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Transportation plays a significant role in carbon dioxide (CO_2) emissions, accounting for approximately a third of the U.S. inventory. To reduce CO_2 emissions in the future, transportation policy makers are planning on making vehicles more efficient and increasing the use of carbon-neutral alternative fuels. In addition, CO_2 emissions can be lowered by improving traffic operations, specifically through the reduction of traffic congestion. Traffic congestion and its impact on CO_2 emissions were examined by using detailed energy and emission models, and they were linked to real-world driving patterns and traffic conditions. With typical traffic conditions in Southern California as an example, it was found that CO_2 emissions could be reduced by up to almost 20% through three different strategies: congestion mitigation strategies that reduce severe congestion, allowing traffic to flow at better speeds; speed management techniques that reduce excessively high free-flow speeds to more moderate conditions; and shock wave suppression techniques that eliminate the acceleration and deceleration events associated with the stop-and-go traffic that exists during congested conditions.

In recent years, planning has begun to stabilize greenhouse gas emissions at levels far below today's emission rate while still meeting long-term energy needs. Goals are being set to stabilize these greenhouse gas emissions in order to avoid global climate change. As one of the key greenhouse gases to control, carbon dioxide (CO_2) has received particular attention, generated from various sectors. In 2004, transportation as a whole accounted for approximately 33% of CO_2 emissions in the United States, of which 80% is from cars and trucks traveling on the roadway system (*1*).

In order to reduce CO_2 emissions from the transportation sector, policy makers are primarily pushing for more efficient vehicles and the use of alternative fuels (*2*). In terms of vehicle improvements, it is thought that

- Vehicles can be made lighter and smaller (while maintaining safety),
- Further improvements can be made in terms of power train efficiency, and
- Alternative technologies can be developed, such as hybrid and fuel-cell vehicles.

In terms of alternative fuels, many carbon-neutral options exist such as biofuels (e.g., ethanol, biodiesel) and synthetic fuels (coupled with carbon capture and storage).

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Although these options look promising, they are unlikely to make a great impact in the near term. Some of them (e.g., fuel-cell vehicles) are still in their early stages of technology development and probably will need a dramatic breakthrough before they can be fully implemented. For those that are technology-ready and have started to enter the market (e.g., hybrid vehicles and alternative fuels), it will still probably take several years for a majority of the existing fleet to be turned over before a significant impact on CO_2 can be seen. That being said, it can be pointed out that comparatively little attention has been given to CO_2 emissions associated with traffic congestion and possible short-term CO_2 reductions as a result of improved traffic operations. Traffic congestion can be considered as a supply management problem. The transportation infrastructure (i.e., roadways) can be considered as supply for use by drivers (demand). If these supplies are limited in terms of capacity and demand is high, congestion is likely to occur.

Several studies have shown that roadway congestion is continuing to get worse. For example, the Texas Transportation Institute (TTI) conducts an urban mobility study that includes estimates of traffic congestion in many large cities and the impact on society (*3*). The study defines congestion as "slow speeds caused by heavy traffic or narrow roadways or both due to construction, incidents, or too few lanes for the demand." Because traffic volume has increased faster than road capacity, congestion has become progressively worse despite the push toward alternative modes of transportation, new technologies, innovative land use patterns, and demand management techniques.

It is commonly known that as traffic congestion increases, CO_2 emissions (and in parallel, fuel consumption) also increase. In general, CO_2 emissions and fuel consumption are sensitive to the type of driving that occurs. Highlighted as part of many "eco-driving" strategies, traveling at a steady-state velocity will give much lower emissions and fuel consumption compared with a stop-and-go driving pattern. By decreasing the stop-and-go driving that is associated with congested traffic, CO_2 emissions can be reduced. However, it is not clear to what degree various congestion mitigation programs will affect CO_2 emissions.

CO_2 emissions are examined here as a function of traffic congestion. After some background information on modeling tools and traffic information data used for analysis, the basis of the congestion analysis is developed, followed by real-world congestion analyses.

BACKGROUND

Comprehensive Modal Emissions Model

In order to carry out a variety of vehicle emission and energy studies, development of the Comprehensive Modal Emissions Model (CMEM) (*4*) began in 1996, sponsored by NCHRP and the U.S.

Environmental Protection Agency (EPA). The need for this type of microscale model that can predict second-by-second vehicle fuel consumption and emissions on the basis of different traffic operations was and remains critical for developing and evaluating transportation policy. In the past, large regional emission inventory models were being applied for these types of microscale evaluations with little success. The majority of the CMEM modeling effort was completed in 2000 and the model has been updated and maintained since then under sponsorship from EPA.

CMEM is a public-domain model and has several hundred registered users worldwide. The model was designed so that it can interface with a wide variety of transportation models, transportation data sets, or both, in order to perform detailed fuel consumption analyses and to produce a localized emissions inventory. CMEM was developed primarily for microscale transportation models that typically produce second-by-second vehicle trajectories (location, speed, acceleration). These vehicle trajectories can be applied directly to the model, resulting in both individual and aggregate energy or emission estimates. Further, CMEM also accounts for the effects of road grade. It has been shown that road grade has a significant effect on fuel consumption and emissions (*5, 6*). During the past several years, CMEM has been integrated into various transportation modeling frameworks, with a focus on corridor-level analysis and intelligent transportation system implementations (e.g., CORSIM, TRANSIMS, PARAMICS, SHIFT). With these combined tools, various projects have been evaluated.

CMEM is comprehensive in the sense that it covers essentially all types of vehicles found on the road today. It consists of nearly 30 vehicle and technology categories from the smallest light-duty vehicles to Class 8 heavy-duty diesel trucks. With CMEM, it is possible to predict energy and emissions from individual vehicles or from an entire fleet of vehicles, operating under a variety of conditions. One of the most important features of CMEM (and other related models) is that it uses a physical, power–demand approach based on a parameterized analytical representation of fuel consumption and emission production. In this type of model, the entire fuel consumption and emission process is broken down into components that correspond to physical phenomena associated with vehicle operation and emission production. Each component is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, emission technology, and level of deterioration. One distinct advantage of this physical approach is that it is possible to adjust many of these physical parameters to predict energy consumption and emissions of future vehicle models and applications of new technology (e.g., aftertreatment devices). Further information on the CMEM effort may be found elsewhere (*4, 7–9*).

Traffic Performance Measurement System

As part of the congestion research, the authors worked closely with the California Department of Transportation (Caltrans) Freeway Performance Measurement System (PeMS). PeMS collects real-time speed, flow, and density data from loop detectors embedded in California's freeways and makes the information available for transportation management, research, and commercial use. The system provides real-time 30-s (and 5-min), per-loop averages of lane occupancy, flow, speed, and delay for various links in the roadway network. All the data are available over the Internet. Although the data from PeMS include a certain amount of uncertainty (e.g., when loop sensors break down), the system is still considered one of the most comprehensive and reliable data sources currently available in California. More information on PeMS may be found elsewhere (*10–12*) and at the PeMS website (http://pems.eecs.berkeley.edu/Public/index.phtml).

CONGESTION AS FUNCTION OF AVERAGE TRAFFIC SPEED

One way to estimate the energy and emission impacts of congestion is to examine velocity patterns of vehicles operating under different levels of congestion. On a freeway, for example, drivers typically want to drive at relatively high speed with very few changes to their speed. However, as more and more vehicles join the flow, average traffic speed tends to be reduced and individual vehicle velocity patterns tend to exhibit fluctuating speeds.

Roadway congestion is often categorized by the level of service (LOS) it provides to travelers (*13*). For freeways (i.e., uninterrupted flow), the LOS is represented by the density of traffic (i.e., number of vehicles per mile of roadway), which is a function of speed and flow. Emission rates are highly dependent on speed; flow is a surrogate for vehicle miles traveled (VMT); and both emission rates and VMT are two major factors contributing to emissions. Therefore, LOS is a measure that can be rationally related to emissions. There are several different LOS values, represented by the letters A through F. For each LOS, a typical vehicle velocity trajectory will have different characteristics. Examples of these velocity trajectories are shown in Figure 1 (*14*). Under LOS A, vehicles typically travel near the highway's free-flow speed, with few acceleration or deceleration perturbations. As LOS conditions get progressively worse (i.e., LOS B, C, D, E, and F), vehicles travel at lower average speeds with more acceleration and deceleration events. For each representative vehicle velocity trajectory (such as those shown in Figure 1), it is possible to estimate fuel consumption as well as CO_2 and pollutant emissions by using a modal model as described in the previous section. This model allows comparisons between velocity trajectories and their impact on CO_2 emissions.

Depending on the trip velocity pattern, CO_2 emissions can vary significantly. To illustrate, a vehicle activity database representing typical trips in Southern California was obtained. This database contains numerous vehicle velocity trip patterns based on the Global Positioning System (GPS) that were collected as an after-census travel survey in 2001 by the Southern California Association of Governments (SCAG). This data set represents approximately 467 households with 626 vehicles. The total miles driven in this data set is approximately 28,000. More information regarding this data set may be found in a report by Barth et al. (*15*).

These representative trips were then applied to CMEM, calibrated for a typical modern light-duty passenger vehicle. On the basis of all the trips, it was possible to develop a histogram of the CO_2 emissions for each trip in the database (Figure 2). It can be seen that most trips had CO_2 emissions of approximately 330 g/mi (corresponding to approximately 26 mi/gal of fuel economy). However, other trips had far fewer and far more CO_2 emissions, depending on the specific driving pattern. Similarly, other vehicle types have quite different CO_2 emissions depending on their weight, power, and other factors. It should be noted that the estimated CO_2 emissions are for typical trips, which can be composed of traveling on various roadway facility types (i.e., freeways, arterials, and local streets).

It is also possible to evaluate CO_2 emissions (in terms of grams per mile) on the basis of the average speed of the trip or trip segment.

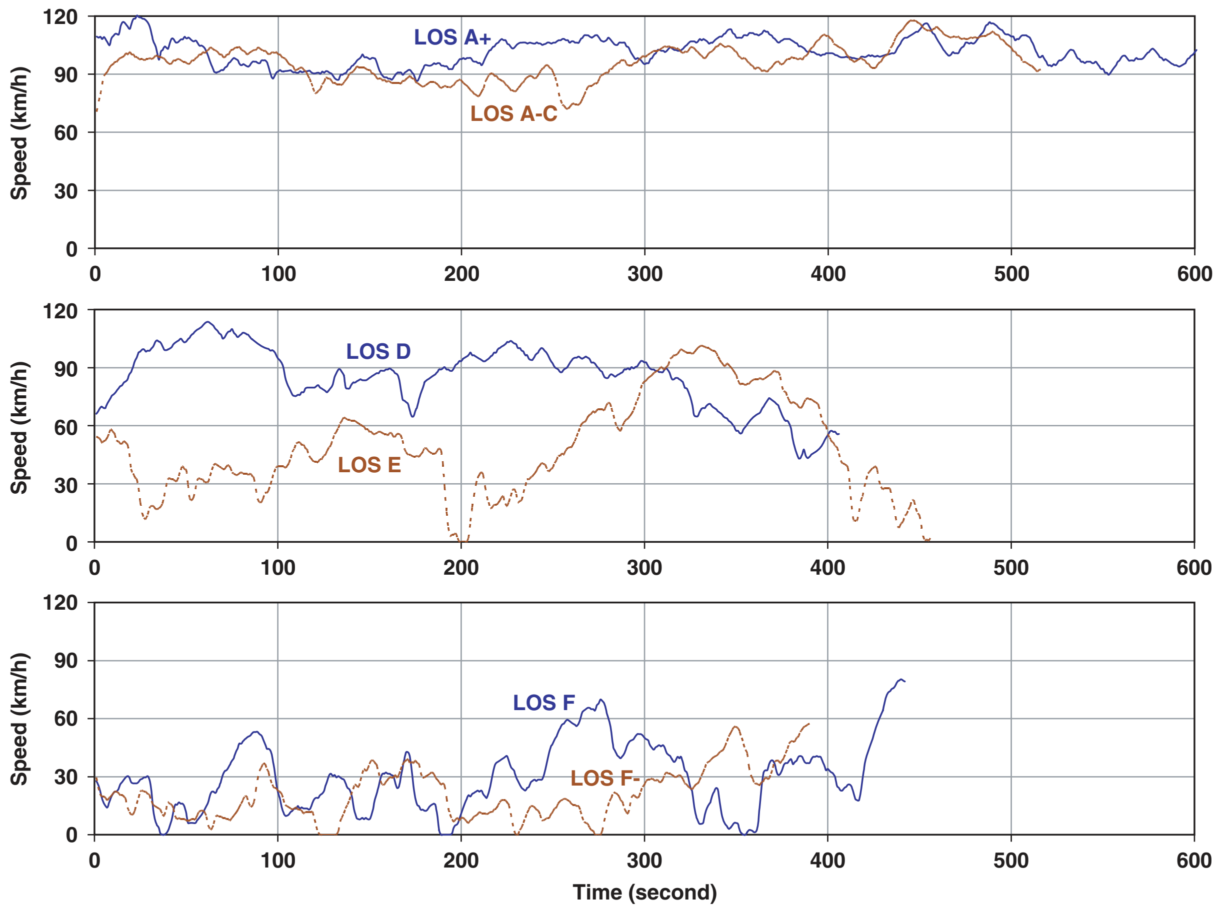


FIGURE 1 Typical vehicle velocity patterns for different congestion LOS on a freeway.

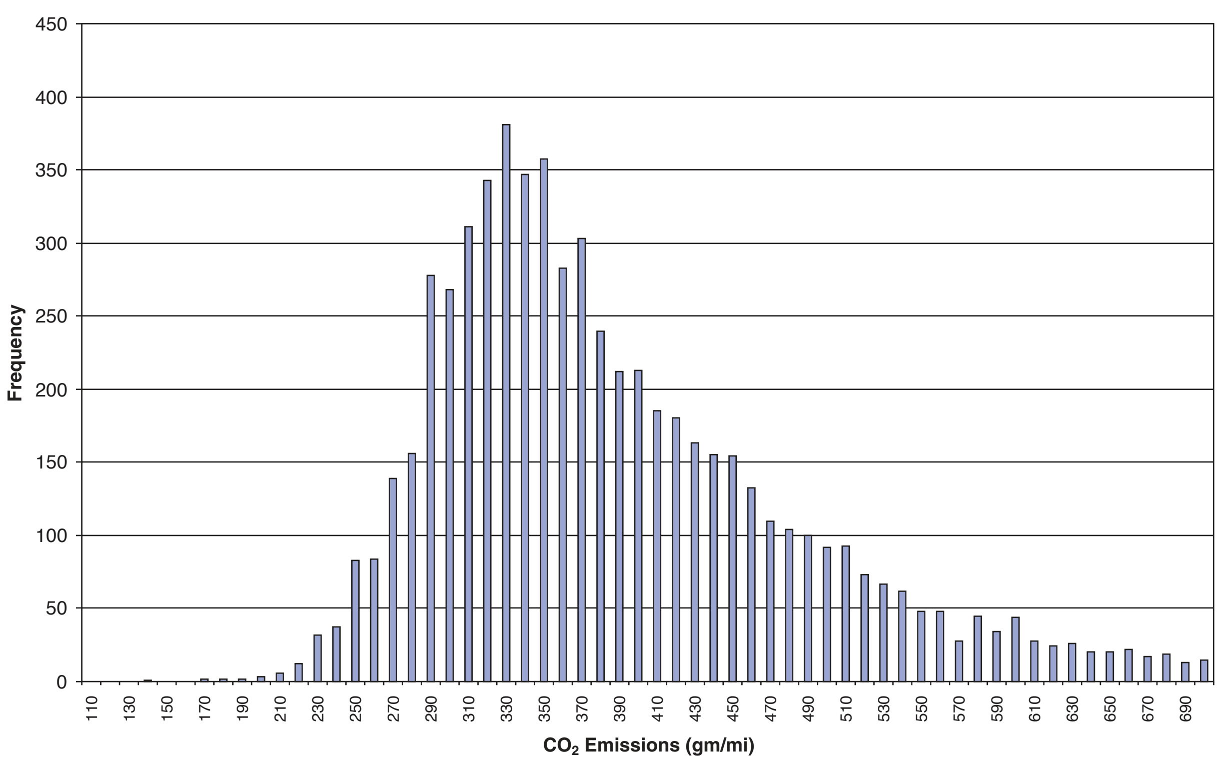


FIGURE 2 CO_2 emission histogram for representative database of trips in Southern California.

To illustrate, a database of vehicle activity on freeways (consisting of second-by-second velocity trajectories) was applied to the CMEM model, and a wide range of vehicle types (28 light-duty vehicle and technology categories in CMEM) was examined. This set of vehicle activity data was collected by probe vehicles (2004 Honda Civics) running specifically on freeway mainlines in Southern California during September 2005, May 2006, and March 2007. In addition to the probe vehicle data, macroscopic traffic data (LOS) from the PeMS were gathered.

With information about latitude, longitude, and time stamp, probe vehicle data were spatially and temporally matched with the PeMS data. Typically, vehicle detector stations (VDSs) in the PeMS network are located around 0.6 to 1.0 mi apart. The spatial coverage of each VDS is from the midpoint between the station and the VDS to its left to the midpoint between the station and the VDS to its right. The LOS for each loop detector at each VDS is updated every 30 s. Therefore, for every 30-s period the second-by-second driving trajectories were spatially mapped with the corresponding VDS. A vehicle running in lane *l* within the coverage of VDS *i* at time *t* is considered to experience the LOS reported by the loop detector in lane *l* at VDS *i* during period *p*. It should be noted that the lane information was simultaneously collected by the driver when the probe vehicle runs were taking place. The LOS of the driving-trajectory lane was then assigned to each second of driving data. This process started at the beginning of the driving trace and was repeated until the end of the driving trace was reached. The database contains 15,096 data records, which is equivalent to more than 4 h worth of driving for a total distance of greater than 180 mi. This data set of vehicle activity covers a variety of freeway congestion levels from LOS A to F.

Before being applied to the CMEM model, the velocity trajectories in the database were split into snippets with a consistent LOS. The length of these snippets ranges from a few seconds to several hundred seconds, with a majority of them being 30 s or shorter. Snippets with an activity of 10 s or less were excluded. At the end, there were 241 remaining snippets, which were used to estimate the corresponding CO_2 emissions. It should be noted that the results of the different vehicle types were weighted on the basis of a typical light-duty fleet found in Southern California and the fleet mix for 2005 (*16*). The purpose was to evaluate the impact of the fleetwide average rather than that of specific vehicle categories. In Figure 3, the estimated CO_2 emissions are plotted as a function of average running speed for the fleet mix. A fourth-order polynomial is then used to fit the data points, shown as a solid line in Figure 3. This polynomial has the following form:

$$\ln(y) = b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4 \quad (1)$$

where y is the CO_2 emissions in grams per mile, and x is the average trip speed in miles per hour. The coefficients for each fitted curve are given in Table 1.

Equation 1 can then be used to estimate CO_2 emissions given an average running speed. Figure 3 also illustrates CO_2 emissions for perfectly constant, steady-state speeds. Of course, vehicles moving in traffic must experience some amount of stop-and-go driving, and the associated accelerations lead to higher CO_2 emissions. The constant, steady-state speed curve in Figure 3 shows the approximate lower bound of CO_2 emissions for any vehicle traveling at that particular speed. It may be noted that some CO_2 estimates of real-world activity fall below this steady-state speed curve. This result is because the vehicle activity of these snippets consists mostly of a series of mild deceleration events, which usually produce low emissions. However, across all the speed ranges, the real-world activity curve never falls below the steady-state speed curve.

When average speeds are very low, vehicles experience frequent acceleration and deceleration events. They also do not travel very far. Therefore, gram-per-mile emission rates are quite high. In fact, when a car is not moving, a distance-normalized emission rate reaches infinity. Conversely, when vehicles travel at higher speeds, they experience higher engine load requirements and therefore have higher CO_2 emission rates. As a result, this type of speed-based CO_2 emission factor curve has a distinctive parabolic shape, with high emission rates on both ends and a minimum rate at moderate speeds of around 45 to 50 mph.

Several important results can be derived from this information, as illustrated in Figure 4:

- In general, whenever congestion brings the average vehicle speed below 45 mph (for a freeway scenario), there is a negative net impact on CO_2 emissions. Vehicles spend more time on the road, which results in higher CO_2 emissions. Therefore, in this scenario, reducing congestion will reduce CO_2 emissions.

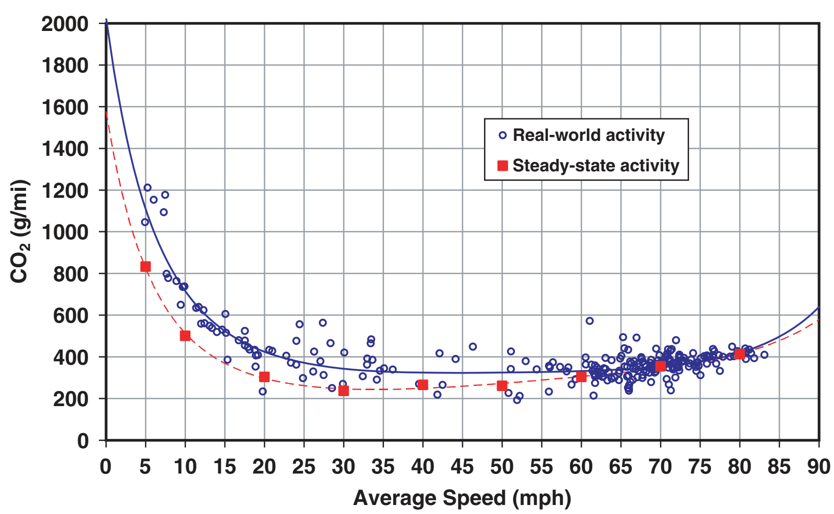


FIGURE 3 CO_2 emissions as a function of average trip speed.

TABLE 1 Derived Line-Fit Parameters for Equation 1 with Data Shown in Figure 3

	Real-World	Steady-State
N	241	9
R^2	0.668	0.992
b_0	7.613534994965560	7.362867270508520
b_1	−0.138565467462594	−0.149814315838651
b_2	0.003915102063854	0.004214810510200
b_3	−0.000049451361017	−0.000049253951464
b_4	0.000000238630156	0.000000217166574

- If moderate congestion brings average speeds down from a free-flow speed of about 65 mph to a slower speed of 45 to 50 mph, this moderate congestion can actually lower CO_2 emissions. If relieving congestion increases average traffic speed to the free-flow level, CO_2 emission levels will go up.
- Extremely high speeds beyond 65 mph can cause an adverse effect on CO_2 emissions. If these excessive speeds can be controlled, there will be not only direct safety benefits but also indirect benefits of CO_2 reduction.
- If the real-world, stop-and-go velocity pattern of vehicles could somehow be smoothed out so an average speed could be maintained, significant CO_2 emission reductions could be achieved.

Figure 4 shows the potential effect of improved traffic operations on CO_2. All of these strategies are important to consider when an attempt is made to reduce CO_2 emissions. They can be grouped into three categories:

1. Congestion mitigation strategies. These strategies are focused on increasing average traffic speeds from slower, heavily congested speeds. Examples include ramp metering and incident management.
2. Speed management techniques. These techniques aim at reducing excessively high speeds to safe speeds. An example includes direct enforcement by police, radar, camera, and aircraft. In addition, there are emerging technologies such as the active accelerator pedal (*17*) and intelligent speed adaptation (ISA), in which top speeds are capped on the basis of specific traffic conditions (*18*).
3. Traffic flow smoothing techniques. These techniques attempt to eliminate the stop-and-go effect, regarded as shock wave suppression, which also helps reduce the number and severity of individual accelerations and decelerations. This goal can be achieved through the use of variable speed limits (*19*). Also, it has been shown that ISA can eliminate much of the stop-and-go effect during congested conditions, which results in 12% of CO_2 reduction (*18*).

Figure 5 shows potential CO_2 reduction from each of the categories just discussed. Figure 5*a* shows that even a small change in average traffic speeds (e.g., 2.5 mph) can result in a strong change in CO_2 emissions, particularly in the lower- and higher-speed regions. Greater CO_2 reduction could be gained if traffic operation improvements led to a greater speed change (e.g., 10 mph). Overall, the speed changes of 2.5, 5, and 10 mph can provide CO_2 benefits up to 25%, 45%, and 70%, respectively. By subtracting the steady-state CO_2 emission curve from the curve of real-world driving in Figure 3, it is possible to see when the greatest CO_2 benefits due to traffic flow smoothing will occur: primarily when freeway congestion results in average speeds around 10 to 30 mph, as shown in Figure 5*b*. Ideally, CO_2 emissions can be reduced as much as almost 45% if traffic flow is smoothed to a steady-state condition. Although such perfectly smooth traffic flow may seem idealistic, it should be noted that moderately smoother traffic flow, even with some reasonable fluctuation in speed, can still result in significant CO_2 reduction. An example is the application of ISA, which reduces CO_2 by 12% as compared with normal driving under congestion (*18*).

A similar analysis can be performed for travel activities on arterials and residential roads (i.e., interrupted-flow patterns). These analyses are relatively more complicated, but they too can show that any measure that keeps traffic flowing smoothly for longer periods of time (e.g., operational measures, such as synchronization of traffic signals) can lower CO_2 emissions significantly. Although not in the scope of this paper, it is also important to note that CO_2 congestion effects will be much more pronounced for heavy-duty trucks, which tend to have much lower power-to-weight ratios than cars.

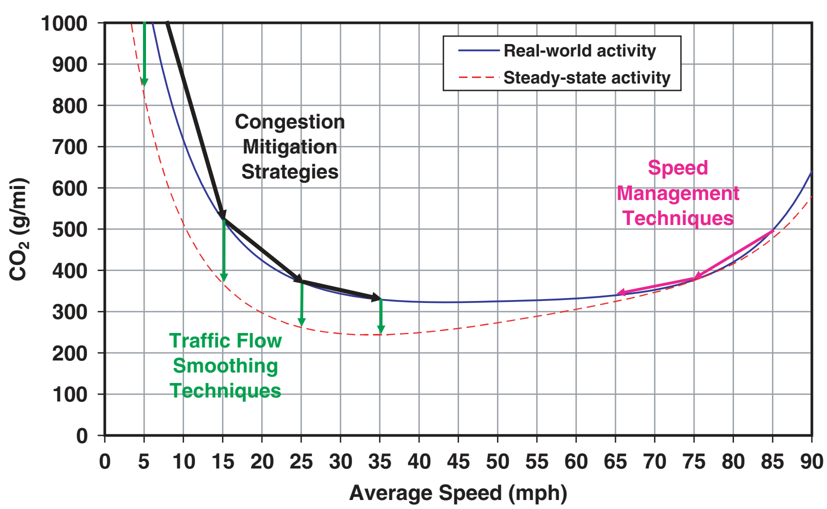


FIGURE 4 Possible use of traffic operation strategies in reducing on-road CO_2 emissions.

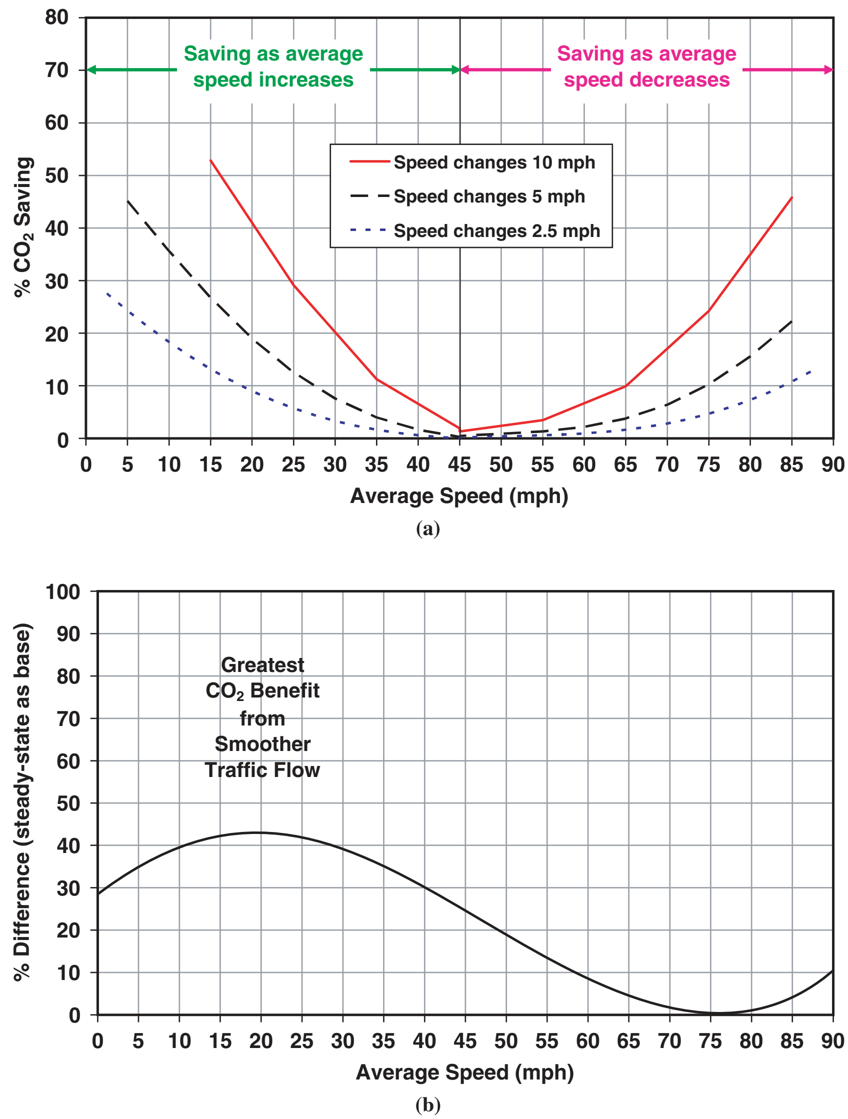


FIGURE 5 Potential CO_2 reduction as a result of (*a*) speed changes and (*b*) smoother traffic flow.

REAL-WORLD CONGESTION

It was shown that CO_2 emissions vary greatly depending on average vehicle speed for a variety of vehicle trajectories. Heavy congestion results in slower speeds and greater speed fluctuation, resulting in higher CO_2 emissions. However, traveling at very high speeds also increases CO_2 emissions. The best scenario is when traffic as a whole moves at smooth, moderate speeds.

It is of interest to evaluate the frequency of congested traffic in order to determine how much CO_2 savings can potentially be gained. For this evaluation, the study focused primarily on Southern California traffic. As an initial case study, the SR-60 corridor that connects Los Angeles to the Inland Empire of Southern California was chosen. With the freeway PeMS, average traffic speed data eastbound on this corridor were collected for weekdays over a 3-week period in June 2007. This corridor is known to be very congested in the afternoon, as shown in Figure 6, where the average traffic speed is plotted as a function of time of day and distance. Postmile 0 refers to the start of this freeway near the downtown Los Angeles area. In Figure 6, the darker colors represent lower speeds and the lighter colors represent faster speeds. Figure 6 shows that the traffic conditions on this corridor vary greatly across different times of the day. For the afternoon peak hour only (5:00 to 6:00 p.m.), the VMT-normalized histogram of speeds is shown in Figure 7*a*. It can be seen that approximately 41% of the VMT that occurs during this hour is travel at an average speed of 30 mph or lower.

It is interesting to see what the impact on CO_2 emissions would be if the congestion during this peak hour were relieved. Different speed thresholds for congestion are currently being used. For example, Caltrans defines congested freeway locations as those at which average speeds are 35 mph or less during peak commute periods on a typical incident-free weekday (*20*). In the TTI urban mobility study (*3*), congested delay is calculated on the basis of the assumed free-flow speed of 60 mph. In order to provide flexibility in the definition of congestion, PeMS reports several delay numbers, which are calculated on the basis of threshold values of 35, 40, 45, 50, 55,

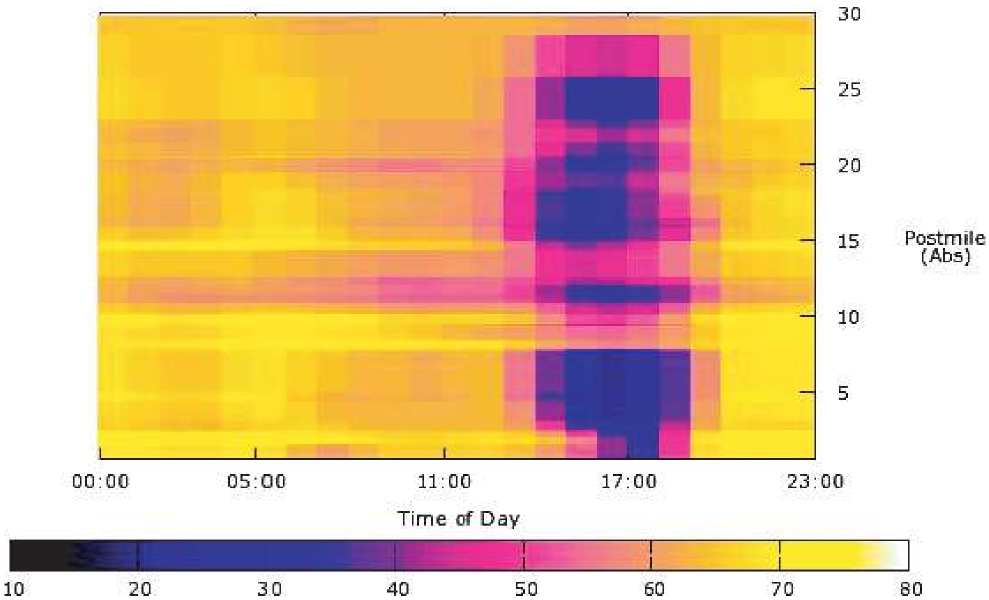
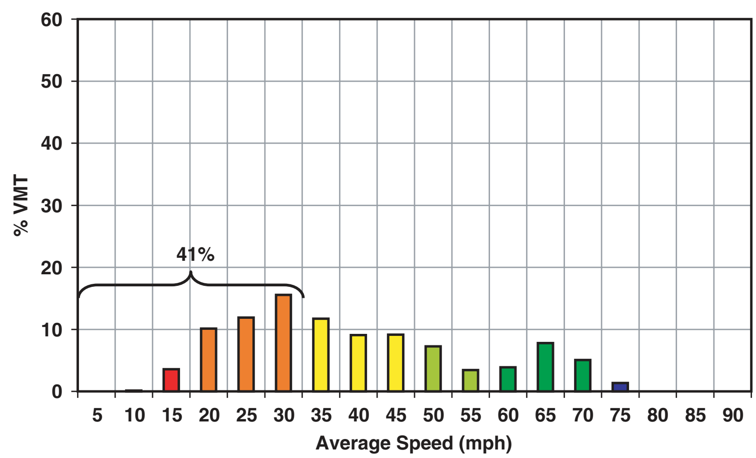
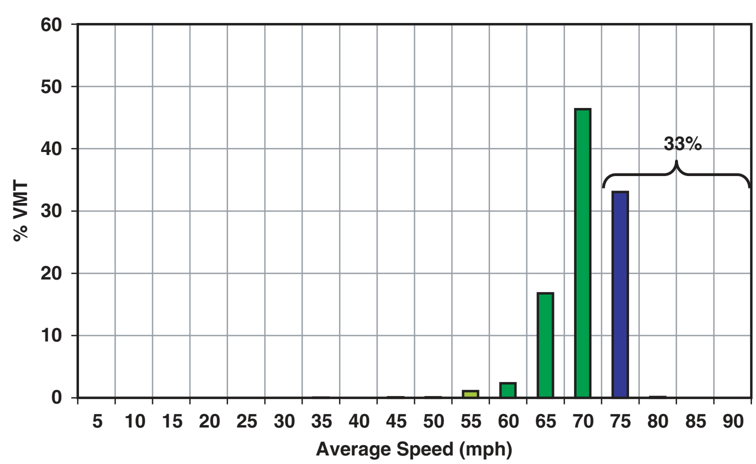


FIGURE 6 Average traffic speed (60% observed) along SR-60 eastbound corridor by time of day (*x*-axis) and distance (*y*-axis), June 4 to June 22, 2007, 23:59:59 (days = Mo, Tu, We, Th, Fr); traffic flows from bottom to top.



(a)



(b)

FIGURE 7 Distribution of %VMT versus speed for SR-60 eastbound for June 2007: (*a*) during p.m. peak hour and (*b*) during late-night hour.

and 60 mph. For the purpose of estimating potential CO_2 reduction in this study, the congested speed threshold of 60 mph was selected. For the simple case study (Figure 7*a*), if this congestion during the peak hour were eliminated so that all VMT were at the average speed of 60 mph, CO_2 emissions could be reduced by approximately 7%. It should be noted that the congested speed threshold of 60 mph is intentionally chosen in such a way that the estimated CO_2 benefits will be the lower bound. That is, if the threshold is lowered, the CO_2 reduction due to congestion mitigation will be even greater. In addition to this particular case study, many other freeway corridors throughout Southern California have similar recurring heavy congestion patterns. Thus, similar CO_2 savings could be achieved by moving the average speed distribution toward the distribution with higher speeds.

Looking from an opposing direction, CO_2 savings could also be obtained by eliminating extremely high speeds on freeways. These excessive speeds usually occur during off-peak periods, especially at night. Figure 7*b* shows the histogram of %VMT versus speed for the same corridor during a late night hour (11:00 p.m. to 12:00 a.m.). It can be seen that about one-third of the VMT during this hour travels at an average speed of 75 mph or higher. This speeding behavior not only poses traffic safety concerns but also adversely affects the environment. Again, assuming that these excessive driving speeds were controlled so that all VMT were at the average speed of 60 mph, CO_2 emissions could be reduced by approximately 8%.

It is interesting to point out that when one examines the distribution of %VMT versus speed for the entire freeway network in Los Angeles County for an entire average day, it is found that speeds around 65 to 70 mph dominate, as shown in Figure 8*a*. This finding implies that the freeway system is still operating in reasonably good condition overall. However, congestion still occurs, which is relatively low in the distribution compared with the dominant free-flow conditions. This finding is because the VMT during the peak period (the afternoon peak for this case study) accounts for only a quarter of the total daily VMT, as shown in Figure 8*b*. Still, if the traffic flow were managed so that all VMT in Figure 8*a* were at the average speed of 60 mph, CO_2 emissions from traffic in the Los Angeles freeway network across 24 h for the month of June 2007 would be almost 5,000 metric tons.

It should be noted that although this study uses traffic in the Los Angeles area as an example, the presented concept and methodology are applicable elsewhere. In other areas, the CO_2 impact of traffic can be different depending on the following factors:

- Local fleet mix. Different fleet composition will cause different fleetwide average CO_2 emission factors. Therefore, the curves of

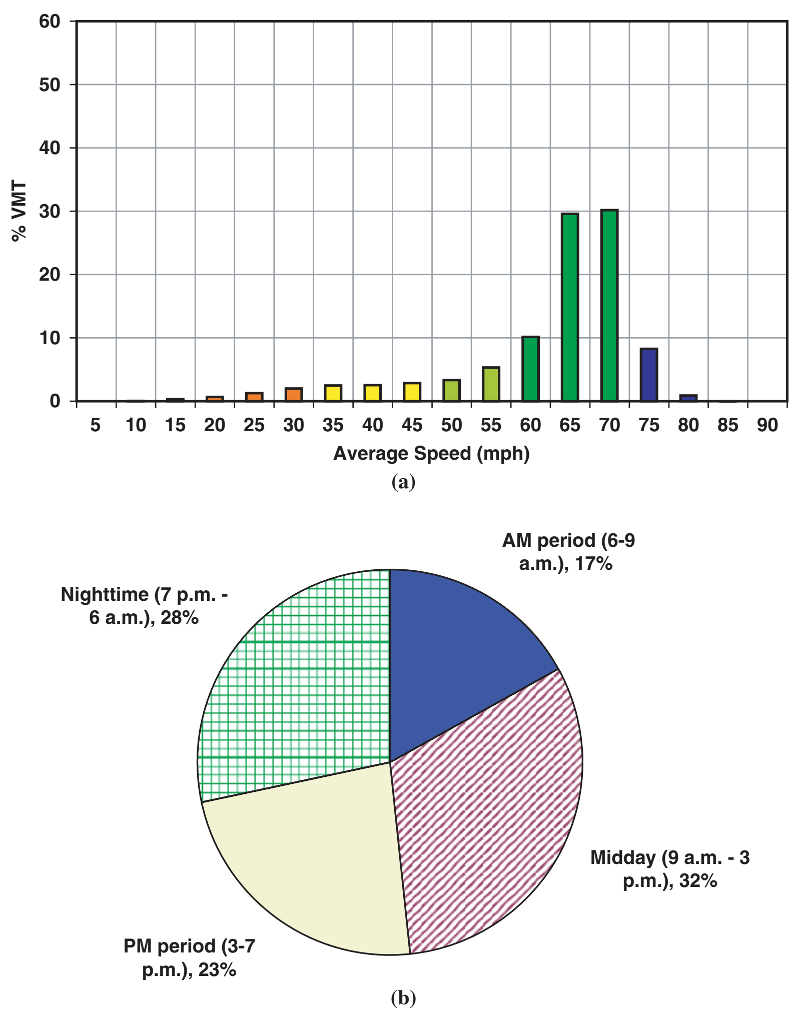


FIGURE 8 (*a*) Distribution of %VMT versus speed for Los Angeles freeway network across 24 h for June 2007 and (*b*) percentage of total daily VMT for different time periods.

CO_2 versus speed are expected to have different magnitudes and possibly different shapes.

- Amount of VMT at congested speed. As presented in TTI's urban mobility report, different metropolitan areas experience different levels of congestion and delay. Thus, the reduction in CO_2 emissions that could be achieved may be less in an area where congestion has not been much of a concern.
- Amount of VMT at excessive speed. The amount of driving occurring at excessive speeds is also area specific, depending on several factors such as speed limit and enforcement. An area with a lower freeway speed limit is likely to have less CO_2 emission because of driving at high speed.

CONCLUSIONS

It is clear that traffic congestion has a significant effect on CO_2 emissions; overall, even small changes in traffic speed can have a significant effect. Several methods for reduction of CO_2 by improved traffic operations (with particular emphasis on freeway operations) were examined:

1. Congestion mitigation strategies that reduce severe congestion such that higher average traffic speeds are achieved (e.g., ramp metering, incident management),
2. Speed management techniques that can bring down excessive speeds to more moderate speeds of approximately 55 mph (e.g., by enforcement and an active accelerator pedal), and
3. Traffic flow smoothing techniques that can suppress shock waves and thus reduce the number of acceleration and deceleration events (e.g., variable speed limits, ISA).

With typical traffic conditions in Southern California as an example, this study has shown that each of those three methods could potentially lower CO_2 by 7% to 12%. Although the individual effects may not be that large, the synergistic effect of the three methods combined could add up to a greater amount. Again, these results are considered as a lower bound because they are estimated on the basis of the congested-speed threshold of 60 mph. If this threshold were lower, the CO_2 reduction could be greater.

Although progress in vehicle efficiency improvements and carbon-neutral fuels is under way, innovative traffic operation improvements (e.g., mitigating congestion, reducing excessive speeds, and smoothing traffic flow) can have a significant impact on vehicle CO_2 emissions and this impact can be realized in the near term. In addition to improving traffic operations as a means of reducing vehicle CO_2 emissions, other transportation measures can also be simultaneously promoted to reduce VMT and thus vehicle CO_2 emissions. These measures include alternative modes of transportation, innovative land use patterns, and travel demand management strategies.

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