Modeling Traffic Emissions in Networks with Macroscopic Traffic Models

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Abstract

Developments in macroscopic models of traffic in cities have shown that for many networks a robust relationship exists between average vehicle flow and average vehicle density known as a Macroscopic Fundamental Diagram (MFD). The consistent relationship between traffic conditions in a network and the number of vehicles circulating within the network is shown to be related to other useful measures of traffic performance. These include the elements of a typical driving cycle, which are closely related to pollutant emissions from vehicles: the time spent cruising at free-flow speed, the time spent idling, and the number of times that vehicles stop per distance traveled. The macroscopic approach is especially useful for quantifying emissions that are important in aggregate rather than at particular locations in the network, such as greenhouse gases. This study makes use of analytical models to approximate the MFD for a network in order to systematically identify the relationship between network parameters (e.g., block length and signal timing) and the vehicle emissions per distance traveled. This systematic and analytical approach for estimating network-wide emissions is useful for accounting for the externality of traffic emissions in the design and management of urban street networks, including dynamic pricing and allocation of road space to cars and other modes.

1 Introduction

Traffic congestion is a problem in cities across the United States and around the world. In the United States, an estimated 1.9 billion gallons (7.2 billion liters) of gasoline and $100 billion were wasted in excess fuel consumption and delays associated with traffic congestion in 2012 (DoT, 2012). In addition to time and fuel, urban traffic congestion is a major contributor of air pollutant emissions, including hydrocarbons, nitrogen oxides, carbon monoxide, and carbon dioxide. It is estimated that the vehicles on the road account for more than half of the dangerous air pollutant emissions and over 30% of carbon dioxide emissions in the United States (EPA, 2013). The ability to model emissions from vehicles in urban areas is critical for developing sustainable policies to manage and control traffic congestion. The relationship between traffic congestion and emissions of greenhouse gases, which are associated with global climate change, are well recognized. It remains a challenge to quantify the effect of traffic policies on the emissions. This paper presents recent research that links emissions of greenhouse gases with models of aggregated urban traffic parameters. This connection extends the applications of macroscopic traffic models to address emissions in addition to conventional measures such as traffic flows, speeds, and delays.

Reliable economic analysis for urban transportation policies requires physically realistic models that relate the usage of the network with network performance outcomes. Recent advances in macroscopic traffic modeling have revealed that there is a systematic relationship between average vehicle density and average vehicle flow in many networks (Daganzo, 2007; Geroliminis and Daganzo, 2008). This relationship has come to be known as a Macroscopic Fundamental Diagram (MFD) or network fundamental diagram. The aggregate level of the MFD is not suitable for all types of transportation analysis, but it has been shown to be useful for managing area-wide traffic conditions in urban networks in which the detailed movements of vehicles on individual streets is less important

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than the overall ability of the network to serve trips. Although some pollutants have highly localized impacts, which require detailed models and measurements (e.g., particulate matter), greenhouse gas emissions have a global impact, and it is more important to be able to estimate the aggregated emissions of greenhouse gases from traffic across a network. For these estimates, it is useful to make use of the robust relationships that have been identified for macroscopic traffic parameters as a basis for estimating aggregated greenhouse gas emissions.

Most research on the relationship between traffic and pollutant emissions focuses on individual vehicles and the effect that engine technologies or a vehicle's driving cycle have on the emissions from each vehicle. The driving cycle is the pattern of acceleration, cruising, deceleration, and idling that each vehicle undergoes as it traverses a network. In urban environments, the design of the street network and the timing of traffic signals have systematic impacts on the driving cycles of the vehicles in the network. The vehicle density also impacts the performance of each vehicle, because traffic congestion causes additional stopping and idling, which directly influence the emissions. In order to evaluate, control, and reduce network-wide emissions of air pollutants, traffic emissions need to be estimated in a way that accounts for the nature of stop-and-go traffic in urban areas. Typically, estimating emissions requires extensive data collection or simulation efforts. This paper shows that emissions factors developed from existing microscopic emissions models can be integrated with macroscopic traffic models in order to estimate the aggregated network-wide emissions of greenhouse gases from vehicles with simple analytical methods.

The paper is organized as follows. Section 2 reviews existing traffic flow and vehicular emissions models. Section 3 shows how aggregated traffic variables from a macroscopic traffic model can be linked with emissions factors to make an estimate of aggregated emissions from the network. The application of emission factors to an analytical approximation of the MFD is compared with measurements from simulations of a ring network and a grid network in Section 4. Section 5 presents a systematic comparison of the effect of network design parameters on vehicular emissions. Finally, insights for urban sustainability policies are discussed in Section 6.

2 Existing Models

There are a number of existing models used by engineers and economists to analyze the costs of traffic congestion and the effectiveness of policies to address it. Advances in macroscopic models of traffic in urban networks have provided new tools that allow analysts to account for realistic dynamics of traffic flow and queueing in entire networks. Traffic emissions models tend to be much more detailed, and the most accurate microscopic models rely on extensive data collection or simulation in order to determine the second-by-second driving cycles of vehicles. Existing macroscopic emissions models tend to be based on over-simplifications of these driving cycles, but an opportunity exists to make use of modern macroscopic traffic flow models to predict realistic driving cycles in a way that is consistent with the physical interactions of vehicles in a network.

2.1 Modeling Traffic in Networks

Traffic in networks can be modeled at many levels of detail. With increasing computing power, there has been a tendency among engineers and planners to use detailed microsimulations to study traffic patterns in networks. Although simulation models are powerful tools for investigating the complex interactions of vehicles, it is costly and challenging to build and calibrate the models appropriately (Dowling et al., 2004). An alternative is to work with analytical traffic flow models, such as thee kinematic wave model (Lighthill and Whitham, 1955; Richards, 1956) that makes some simplifying assumptions about the variability of driver and road characteristics but can describe the evolution of traffic states on a road segment by tracking the interfaces between traffic states over space and time. The benefit of this analytical approach is that a wide variety of traffic scenarios can be evaluated in a robust and consistent way that leads to general insights with far less data and computational complexity than a microsimulation. At the level of intersections and individual arterials, kinematic wave theory has been a basis of traffic modeling for decades.

For networks that are homogeneous, well-connected, and on which demand is uniformly spread, a consistent relationship between average network flow and average network density has been shown to exist in theory (Daganzo, 2007; Daganzo and Geroliminis, 2008), in simulations (Ji et al., 2010), and in the real world (Geroliminis and Daganzo, 2008; Buisson and Ladier, 2009). This relation is often referred to as the Macroscopic Fundamental Diagram (MFD) or network fundamental diagram. The size and shape of the MFD depends primarily on the physical properties of the network including the saturation flow rate, block length, and traffic signal settings (i.e., cycle length, duration of signal phases, and signal offsets).

To evaluate the performance of a network and the policies to control it, an analyst must choose a model that is suitably detailed capture the behavior of the system without requiring excessive data and time for model calibration and computation. For many types of aggregate analyses, the MFD has become a useful tool because it represents the correct physics of traffic in cities, including hypercongested traffic states that occur when increased vehicle density results in reduced flows (Small and Chu, 2003). Recent analysis of traffic congestion in engineering and economics fields have demonstrated that the MFD can be useful for a network manager, because it can be used to monitor the network performance or implement control strategies to increase throughput and decrease delays in the system (Geroliminis and Levinson, 2009; Geroliminis et al., 2013; Arnott, 2013).

2.2 Modeling Vehicular Emissions

Existing models for vehicular emissions generally fall into two main categories: microscopic models that focus on the specific movements of individual vehicles and macroscopic models that are based on aggregated data and average values. Microscopic models are the most detailed models, and they often provide instantaneous emissions estimates based on concurrent operating conditions of an equipped vehicle or a simulation. These models typically require extensive data inputs such as second by second trajectories for each vehicle. VT-Micro (Rakha et al., 2000), CMEM (Barth et al., 2000), and the project level of MOVES (EPA, 2010) are microscopic models that are widely used in the United States.

In order to analyze the overall effect of a policy that changes a characteristic of the network (e.g., changing signal timings, designing longer blocks, or managing the accumulation of vehicles on the streets), microscopic models require that a detailed microsimulation be developed to generate the detailed second-by-second trajectory of each vehicle in the system. These trajectories are then used to produce the emission estimate for for facility or network. This is a time-consuming and costly process, which makes these microscopic models prohibitively burdensome for estimating emissions in large urban networks. As a result, microscopic models are typically only used in practice for analyzing small-scale projects. For greenhouse gas emissions, such detailed model outputs are not necessary in of themselves except that they tend to be more accurate than emissions estimates from macroscopic models (Rakha et al., 2003).

Macroscopic emission models are designed to estimate regional emissions from vehicles based on the average network speed, the total number of vehicles, and some assumed driving cycles (Akcelik, 1985; Bai et al., 2009). These models require relatively few data inputs, so they are much easier to implement for large urban networks, but they tend to relate a single average speed with a single emission rate. In reality a single average speed could be associated with many different driving cycles ranging from a small number of long stops to a large number of short stops, and these driving cycles should be associated with different emission rates.

Mesoscopic emission models have emerged in recent years to use aggregated traffic data that reflect the traffic conditions and congestion in the network to provide more accurate network-wide emissions estimates than conventional macroscopic emission models. One example is VT-Meso, which utilizes link-by-link average speed, the number of vehicle stops, and the stopped delay as aggregated traffic inputs (Yue, 2008). The model synthesizes a typical driving cycle, and by using the microscopic VT-Micro model, it estimates the average link fuel consumption and emission rates. Gori et al. (2012) presents an approach to estimate emissions from aggregated distance traveled at free-flow speed, the average speed of vehicles in queues, and the length of the queues.

The challenge that remains is how to acquire reliable estimates of aggregated traffic parameters for a network. Since the critical input for emissions models is an accurate driving cycle, traffic models need to relate the time that vehicles spend accelerating, cruising, decelerating, and idling to the traffic conditions on the roadway. An arterial-level model has been developed to estimate emissions assuming that some traffic data such as flows and number of vehicle stops are measured directly from links in the network and then estimating the other relevant parts of the driving cycle (Skabardonis et al., 2013). Another recent model uses kinematic wave theory to make analytical estimates of the entire driving cycle for traffic on a single link approaching an isolated intersection (Shabihkhani and Gonzales, 2013). The model presented in this paper goes a step further to estimate emissions based on aggregated traffic characteristics using the MFD, which can be approximated analytically, and readily observable characteristics of the network.

3 Integrated Traffic Emission Model for a Network

The proposed modeling approach is to make use of analytical approximations of the MFD to estimate aggregated elements of the driving cycles of vehicles in the network: the time spent cruising per distance traveled, the time spent idling per distance traveled, and the number of times vehicles stop per distance traveled. A similar approach has been shown to produce reliable emissions estimates at isolated intersections (Shabihkhani and Gonzales, 2013), and the proposed model extends this framework to traffic in networks.

In order to make accurate estimates of emissions, it is important that estimates of the components of the driving cycle and emission factors are accurate. This paper focuses on investigating simple homogeneous networks in which a well-defined MFD is known to exist so that the MFD can be used to estimate driving cycles. Then driving cycles are converted to emissions estimates by using emission factors acquired from analysis of a few sample trajectories with a conventional microscopic model. Although the method may be applied to measured or simulated vehicle data from any road or network, our investigation will use a simulation approach to study the performance of idealized networks.

3.1 Analytical Model for the Driving Cycle

Existing macroscopic models for network-wide traffic conditions relate the average network flow, q, to the average network density, k. For a network that is homogeneous and well-connected with a relatively uniform distribution of vehicles, a consistent MFD relates flow to density by a concave function $q = Q(k)$ (Daganzo, 2007). Although the MFD for a real network can be measured from the field or simulation, $Q(k)$ can be approximated analytically based on readily observable network characteristics: the block length, signal timings, maximum discharge flow per lane, free-flow speed of cars, and the jam density. The full details of how to construct this analytical approximation of the MFD are in Daganzo and Geroliminis (2008) and are not repeated in this paper. It is sufficient for the purposes of this paper to suppose that $Q(k)$ is known, and we will use it to obtain an analytical approximation for the idling time, cruising time, and number of stops for vehicles in the network. The goal is to develop a model with sufficient detail to estimate aggregated emissions in the network without the need to track the details of each vehicle's movements.

The trajectories of vehicles approaching an intersection or traversing a network have repeating patterns of cruising at the free-flow speed, v_f, idling while stopped, and decelerating and then accelerating between speeds v_f and 0 for every stop. Therefore, three components of the driving cycle that must be estimated from the traffic model in order to account for emissions from the vehicles: the time spent cruising per distance traveled, T_c; the time spent idling per distance traveled, T_i; and the number of times that vehicles must stop per distance traveled, n. We will first consider how T_c and T_i can be estimated if n is known. Then we will consider how the number of stops per distance can be estimated as well.

Suppose that traffic on a homogeneous network has a triangular fundamental diagram with free-flow speed of v_f, jam density k_j, and backward interface speed w (the downward sloping branch of the flow-density relation). If we ignore for the moment the range of speeds that are associated with acceleration and deceleration, vehicles will have piecewise linear trajectories with speed v_f while moving (i.e., cruising) or stopped while idling. All travel time for vehicles can be classified as effectively cruising or effectively idling. The kinematic waves associated with these idealized trajectories are the same as the aggregated dynamics of traffic with more realistic acceleration and deceleration patterns (Lighthill and Whitham, 1955; Richards, 1956).

Every vehicle that stops must decelerate from v_f to 0 and then accelerate from 0 back to v_f. The duration of the deceleration is τ_d and the duration of the acceleration is τ_a, and these values depend on the behavior of drivers in a particular network. If the deceleration and acceleration are at constant rates, then half of τ_d and τ_a is effectively cruising time and the other half is effectively idling time. Figure 1 shows how a piecewise linear trajectory and a more realistic trajectory with constant rates of deceleration and acceleration. For simplicity, we will consider a single time associated with the cycle of deceleration and acceleration for each vehicle stop $\tau = \tau_d + \tau_a$. Therefore the each stop reduces the actual time spent cruising by $\tau/2$ and the actual time spent idling by $\tau/2$. It is important to account for τ when modeling traffic emissions, because the emission rates for cruising and idling should be multiplied by the actual cruising and idling times rather than the effective times.

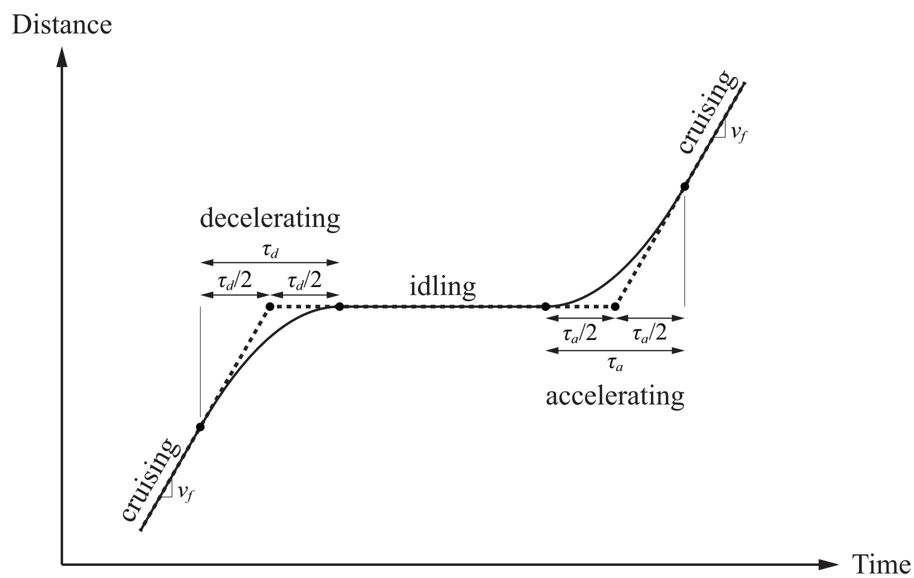


Figure 1. Relationship between a trajectory with constant deceleration and acceleration rates (solid) and a piecewise linear trajectory simplified to effective cruising and effective idling (dashed).

The effective cruising time per unit distance is simply the inverse of the free-flow cruising speed, because no distance is traversed while idling. The actual cruising time per unit distance is then calculated by reducing the effective cruising time by half of deceleration and acceleration time for each stop:

$$T_c = \frac{1}{v_f} - \frac{\tau}{2}n \tag{1}$$

where n is the number of times a vehicle stops per unit distance traveled.

The effective idling time is the difference between the total travel time per unit distance, which is the inverse of the average traffic speed, v, and the effective cruising time. The actual idling time per unit distance is again calculated by reducing the effective idling time by the other half of the deceleration and acceleration time per stop:

$$T_i = \frac{1}{v} - \frac{1}{v_f} - \frac{\tau}{2}n. \tag{2}$$

Identifying the relevant traffic state on the MFD is useful at this point, because each traffic state is defined by q and k, which together imply the average speed of vehicles in the network:

$$v = q/k. \tag{3}$$

The number of vehicle stops per distance traveled, n, is an important element of the driving cycle, because it represents how often a vehicle accelerates and decelerates between cruising and idling. A simple approximation is that vehicles stop on average once per signal cycle. The average distance traveled during a signal cycle of length C is vC, so the number of stops per distance is given by:

$$n = \frac{1}{vC}. \tag{4}$$

This approximation is appropriate when the signal offset is 0 and when the duration of the red signal exceeds the time required to travel the length of a block at free-flow speed: $C - G \geq \ell/v_f$, where G is the effective length of the green phase and ℓ is the length of a block. In this case, the red phase is sufficiently long that a vehicle will always have to stop once per cycle when caught at a red signal.[1]

A complication occurs in urban networks because the platoon of vehicles being served by an upstream signal may reach the back of a downstream queue before it has completely dissipated at a downstream signal causing every vehicle to stop a second time. This condition can be identified by tracking whether the front of the platoon moving at free flow speed v_f reaches the interface at the front of the dissipating queue moving backward at speed w as illustrated by point A in Figure 2.[2] If the queue exceeds length d, the platoon gets blocked and each vehicle stops a second time.

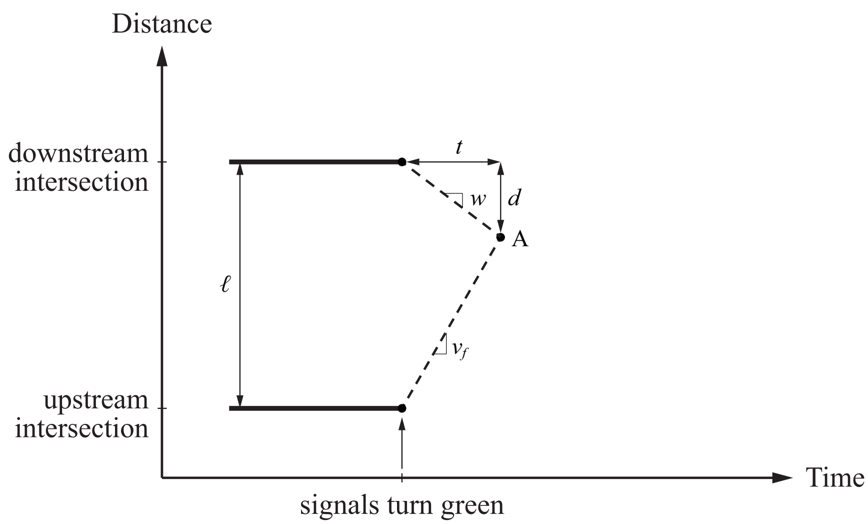


Figure 2. Time space diagram showing two consecutive signals located a block length ℓ apart and the condition that the platoon moving forward at speed v_f meets the queue that dissipates with interface speed w (at point A), which imposes an extra stop to all vehicles in the platoon.

Mathematically, the condition that the platoon gets blocked occurs if the number of vehicles queued on the link exceeds the number that would be in a queue of length d. The number of vehicles in a queue of length d is $k_j d$ and the number of vehicles on the link may be defined as $k\ell$, so the a blockage of the platoon is implied by the following condition:

$$k\ell > k_j d. \tag{5}$$

[1] When block lengths are long enough or red phases are short enough that $C - G < \ell/v_f$, it is possible for some vehicles to traverse the network without stopping during every cycle. This may become a source of error, although the condition does not occur for any of the examples in this paper.

[2] The free-flow speed v_f is represented graphically by the slope of the upward branch of the link's fundamental diagram, and the backward wave speed w is represented graphically by the slope of the downward branch of the link's fundamental diagram. For additional explanation of the principles of fundamental diagrams, interfaces, and time-space diagrams, see for example Daganzo (1997) or Cassidy (2003).

From the geometry of Figure 2, it follows that $d = wt$ and $\ell = wt + v_f t$. By substituting these expressions into (5), cancelling out t from all terms, and using this as the condition to determine if the average vehicle stops once or twice per cycle, (4) can be re-written as:

$$n = \begin{cases} 1/vC & \text{if } k\,(w + v_f) \leq k_j w \\ 2/vC & \text{otherwise.} \end{cases} \tag{6}$$

3.2 Emission Factors

Emission factors are obtained for time spent cruising, time spent idling, and each acceleration and deceleration associated with a stop. A microscopic emission model can be used to obtain emission factors by analyzing example trajectories of vehicles from the network. In this case, a microsimulation was constructed and second-by-second trajectories from a sample of vehicles were extracted for analysis. If there are a variety of vehicle types in the network, a representative sampling of trajectories from these vehicles should be used. Our goal is to estimate emission factors for each component of the driving cycle, so the sample of trajectories is parsed into cruising, idling, acceleration, and deceleration.

Each trajectory segment has a duration and is analyzed with a microscopic emission model to estimate the corresponding emission quantity. For idling and cruising, the results are simply averaged to obtain an average emission rate for each second of idling and each second of cruising. For the accelerations and decelerations, the duration and total emission are both important quantities. Each stop requires that a vehicle decelerate and accelerate, so the sum of the deceleration and acceleration durations are the period of time when vehicles are neither cruising nor idling. The cycle of decelerating and accelerating for a stop is associated with a quantity of pollutants emitted per vehicle stop.

In this paper, we evaluate a number of different network scenarios in which the free-flow speed is $v_f = 53$ km/hr. The project level of MOVES (EPA, 2010) was used to analyze a sample of trajectories extracted from an Aimsun simulation of a simple network with traffic signals, although any microscopic emission model and microsimulation package could be used with the same procedure. The emissions of interest for our study are greenhouse gases, because these are global pollutants that are most important to estimate in aggregate for a network. The relevant unit of measure for greenhouse gases is grams of carbon dioxide equivalents (gCO_2eq) because, this represents the Global Warming Potential (GWP) of all greenhouse gases emitted from the vehicles in terms of an equivalent amount of CO_2. The emissions factors for this case are $e_c = 2.79$ gCO_2eq/sec for each vehicle while cruising, $e_i = 0.88$ gCO_2eq/sec for each vehicle while idling, $e_s = 22.23$ gCO_2eq/stop, and the average duration of an deceleration and acceleration cycle is $\tau = 8.75$ sec.

3.3 Analytical Emissions Model

Equipped with an analytical MFD, we have a set of derived aggregated driving cycle components based on the traffic state from Section 3.1. Each of these components can be multiplied by the corresponding emission factor from Section 3.2 to obtain the total emissions per vehicle distance traveled, E:

$$E = e_c T_c + e_i T_i + e_s n \tag{7}$$

where e_c is the emission of interest per unit cruising time, e_i is the emission of interest per unit idling time, and e_s is the total emission of interest associated with a complete deceleration from v_f to 0 and a complete acceleration from 0 to v_f.

The driving cycle components (T_c, T_i, and n) are determined in terms of the characteristics of the link-level fundamental diagram (free-flow speed v_f, jam density k_j, and backward interface speed w), the average vehicle speed v, the cycle length C, and the duration of an acceleration and deceleration cycle τ. The speed v is a reflection of the traffic state as defined by flow q and density k, which can be approximated by the analytical MFD in the form of a concave function $Q(k)$. If $Q(k)$ is known (e.g., by analytically approximating the MFD), the average speed of vehicles in the network can be expressed as a function of density, so (3) becomes $v(k) = Q(k)/k$. The emissions in a network are estimated by evaluating T_c, T_i, and n with $v(k)$ and substituting the resulting driving cycle components into (7).

4 Application to Ring and Grid Networks

In order to evaluate the proposed analytical emission model, we compare the results with a more conventional analysis. The conventioanl approach uses a microsimulation to obtain detailed trajectories from the network and then a microscopic emission model to analyze the emissions from all of the trajectories.

Two networks were simulated. First, a simple ring model was constructed in which a link of length $\ell = 150$ m wraps back on itself at a single intersection. In the ring model, vehicles travel around in a circle, and this provides a representation of the simplest network in which spillbacks can block traffic flow through the intersection. Second, a simple grid model was constructed with several one-way links of length $\ell = 150$ m. Vehicles are uniformly distributed on the homogeneous network so the simulation also represents an idealized network. By simulating many vehicles on both of these networks, a large number of detailed second-by-second trajectories were created which could be analyzed using the microscopic emission model. The results of the proposed analytical emission model based on the analytical approximation of the MFD is compared with the emissions estimated from direct simulation and computation.

The base case network that is used to illustrate the performance of the proposed analytical model has the following properties: free-flow speed, $v_f = 53$ km/hr; saturation flow, $s = 1900$ veh/lane-hr; jam density, $k_j = 200$ veh/lane-km; green ratio (length of green phase divided by signal cycle length), $G/C = 0.50$; signal cycle length, $C = 60$ sec; block length, $\ell = 150$ m; and no signal offset. Running the simulation for a range of densities between 0 and k_j, the average network flow q is plotted for each density k in Figure 3. The circular points in the figure indicate the measurements from the simulation of the ring model, square points are measurements from the simulation of the grid model, and the line is the analytical approximation of the MFD obtained using the method described in Daganzo and Geroliminis (2008).

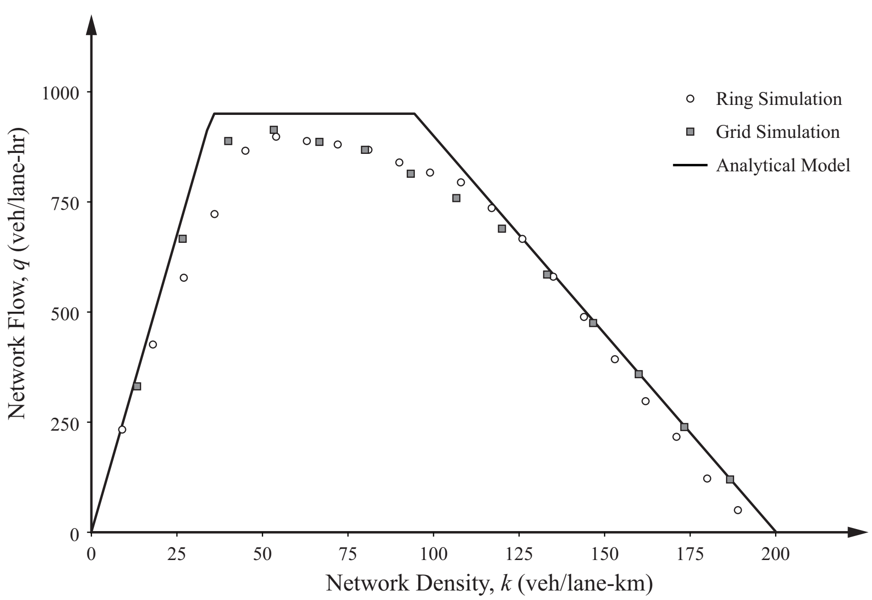
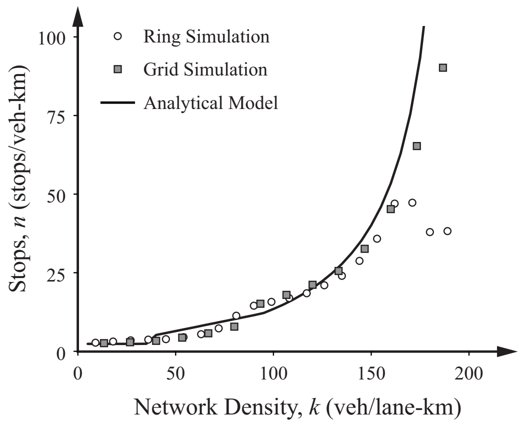
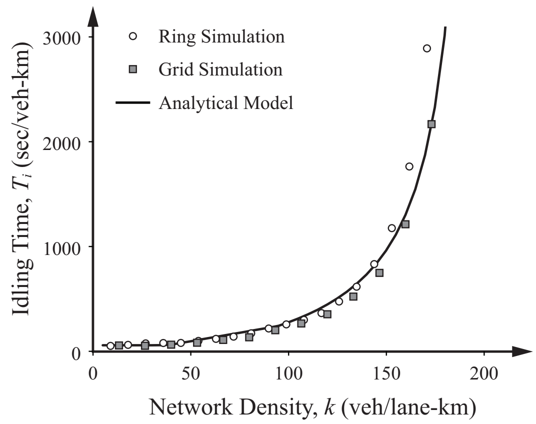


Figure 3. Network flow-density relation (MFD) measured from the simulation of an idealized ring network, simulation of an idealized grid network, and the analytical approximation ($G/C = 0.50$; $C = 60$ sec; $\ell = 150$ m).

Using average network speed at each density, $v(k) = Q(k)/k$, the number of stops is estimated from (4). Figure 4(a) shows the analytically estimated value of n (solid line) and the measured number of stops determined by analysis of the simulated vehicle trajectories from the ring simulation (circular points) and grid simulation (square points). The plot shows that the analytically estimated number of stops has a similar trend to simulated values. At the highest densities ($k > 150$ veh/lane-km), where traffic is nearly completely jammed, the estimated number of stops per distance soars while the observed number of stops actually declines. This is due to the fact that in extremely congested conditions, vehicles move so little during each cycle that the trajectories do not trigger the necessary thresholds for the stops to get counted.



(a) Number of Stops



(b) Idling Time

Figure 4. Components of the driving cycle measured from simulation of the ring and grid and estimated using the analytical model ($G/C = 0.50$; $C = 60$ sec; $\ell = 150$ m).

The analytically computed values for n are then used along with the values of $v(k)$ to estimate the time per distance spent cruising, based on (1), and idling, based on (2). Figure 4(b) shows the analytically estimated idling time (solid line) and the idling time measured from the simulated trajectories (points). The analytical approximation closely matches the simulated values.

The total greenhouse gas emissions per vehicle distance traveled is calculated by multiplying each of the estimated driving cycle components by the associated emission factors as show in (7). These results can be compared with the outcome of a conventional microscopic emissions analysis using the detailed second-by-second simulated vehicle trajectories. A comparison of the analytically estimated emissions (solid line) and the aggregated simulation outputs (points) is shown in Figure 5.

The analytical estimate based entirely on the analytical approximation of the MFD and associated estimates of the driving cycle components is always within 15% of the measured emissions from simulation, and in most cases the estimate is within 10% of the measured value. The close agreement between the analytical macroscopic model and the detailed simulation model occurs because aggregating the emissions from all vehicle trajectories together has the effect of averaging out variations from vehicle to vehicle.

5 Effect of Changing Network Characteristics

The value of an analytical model for emissions from vehicles in urban networks is that the effect of changing network and demand characteristics can be quantified quickly. Whereas the conventional simulation and microscopic emission modeling approach require that the network be reconstructed and recalculated for each scenario considered, the analytical approach allows for systematic comparisons of network performance based on evaluation of mathematical functions. This makes the analytical model especially useful for large-scale analysis of the effects that transportation policies are likely to have on the performance of the traffic network, including the emissions from vehicles. Unlike existing macroscopic emission models, this analytical approach explicitly accounts for the

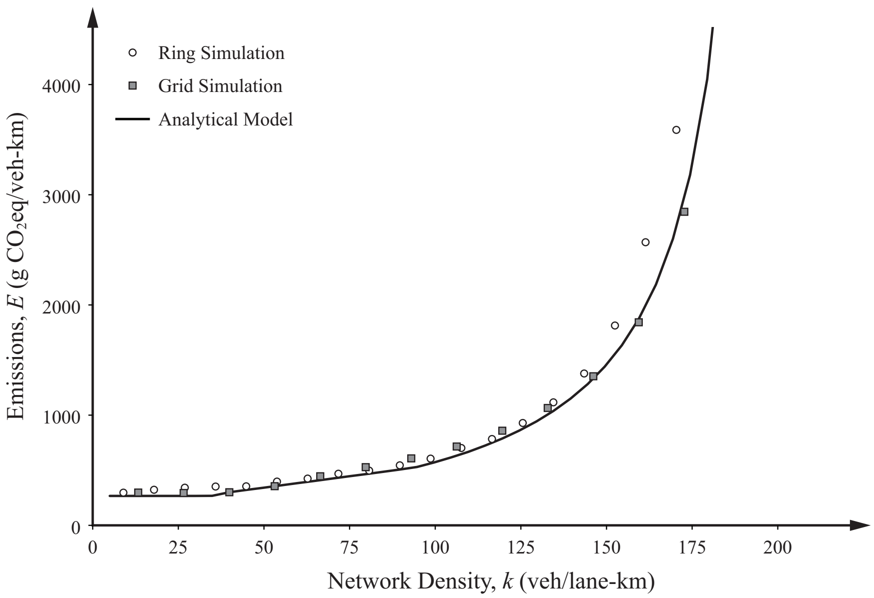


Figure 5. Network-wide emissions estimated using detailed trajectories from a simulation and microscopic emission analysis for the ring and grid and estimated using an analytical model based on the MFD ($G/C = 0.50$; $C = 60$ sec; $\ell = 150$ m).

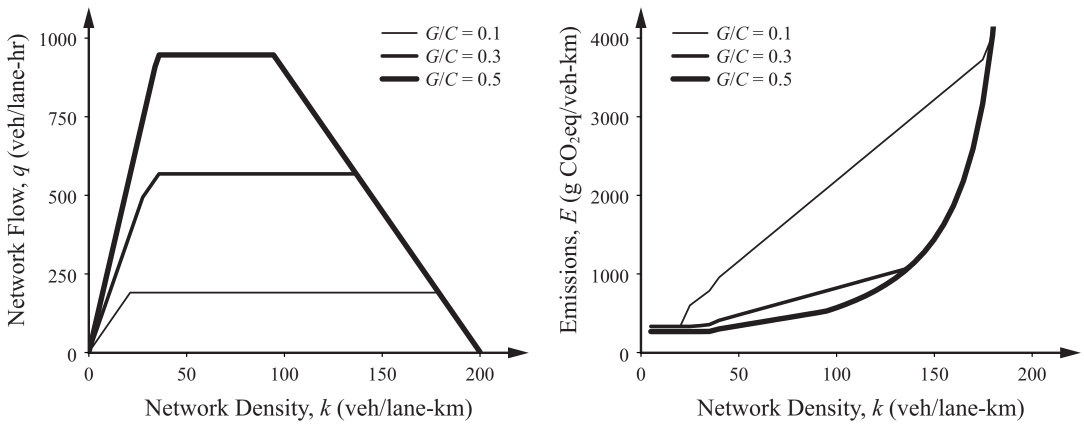
physical interactions of vehicles in the network so that the effect is captured of changes in signal timings and vehicle densities have on the driving cycles and resulting emissions from vehicles.

One characteristic of a network that can be changed relatively easily is the ratio of the cycle time that is effectively green for each approach, G/C. Using all of the same network parameters as in the base case presented in Section 4, an evaluation of the effect of changing the green ratio is conducted by changing only the value of G/C. Figure 6(a) shows the analytical MFD for each of the green ratios $G/C \in \{0.1, 0.3, 0.5\}$. The last value is the same base case presented in Figure 3. The green ratio for through traffic in a network may get reduced if signals are timed to include dedicated turning phases, and one effect of reduced green time is the obvious reduction in the maximum flow that can progress through the network. Reduced green times also reduce the speed that vehicles can traverse the network at lower densities as indicated by the lower slopes on the left side of the MFDs for lower values of G/C in Figure 6(a).

The analytically estimated emissions for each of the cases are shown in Figure 6(b). The results indicate that the more restricted green ratio is associated with greater emissions per vehicle distance traveled. Although this qualitative effect may be expected, the analytical model allows us to quantify the effect over the full range of vehicle densities. The effect on emissions per distance traveled increases dramatically as the green ratio is restricted. A reduction of G/C from 0.5 to 0.3 results in a modest increase in the emission rate compared to a further reduction to 0.1. Emissions do not differ much at the lowest densities, when traffic is freely flowing, and at the highest densities, when conditions are nearly gridlocked.

Another characteristic of the network that can be changed as part of a traffic control plan is the length of the signal cycle, C. Figure 7(a) shows the analytical MFD for cycle lengths $C \in \{30, 60, 90\}$ seconds with the green ratio held constant at $G/C = 0.5$.[3] Changing the cycle length has little effect on the MFD, especially in free flowing conditions. In fact the MFD for $C = 30$ seconds is almost identical to the MFD for $C = 60$ seconds. Although the MFD is similar, the emissions rate varies as shown in Figure 7(b), because the number of vehicle stops in the driving cycle is affected by C in addition to the average speed of traffic as given by (6). For the same flow and density, a longer cycle

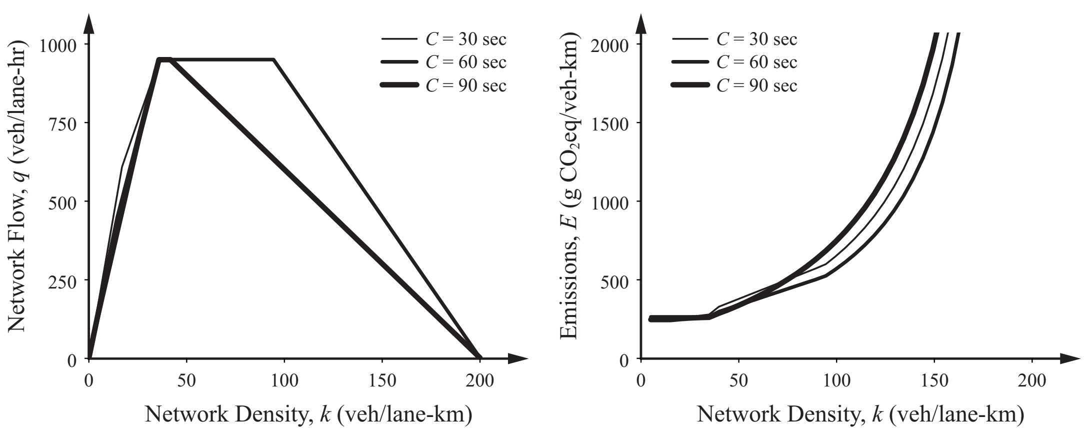
[3]In practice, a longer cycle usually allows a higher green ratio to be achieved, because the loss time due to switching signals makes up a smaller portion of the whole cycle. We ignore this effect here to focus our attention on the effect of changing only one parameter on the resulting emissions.



(a) Network Flow (MFD) (b) Network Emissions

Figure 6. Comparison of MFD and analytically estimated emissions for varying green ratios, $G/C \in \{0.1, 0.3, 0.5\}$.

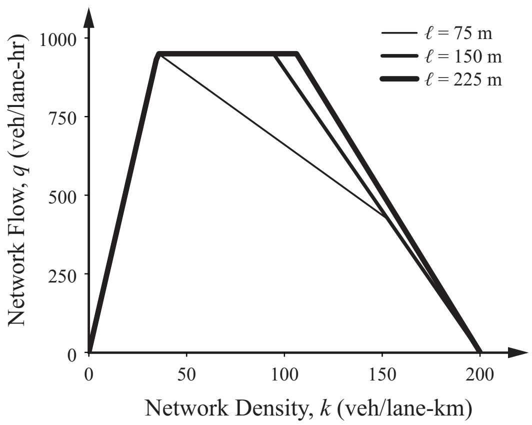
length results in fewer stops per distance traveled, and this translates to reduced emissions. However, the cycle length of $C = 90$ seconds is associated with a longer red phase, which causes additional queueing that constrains flows on the congested branch of the MFD. The reduced congested speeds result in greater emission rates. Evidently, the detailed effects of the cycle length on the driving cycle matter for the resulting emissions, and the analytical model accounts for these effects.



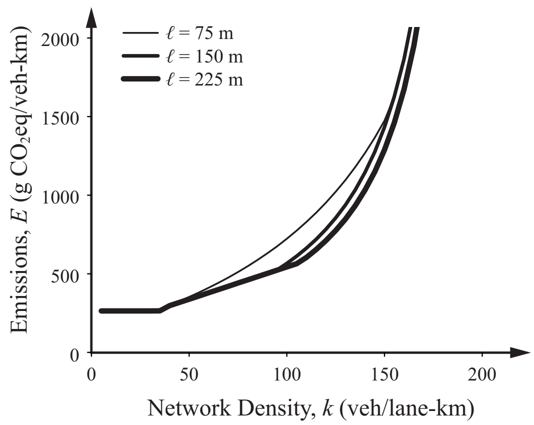
(a) Network Flow (MFD) (b) Network Emissions

Figure 7. Comparison of MFD and analytically estimated emissions for varying green ratios, $C \in \{30, 60, 90\}$ sec.

A third characteristic of the network that can be compared is the effect of the block length on emission rates. As a policy, it is difficult to change the length of city blocks once the street network has been built, but when new neighborhoods are developed there is an opportunity to choose the size of city blocks and to consider the effect that this will have on traffic flows and emissions. Figure 8(a) shows the comparison of analytical MFDs for $\ell \in \{75, 150, 225\}$ meters. The shortest block length corresponds to the approximate size of a city block in Portland, Oregon, and the longest block length is the approximate size of a city block in Salt Lake City, Utah. In free flowing conditions, the block length does not make much difference, but in congested conditions, the length of blocks determines the storage space for queues of vehicles and the likelihood of a queue spillback. The effect on emissions is shown in Figure 8(b). For the lowest densities (i.e., free-flowing conditions), the traffic states and emissions do not vary. From a flow and emissions perspective, there is a benefit to increasing block lengths, but in practice this is only necessary up to a point. The emissions are only incrementally improved from $\ell = 150$ m to 225 m and only in the most congested conditions, which an efficient traffic management program should seek to avoid anyway.



(a) Network Flow (MFD)



(b) Network Emissions

Figure 8. Comparison of MFD and analytically estimated emissions for varying green ratios, $\ell \in \{75, 150, 225\}$ m.

The analytical model for emissions based on the MFD is flexible for many analyses, but it does have limitations. All of the cases presented are associated with the same free-flow speed, v_f, so the set of the emission factors (e_c, e_i, and e_s) and the duration of each acceleration and deceleration cycle (τ) remains the same as the base case. If the free-flow speed in the network were to change, these factors would have to be re-estimated because the acceleration and deceleration associated with each stop would span a different variation of speeds. In practice this may not be a big problem, because free-flow speeds on city streets tends to be stable, and the effect of traffic policies for urban networks tends to be more geared toward control strategies and demand management, which the MFD is appropriate for addressing.

6 Insights for Urban Sustainability Policy

A model has been proposed that makes use of the macroscopic relationship between average flow and density known as the MFD to make analytical estimates of the network-wide emissions from traffic. A robust relationship exists between the components of the driving cycle that are associated with vehicular emissions and the fundamental properties of the network, just as a robust flow-density relation exists for many urban street networks. The components of the driving cycle per vehicle distance traveled (i.e., cruising time, idling time, and number of stops) are estimated based on the aggregated flow-density relation (MFD), the free-flow speed in the network, the duration of a typical acceleration and deceleration associated with a vehicle stop, and the signal cycle length. These components are then multiplied by emission factors that are developed using a detailed microscopic emission model, such as the project level of MOVES.

The value of this modeling approach is that vehicles in street networks do not need to be tracked in exact detail in order make reliable estimates of the network-wide emissions. The MFD is useful for traffic analysis because knowledge of a small number of network parameters and the average density of vehicles in the network provides sufficient information to predict the average flows, speeds, and delays in the network. Simple analytical tools lower the barrier for quantifying emissions and including consideration of environmental impacts in analysis of area-wide policies related to traffic control and demand management, such as dynamic signal control or congestion pricing strategies.

Additional work is needed to consider the effect of some other important network characteristics on aggregated emissions. For example, the offset in timing between adjacent traffic signals plays a very important role in how smoothly traffic progresses along an arterial corridor. There are methods to analytically approximate the MFD for a network with signal offsets (Daganzo and Geroliminis, 2008), and accounting for this effect on the number of stops requires making some adjustments to equation (6). Another important difference between the simulations of idealized networks presented in this paper and traffic in real cities is that the vehicles are often not uniformly distributed across the network. This means that some links may incur queue spillbacks while other streets are underutilized, which reduces the average flows sustained on the network. Preliminary findings suggest that if the realized flow on a network can obtained be measurement or estimation, the model continues to provide a near approximation of the emissions calculated through extensive analysis of second-by-second vehicle trajectories.

Although average vehicle speeds in the network and the length of a signal cycle play a large role in determining the average emission rates from vehicles in a network, it is important to account for the effects of network characteristics like the block length and signal timing on the driving cycles for each vehicle. Whereas existing macroscopic models tend to use a set of pre-defined driving cycles to derive emission rates based on average speeds, we know that real vehicle trajectories are more complex and that changes in network characteristics may change the frequency of acceleration and deceleration cycles associated with stops without affecting the overall flow or average speed in a network. There remains a role for microscopic emissions modeling in finding ways to optimize individual driving behavior or to quantify localized impacts for pollutants that must be monitored at individual facilities. The proposed model provides new value because it provides a less data-intensive way to estimate aggregated network emissions, which is especially important for tracking pollutants like greenhouse gases that have a global impact.

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