. Southbound emissions may be less sensitive to volume changes because drivers are cruising downhill rather than accelerating uphill. There has been a posted truck speed limit of 35 mph since at least 1998 for this section of road due to the steep grade. Drivers stuck behind the trucks in a 2-lane roadway may accelerate upon passing slow moving trucks, and prior research has shown that acceleration can account for up to half of vehicle emissions [11]. With the newly

Citation: Edward Tang, Hatem Abou-Senna, Anurag Pande, Robert L Bertini. High-Resolution Modelling of Carbon Dioxide Emissions Before and After the Implementation of a Designated Truck Lane. Cur Trends Civil & Struct Eng. 8(4): 2022. CTCSE. MS.ID.000691. DOI: 10.33552/CTCSE.2022.08.000691.

added lane, to which trucks are restricted to, the need for this sudden acceleration by passenger cars has been all but obviated. The varying relationship between traffic volumes and emissions indicated the need for sensitivity analysis presented in the next section.

Sensitivity Analysis

Because emissions are also sensitive to speed at the microscopic level, a sensitivity analysis was conducted with varying travel speeds in the simulation assuming different truck speed limits for the corridor. For both the 1998 and 2012 networks, varying truck speed distributions of 35 mph, 40 mph, 45 mph, and 50 mph were simulated in the northbound and southbound directions. Table 6 shows the results of the sensitivity analysis. Due to changes in volumes from 1998 and 2012, emission rates (emissions normalized by traffic volumes) were used instead of total emissions to observe a fair comparison. The sensitivity analysis showed very little influence from speed on the northbound emission rates due to the steep upgrade. Moreover, the addition of a truck lane reduced emission rates by 8.78% for the truck lane section due to segregation of traffic and improvement of passenger car speeds. In the southbound direction, the emission rates were heavily influenced by the different speeds showing a 24% decrease between the 35 mph and 50 mph scenario where there was no truck lane and 10% decrease with a truck lane. The truck lane had the largest effect when speeds were restricted to 35 mph (as is the case today) as this would greatly improve traffic segregation and passenger car speeds. Further details of this analysis may be found in Tang [22].

Table 6: Sensitivity Analysis Results.

Northbound	1998 (Without Truck Lane)		2012 (With Truck Lane)		
Posted Speed (mph)	**Total Emissions (kg)**	**Emission Rate (kg/Veh mile)**	**Total Emissions (kg)**	**Emission Rate (kg/Veh mile)**	**Truck Lane Effect**
35	8,690	1.14	7,227	1.04	
40	8,697	1.14	7,217	1.04	-8.78%
45	8,692	1.14	7,210	1.04	
50	8,685	1.14	7,205	1.04	
Speed Limit Effect		0%	--	0%	--
Southbound	**1998 (Without Truck Lane)**		**2012 (With Truck Lane)**		
Posted Speed (mph)	**Total Emissions (kg)**	**Emission Rate (kg/Veh mile)**	**Total Emissions (kg)**	**Emission Rate (kg/Veh mile)**	**Truck Lane Effect**
35	3,562	0.74	3,107	0.56	-23.68%
40	3,142	0.65	2,978	0.54	-17.07%
45	2,976	0.62	2,934	0.53	-13.73%
50	2,870	0.6	2,830	0.51	-13.72%
Speed Limit Effect		-24%	--	-10%	--

Conclusions

This paper sought to estimate CO_2 emissions on a limited-access highway before and after the addition of a designated truck lane using a microsimulation tool, VISSIM, with an emissions estimator, MOVES. The data obtained from this research suggest that the designated truck lane reduced CO_2 emissions along the Cuesta Grade. One factor to be accounted for is the change in volume which seems to play a much larger role in emissions than roadway features or topography. Additionally, the sensitivity analysis showed that vehicle speeds have a high influence on CO_2 emission rates in the southbound (downhill) direction. The designated truck lane may be beneficial in situations with high congestion causing vehicles to behave more erratically than cruising smoothly. It should be noted that although there is a posted truck speed limit of 35 mph in the southbound (downhill) section, there is no posted limit for trucks in the northbound (uphill) direction. This paper assumes that trucks have a specific speed distribution centered around 35 mph in the northbound (uphill) direction; however, emissions estimates may differ if modern trucks are capable of traveling at higher speeds, especially on the steep uphill gradient. Field measurement of in-situ CO_2 concentration (e. g., with a test vehicle equipped with a probe) would provide be an excellent way to further validate the estimates from MOVES. It should be noted that the CO_2 concentrations measured in the field through probe would need to be converted into emissions estimates (e.g., with methodology provided by [23]) for comparison between field measurement and simulation estimates.

Authors Contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Edward Tang, Hatem Abou-Senna and Anurag Pande. The first draft of the manuscript was written by Edward Tang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments

The authors gratefully acknowledge the Office of Research and Economic Development at California Polytechnic State University for supporting this work.

Conflict of Interest

No conflict of interest.

References

1. Environmental Protection Agency (EPA) (2014) Sources of Greenhouse Gas Emissions.
2. Abou-Senna H, Radwan E (2013) VISSIM/MOVES integration to investigate the effect of major key parameters on CO_2 emissions, Journal of Transportation Research Part D: Transport and Environment 21: 39-46.
3. Abou-Senna H, Radwan E, Westerlund K, Cooper CD (2013) Using a traffic simulation model (VISSIM) with an emissions model (MOVES) to predict emissions from vehicles on a limited-access highway, Journal of the Air & Waste Management Association 63(7): 819-831.
4. Ahn K, Rakha H, Trani A, Aerde MV (2002) Estimating Vehicle Fuel Consumption and Emissions based on Instantaneous Speed and Acceleration Levels, Journal of Transportation Engineering 128(2): 182-190.
5. Chamberlin R, Swanson B, Talbor E, Dumont J, Pesci S (2010) Analysis of MOVES and CMEM for Evaluating the Emissions Impacts of an Intersection Control Change. Paper presented at Transportation Research Board 2011. Washington DC, USA.
6. Barth M, Scora G, Younglove T (2014) Model Emissions Model for Heavy-Duty Diesel Vehicles, Transportation Research Record: Journal of the Transportation Research Board 1880(1): 10-20.
7. Nam EK, Gierczak CA, Butler JW (2002) A Comparison of Real-World and Modeled Emissions Under Conditions of Variable Driver Aggressiveness. Paper presented at Transportation Research Board 2003. Washington DC, USA.
8. Chamberlin R, Swanson B, Talbot E, Sharma S, Crouch P (2011) Toward Best Practices for Conducting a MOVES Project-Level Analysis. Paper presented at Transportation Research Board 2012. Washington DC, USA.
9. Chu H, Meyer MD (2009) Methodology for assessing emission reduction of truck-only toll lanes, Energy Policy 37: 3287-3294.
10. Boriboonsomsin K, Barth M (2009) Impacts of Road Grade on Fuel Consumption and Carbon Dioxide Emissions Evidenced by Use of Advanced Navigation Systems, Transportation Research Record: Journal of the Transportation Research Board 2139: 21-30.
11. Liu H, Rodgers M, Guensler R (2019) Impact of road grade on vehicle speed-acceleration distribution, emissions and dispersion odeling on freeways. Transportation Research Part D: Transport and Environment 69: 107-122.
12. Llopis-Castelló D, Pérez-Zuriaga A, Camacho-Torregrosa F, García A (2018) Impact of horizontal geometric design of two-lane rural roads on vehicle co_2 emissions. Transportation Research Part D: Transport and Environment 59: 46-57.
13. Llopis-Castelló D, Camacho-Torregrosa F, García A (2019) Analysis of the influence of geometric design consistency on vehicle CO2 emissions, Transportation Research Part D: Transport and Environment 69: 40-50.
14. Papson A, Hartley S, Kuo K (2011) Analysis of Emissions at Congested and Uncongested Intersections Using MOVES2010. Paper presented at Transportation Research Board 2012. Washington DC, USA.
15. Perugu H, Wei H, Yao Z (2017) Developing high-resolution urban scale heavy-duty truck emission inventory using the data-driven truck activity model output. Atmospheric Environment 155: 210-230.
16. Punzo V, Simonelli F (2005) Analysis and comparison of microscopic traffic flow models with real traffic microscopic data, transportation Research Record 1934: 53-63.
17. Mahesh S, Ramadurai G, Nagendra S (2019) On-board measurement of emissions from freight trucks in urban arterials: Effect of operating conditions, emission standards, and truck size. Atmospheric Environment 212: 75-82.
18. San Luis Obispo County of Governments (SLOCOG) (2003) .
19. Cuesta Grade Project Completed, Caltrans (2016) Traffic Census Program.
20. Wisconsin Department of Transportation (2014) Model Calibration.
21. Bliemel F (1973) Theil's Forecast Accuracy Coefficient: A Clarification, Journal of Marketing Research, X, 444-446.
22. Tang EC (2017) Quantifying the Impact of Truck only lanes on Vehicular Emissions on a Limited-Access Highway. MS Thesis, California Polytechnic State University, San Luis Obispo, CA.
23. Maness HL, Thurlow ME, McDonald BC, Harley RA (2015) Estimates of CO_2 traffic emissions from mobile concentration measurements, Journal of Geophysical Research: Atmospheres p.120.

Citation: Edward Tang, Hatem Abou-Senna, Anurag Pande, Robert L Bertini. High-Resolution Modelling of Carbon Dioxide Emissions Before and After the Implementation of a Designated Truck Lane. Cur Trends Civil & Struct Eng. 8(4): 2022. CTCSE. MS.ID.000691. DOI: 10.33552/CTCSE.2022.08.000691.