Vehicles' Emissions Consideration in Transportation Network Design Using Markov Chain Traffic Assignment

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Abstract

Markov chain traffic assignment (MCTA) is a relatively recent approach for modeling traffic conditions in a road network. It results in traffic density measurements that express congestion levels in the network at the road level. While the stochastic approach is powerful analytically, the resulting traffic density does not readily lend itself to emissions estimation. Typically, average-speed emission models are utilized to estimate emissions on an aggregate network level. However, while this is easily done in user equilibrium (UE) models using the Bureau of Public Roads (BPR) relationship to derive vehicles' average speed from traffic flow, no such relationship exists for traffic density. We highlight the mathematical challenge here and propose an approach to estimate vehicles' average speed based on traffic density obtained from MCTA. The average speeds are then used to estimate vehicles' Greenhouse Gas emissions using average-speed emission estimation models. This approach can be applied on a road level or aggregated to a network level. We utilize the BPR relationship to build a linear piece-wise approximation function and illustrate its use through two widely used average-speed emission estimation models: TRANSYT-7F and COPERT v5.

Keywords
Vehicles Emissions, Network Design, Markov Chain Traffic Assessment.

1. Introduction

The ever-growing demand on transportation resources to facilitate increasing mobility requirements and human activities continues to place mounting pressure on transportation networks. This is reflected in the number and frequency of studies considering the transportation network design problem (NDP), and the many modeling and solution approaches proposed to address it over the years. In essence, the NDP is the problem of designing a transportation road network to reduce some cost or improve some benefit. Many studies use total travel time, total vehicle miles, construction costs, or congestion as their cost objective. Different design approaches are adopted in studies to achieve these objectives, they include street capacity expansions, scheduling traffic lights, traffic turning or direction restrictions, and determining road tolls. A review of transportation network design literature is found in (Farahani et al., 2013).

In recent years a new alternative approach to the User Equilibrium (UE) traffic assignment model was proposed by (E. Crisostomi, Kirkland and Shorten, 2011). The new approach utilizes Markov chain theory to model vehicle traffic on the network stochastically and estimate vehicles' distribution on the network establishing its' traffic assignment, and as such the approach is referred to as the Markov Chain Traffic Assignment (MCTA) model. The MCTA approach is used in (Salman and Alaswad, 2018) to model traffic assignment as part of their NDP model, where roads' traffic direction restriction is used to convert two-way roads to one-way roads to alleviate congestion.

Since UE and MCTA take very different approaches to modeling traffic on a network, their input data requirements and expected outputs are also different. For input data, UE requires the generation of an origin-destination (OD) demand matrix, which requires conducting a home interview survey followed by a transportation forecasting model (Sheffi, 1984). In contrast, MCTA requires vehicle turning frequency data from all intersections in the network, which may be obtained using sensors deployed on the road network. As for traffic assignment results, on one hand, UE results in traffic flow estimates for individual roads based on network design and traffic conditions. On the other hand, MCTA results in an expected number of vehicles traversing each of the roads in the network, again based on its design and traffic conditions.

Recently, more attention has been given to the environmental aspects of NDP as global climate change awareness increases and the impacts of transportation activities on the environment become more widely recognized. After all, transportation is the top contributor to Greenhouse Gas emissions (GHG), with light-duty vehicles making the bulk of these emissions (US EPA, 2015). Environmental considerations in NDP can be found in studies such as (Sharma and Mathew, 2011; Szeto et al., 2015; Wang and Szeto, 2017). The vast majority of the NDP literature builds on the classic Wardrop approach (Wardrop, 1953) for modeling traffic assignment using UE (Farahani et al., 2013; Yang and H. Bell, 1998). Similarly, most studies considering environmental impacts of NDP also utilize the UE modeling approach (Szeto, Jaber and Wong, 2012).

Studies considering environmental impacts of transportation using UE traffic assignment typically estimate vehicle emissions using an average-speed emissions estimation model. This requires vehicles' average speed for individual roads in the network as input, which can be determined using flow-travel-time relationships such as the Bureau of Public Roads (BPR) equation (discussed in section 3.1). While this is trivial in UE models, no such relationship exists for traffic density and travel time, which is a gap for applying MCTA models to NDP with emissions considerations.

This paper attempts to address this gap by proposing an approach to estimate vehicles' average speed using MCTA traffic density results. The resulting average speed is then used to estimate total vehicles' emissions in a road network. The ultimate goal is to enable NDP models utilizing MCTA to consider vehicle emissions as an optimization objective. This allows the use of MCTA modeling power and simplicity to be applied to a wider range of problems in the NDP field.

The rest of this paper is organized as follows. Section 2 provides a brief overview of MCTA theory. Section 3 establishes the proposed vehicles' average speed estimation approach and demonstrate it using two of the widely used average-speed emissions estimation models: TRANSYT-7F and COPERT v5. Finally, Section 4 concludes this paper and points to future work.

2. Markov Chain Traffic Assignment

This section provides a brief overview of the MCTA theory, as described in (E. Crisostomi et al., 2011). The MCTA model takes its name from deploying Markov chain theory to road network traffic analysis. The approach requires collecting data describing vehicles' turning frequency at all network intersections. This is possible using traffic sensors increasingly being deployed into road networks in major cities. Such data describes the number of vehicles that at each intersection turns from one road into another. This is then converted into a percentage of vehicles that makes turns at each intersection. The percentages can also be interpreted as probabilities of vehicles making turns in the network. These probabilities are collected into a turn transition matrix $\acute{P}$, with elements $\acute{p}_{ij}$, where i and j indicate the starting road and the turned into road, respectively. The resulting matrix is a sparse matrix as each intersection will include only a few possible turning options leaving the remaining probabilities with zero values.

To accommodate varying road lengths into the model the probability of a vehicle staying in a road, p_{ii}, is calculated based on normalized travel time (t) vehicles take to traverse the road. The inclusion of p_{ii} requires a modification to the remaining probabilities, resulting in a new transition probability matrix P, whose elements p_{ij} are calculated using equations 1 and 2 below:

$$p_{ii} = \frac{t_i - 1}{t_i}, \; \mathrm{i} = 1, \ldots, \mathrm{n} \qquad (1)$$

$$p_{ij} = (1 - p_{ii})\, \acute{p}_{ij},\ \ i \neq j \tag{2}$$

Applying Markov chain theory to P results in the stationary distribution vector $\boldsymbol{\pi}$. This is accomplished via solving the algebraic system presented in matrix form in equation 3. $\boldsymbol{\pi}$'s elements (π_i) describe the probability of a vehicle to traverse a given road after the network have reached steady state. Given an estimated total number of vehicles (V) using the network at the time of data collection, and knowing roads' lengths (L), and number of lanes (N) it is possible to calculate traffic density (D) at each of the network roads using equation 4:

$$\boldsymbol{\pi}\,\mathrm{P} = \boldsymbol{\pi} \tag{3}$$

$$D_i = \frac{V\,\pi_i}{L_i\,N_i},\ \ \mathrm{i} = 1, \dots, \mathrm{n} \tag{4}$$

Individual road traffic densities can then be compared to levels published in the highway capacity manual (*Highway capacity manual*, 2000) to determine the traffic conditions severity and the service level experienced by road users. The reader is referred to (E. Crisostomi et al., 2011; Salman and Alaswad, 2018) for additional details of the MCTA approach.

The approach results in a traffic density measurement for each road in the network and while the fundamental traffic flow law (equation 5) relates density (D) to flow (v), it does so using average vehicles' speed (S). This poses a challenge since vehicles' average speed itself is unknown as it is the product of traffic conditions, measured here using D. Average speed is also the quantity we require to estimate emissions, which highlights the gap this paper attempts to address and where section 3.1 picks up.

$$\mathrm{D} = \mathrm{v}/\mathrm{S} \tag{5}$$

3. Estimating Vehicle Emissions in NDP using MCTA

Emissions estimation models are typically classified based on input data requirements and model granularity level. Several estimation models exist to suite varying modeling needs and data availability (Demir, Bektaş and Laporte, 2011; Franco et al., 2013; Gokhale and Khare, 2004; Joumard et al., 2007; Smit, 2006). While estimation models which use trip-profile produce accurate results, their data requirements (acceleration, engine speed, and other vehicle operational measurements) render them suitable only for single-vehicle emissions estimation and for operational and not network-wide planning purposes. On the other hand, average-speed models are more suitable for planning as they can be used on an aggregated level to produce representative emissions estimates for the entire network. Average-speed emission models are frequently used in transportation network studies (Emanuele Crisostomi et al., 2011; Ma, Ban and Szeto, 2015; Sharma and Mathew, 2011; Szeto et al., 2015; Wang and Szeto, 2017).

In this paper we use two of the most widely used average-speed emissions estimation models: TRANSYT-7F and COPERT v5. While both models can estimate several GHG emissions, we will focus on the top three GHG typically used in similar studies: carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOC).

This section starts by illustrating the classic Bureau of Public Roads (BPR) relationship between travel time (transformed into speed in Figure 1) and flow. The BPR relationship is then used to derive a piece-wise linear approximation function for the relationship between speed and density (Figure 2). This approximation function is in turn used to estimate GHG emissions for various traffic densities using the TRANSYT-7F (Figures 3, 4, and 5) and COPERT v5 (Figures 6, 7, and 8) models.

3.1 Vehicles' Average Speed Estimation

The BPR relationship (equation 6) is popular in NDP studies dealing with GHG emissions due to its simplicity and established use in transportation modeling. Here, t is travel time based on flow conditions (v) for a road with practical flow capacity of c and t_f travel time at free flow speed. Figure 1 illustrate this relationship for roads with different free flow speeds (S_f).

$$t = t_f \left(1 + 0.15 \left(\frac{v}{c}\right)^4 \right) \tag{6}$$

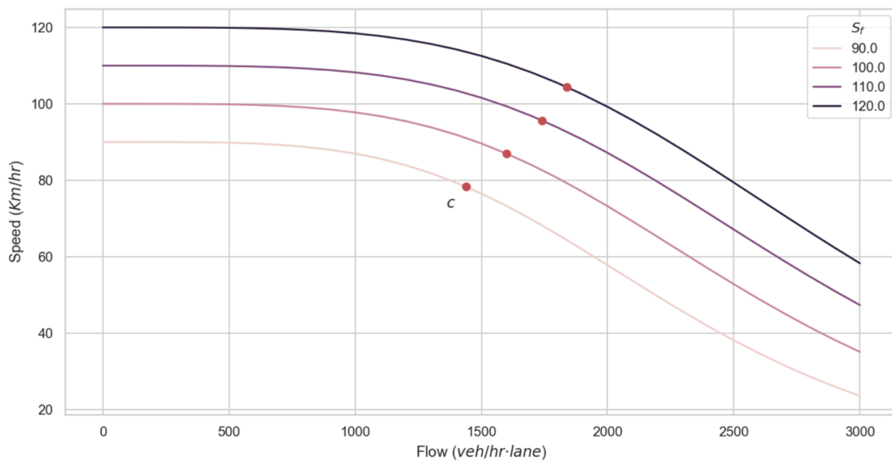

Figure 1: The Bureau of Public Roads (BPR) relationship

While the BPR relationship comes in handy in UE traffic assignment, it is not readily applicable to MCTA since the latter does not result in traffic flow condition. We can use the fundamental flow law in equation 5 to substitute flow for density in the BPR relationship and convert travel time to speed using road lengths, which results in the relationship described by equation 7. In the equation, D_c represents the traffic density at the road's practical flow capacity (c).

$$\frac{1}{S^5} - \frac{1}{S_f \cdot S^4} - 0.2624 \left(\frac{D}{D_c}\right)^4 \frac{1}{{S_f}^5} = 0 \tag{7}$$

However, the resulting polynomial relationship is quintic, which does not have a general form solution. Still, we could approximate the relationship between density (D) and speed (S) by calculating the various travel times and density values corresponding to flow values over a predefined range of v-values using equations 5 and 6. The result is illustrated in Figure 2 for v-values between 0 and 3000 veh/hr·lane. The resulting values can be used to approximate this relationship by a piece-wise linear function, $S = f(D, S_f)$, and given enough resolution in range of v-values, the resulting curve can approximate the non-linear relationship for most practical applications.

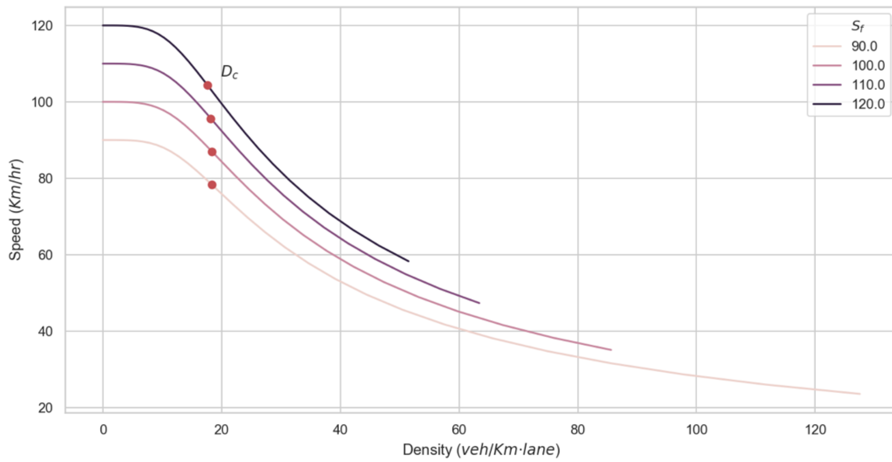

Figure 2: Density-speed relationship based on the BPR relationship

Now that we can estimate vehicles' speeds using MCTA's traffic density values, we can apply average-speed emissions estimation models. The following two sections illustrates these results.

3.2 TRANSYT-7F

One of the early average-speed emissions estimation models is the TRANSYT-7F model proposed by (Penic and Upchurch, 1992) which is utilized in various transportation models found in the literature (Chen and Yang, 2012; Long, Szeto and Huang, 2014; Ma et al., 2015; Szeto et al., 2015; Yin and Lawphongpanich, 2006). The model estimates several GHG emissions as well as fuel and oil consumption. Equation 8 shows the TRANSYT-7F model, where Q^P is the estimated emission for GHG pollutant P, expressed in g/ft·veh. We then convert Q^P to g/km·veh. Values for the coefficients A^p, B^p, and C^p for each pollutant used in this study are listed in Table 1. The listed values agree with studies found in literature (Penic and Upchurch, 1992; Szeto, Wang and Wong, 2014; Wang and Szeto, 2017). Figures 3, 4, and 5 illustrate the estimated emissions for CO, NO_x, and VOC respectively depending on traffic density values.

$$Q^P = \frac{A^p \cdot e^{(B^p \cdot S)}}{C^p \cdot S} \quad (8)$$

Table 1: TRANSYT-7F coefficients

	Constants		
Pollutants	A^p (g/ft·veh)	B^p (s/ft)	C^p (s/ft)
CO	3.3963	0.014561	1,000
NO_x	1.5718	0.040732	10,000
VOC	2.7843	0.015062	10,000

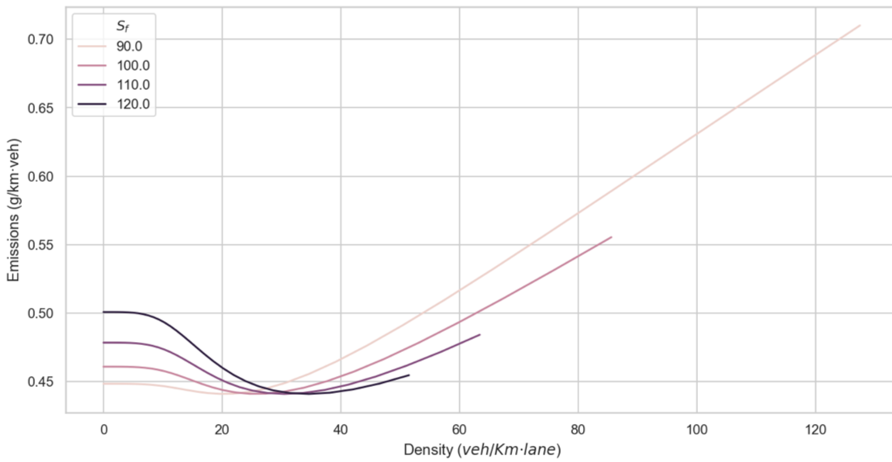

Figure 3: CO emissions vs. traffic density using TRANSYT-7F

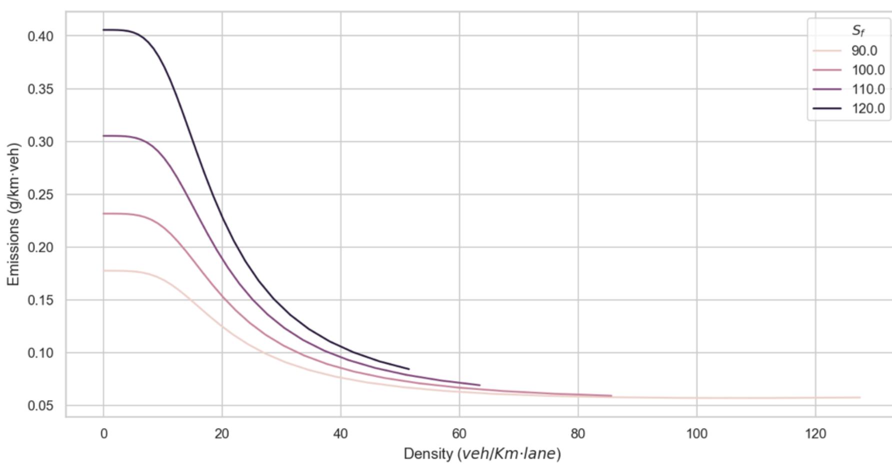

Figure 4: NO_x emissions vs. traffic density using TRANSYT-7F

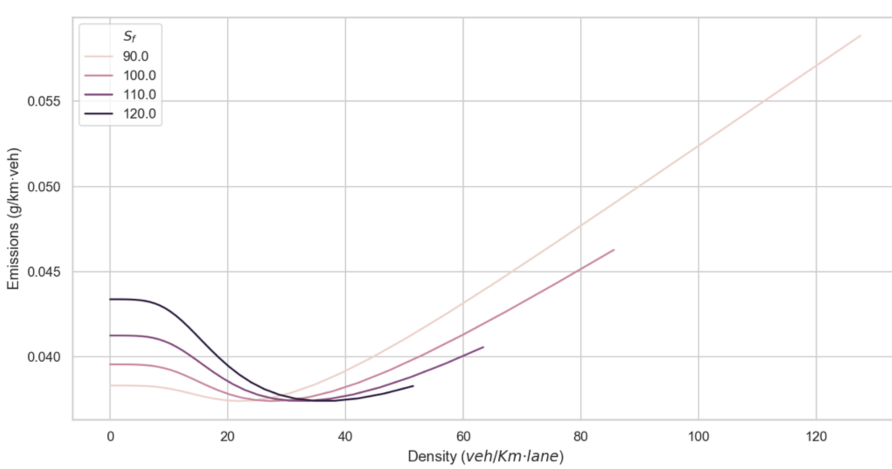

Figure 5: VOC emissions vs. traffic density using TRANSYT-7F

3.3 COPERT v5

The European Environmental Agency (EEA) adopts the COPERT emissions estimation suite of methodologies (Ntziachristos and Samaras, 2017). We utilize here the average-speed hot emissions estimation model from the COPERT v5 methodology. For simplicity we assume that vehicles on the road can be approximately described by the following attributes: petrol-powered small passenger cars of the Euro 5 standard. Equation 9 shows the COPERT v5 hot emissions estimation model, where α, β, γ, δ, ϵ, ζ, η, and R_f are all pollutant and vehicle type dependent parameters. Parameters values (listed in Table 2) are chosen from the COPERT v5 documentation (Ntziachristos and Samaras, 2017) based on the above assumptions. Figures 6, 7, and 8 illustrate the estimated emissions for CO, NO_x, and VOC respectively depending on traffic density values.

$$Q = \frac{(\alpha S^2 + \beta S + \gamma + \delta / S)}{(\epsilon S^2 + \zeta S + \eta)}\left(1 - R_f\right) \tag{9}$$

Table 2: COPERT v5 hot emissions estimation parameters for
petrol-powered small passenger cars of the Euro 5 standard

	Parameters							
Pollutants	α	β	γ	δ	ϵ	ζ	η	R_f
CO	0.000445	-0.1021	6.8769	10.3838	0.0016	-0.4376	30.3373	0
NO_x	-0.000315	0.1031	0.2391	-0.3393	0.0345	1.9860	1.2638	0
VOC	0.000004	-0.0007	0.0452	0.1731	0.0001	-0.0475	6.2121	0

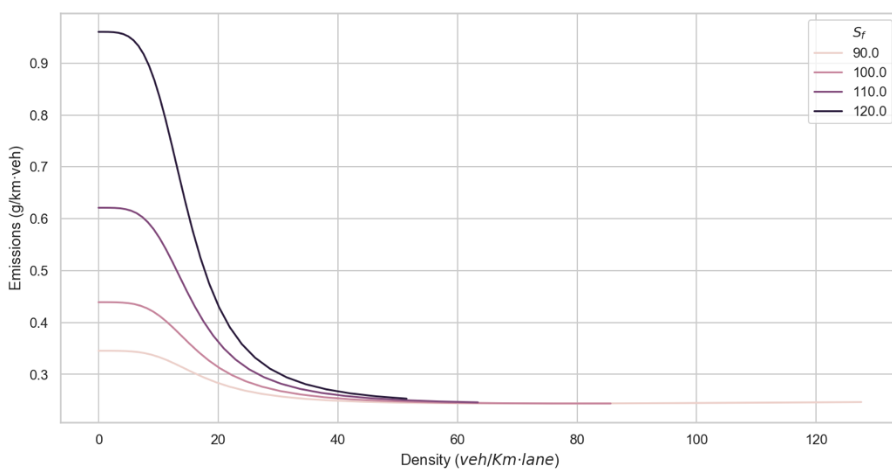

Figure 6: CO emissions vs. traffic density using COPERT v5

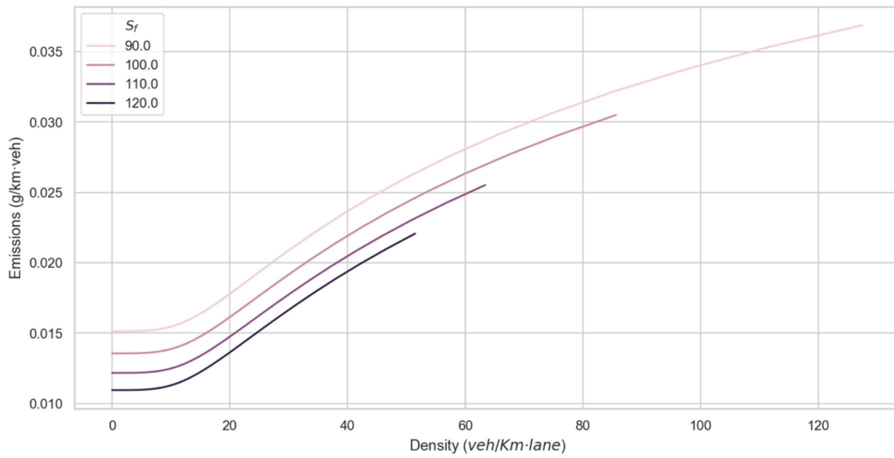

Figure 7: NO_x emissions vs. traffic density using COPERT v5

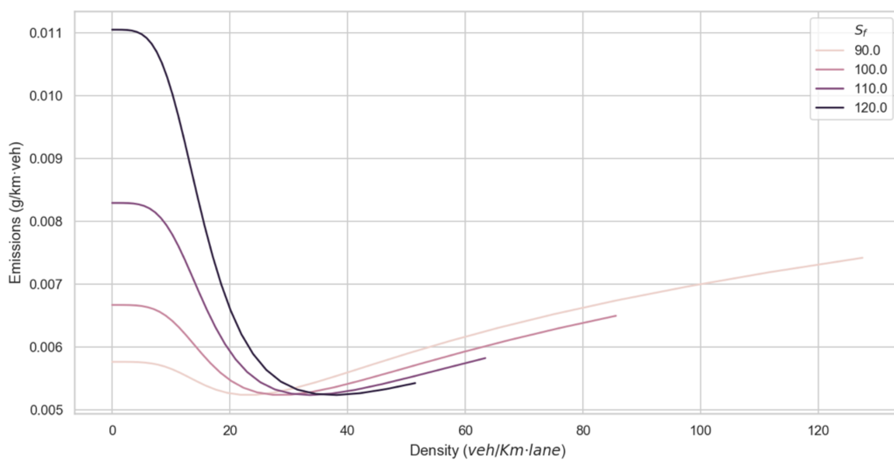

Figure 8: VOC emissions vs. traffic density using COPERT v5

4. Conclusion

While a closed-form mathematical relationship relating average vehicles' speed to traffic density is not possible, we propose piece-wise approximation function to bridge this gap. The approximation function can satisfy most practical emission estimation applications. We tested the approach using two widely used average-speed emissions estimation models: TRANSYT-7F and COPERT v5. The model can be deployed to road level as well as network level estimations.

This work opens the door for NDP models using MCTA to consider environmental objectives in its optimization through GHG emissions. An NDP model such as the one proposed by (Salman and Alaswad, 2018) can be extended into a bi-objective optimization model which simultaneously considers network congestion and its environmental impact. This research direction is the subject of another paper that is currently under review.

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