2024 European Control Conference (ECC)
June 25-28, 2024. Stockholm, Sweden

Quantitative approach for coordination, at scale, of signalized intersection pairs

Jack Haddad*, Nitzan Tur, Danny Veikherman, Eliav Buchnik, Shai Ferster, Tom Kalvari, Dan Karliner, Omer Litov, Avishai Zagoury, Ori Rottenstreich, Dotan Emanuel**, and Avinatan Hassidim

Abstract— **The coordination of signalized intersections in urban cities improves both traffic operations and environmental aspects. Traffic signal coordination has a long history, where the impact of offset on delays and emissions at signalized intersections has been investigated through simulations and a limited number of experimental findings. Coordinating intersections is often warranted by specific engineering requirements and judgment. However, as a consequence, many intersections in cities remain without coordination.**

In this paper, we examine the potential benefits of coordinating signalized intersections at scale. Unlike previous studies, our analysis is based on aggregated anonymized probe data analysis and does not need to explicitly model traffic-oriented issues such as queue spillback and platoon dispersion. We follow a quantitative approach by considering an intersection pair, i.e. a system of two signalized intersections which can be spatially coupled. We introduce a new method for coordinating those signalized intersections. The method first evaluates the effect of different offsets on vehicle travel times and fuel consumption (or emissions). Then, it coordinates the two intersections by setting a common cycle and finding the optimal offset that minimizes fuel consumption and/or travel times. We present the analysis for several case studies from real intersections at Jakarta, Rio de Janeiro, Kolkata, and Haifa. Finally, we evaluated our method by implementing it in a real experimental study at Jakarta. We collaborated with the city to implement the optimal offset determined by the proposed method, and we compared the results before and after coordination.

I. Introduction

Coordinating signalized intersections in cities can enhance traffic operations and resolve environmental issues. Coordination of an intersection pair, i.e. two consecutive intersections, is mainly designed by determining an offset. The offset is a time difference between the timing signal plans, usually between the start of green lights at both intersections. Previous works show the effect of offset design on the traffic performance, as delays and capacity, see e.g. [1].

Traffic coordination of signalized intersections has a long history [2]–[10]. The literature includes various methods for coordination, which are usually classified into progression methods and direct performance methods. Progression methods are based on bandwidth maximization, i.e. coordinating green durations to maximize number of vehicles that can move efficiently through a set of signals. On the other hand, direct performance methods are based on analytical models which estimate vehicle delays and/or number of stops for a given signal setting. These models are used as prediction to find the optimal signal decisions, e.g. offsets, green durations, cycle time, and others. It should be noted that progression methods are simple methods but limited for some cases and traffic scenarios; while direct performance methods are computationally more complex, and sensitive to the accuracy of the models, their calibrated parameters, and uncertainty.

As traffic becomes more congested in urban areas, both methods are less suitable to design and implement at a city scale, with large number of signalized intersections and different competing directions. Moreover, coordinating intersections is often justified based on certain requirements, operational needs, and engineering judgment. However, as a consequence of these challenges, many intersections in cities remain without coordination. In fact, according to the Federal Highway Administration (FHWA), about 75% of all signalized intersections in the US are not coordinated [11]. The potential benefits of coordinating these intersections at scale has not been evaluated. Finally, in previous studies, the performance of coordinating intersections has been evaluated using traffic simulations and several experimental results. In most previous studies, the performance measure was travel delays, while some other studies, see e.g. [12]–[17], consider also vehicle emissions (or fuel consumption).

In this paper, we follow a quantitative control approach to coordinate signalized intersections in the network. Instead of considering multiple candidate intersections for coordination simultaneously (e.g., several intersections of an arterial), we consider the smallest system size which consists of intersection pair. The idea is to coordinate every two intersections, with overlapping coverage to include the entire arterial or network. Coordination of intersection pair is carried out by coupling the two intersections with a common cycle length and setting an optimal offset between them that optimizes a performance measure.

Previous works, e.g. [1], [18], have focused on two closely signalized intersections, where different strategies and methodologies for analyzing the operation of such systems were established. E.g. the operational analysis of the diamond intersections under certain settings (three and four phases, fixed and actuated timing plans) were examined and evaluated by a performance index of capacity and/or delays. Analytical models that provide insights into the potential impediments to the traffic flow at upper stream intersection, e.g. queue spillback from downstream intersection, were proposed by [1], [19], [20], and many others. One can conclude from previous works on paired signalized intersections that:

Authors are with the Green Light team, Google Research. Authors contributed equally to this work.

* Work done while the author was a Visiting Faculty Researcher at Google. J. Haddad is also within Technion-Israel Institute of Technology.

** Corresponding author: dotan@google.com

(i) queue interaction effects may develop even when both intersections operate below capacity, and (ii) a timing plan strategy which minimizes delays but does not treat queue interaction is a weak strategy.

The main contributions of the current paper are summarized as follows. We examine the potential benefits of coordinating signalized intersections at scale. Our analysis is based on aggregated anonymized probe data analysis and does not need to explicitly model traffic-oriented issues such as queue spillback and platoon dispersion. We follow a decentralized approach by considering intersection pair, i.e. a system of two signalized intersections which can be spatially coupled, but operate with different cycle lengths. Then, we introduce a new method for coordinating those signalized intersections. The method first evaluates the effect of different offsets on vehicle travel times and fuel consumption. Then, it coordinates the two intersections by setting a common cycle and finding the optimal offset that minimizes travel times and/or fuel consumption. We present the analysis for several case studies from real intersections at Jakarta, Rio de Janeiro, Kolkata, and Haifa. Finally, we evaluated our method by implementing it in a real experimental study at Jakarta. We collaborated with the city to implement the optimal offset determined by the proposed method, and we compared the results before and after coordination.

II. Coordination Method for Signalized Intersection Pairs

In this section, we introduce a new traffic signal coordination method based on anonymized probe data. The method is capable of evaluating signal timing plans with different offsets.

A. Problem definition

Let us define a system of signalized intersection pair (SIP) as two signalized intersections which are spatially coupled, as schematically shown in Fig. 1. Two traffic movements are distinguished in SIP: movements that pass through both intersections (e.g. movements 1 and 2), and movements that pass through only one intersection (e.g. movement 3). The movements that are affected by the offset between the two intersections are those that pass through both intersections. The other movements are not affected by the offset change. The first intersection that a given movement passes through is called Upstream Intersection (USI), while the second intersection is called Downstream Intersection (DSI).

The problem is defined as follows. Consider a system of SIP with similar cycle lengths, i.e. close cycle values with a maximum difference of 10%. Then, based only on aggregated anonymized probe data analysis, coordinate the SIP by setting both intersections to a common cycle, and determine the optimal offset that minimizes travel times and/or fuel consumption (or emissions).

B. Method

1) Main steps of the method: Since the difference in cycle lengths of SIP is relatively small, we will assume that the individual timing plan changes (green durations) will be negligible when setting a common cycle (one among the two cycles), and we will focus on determining the optimal offset.

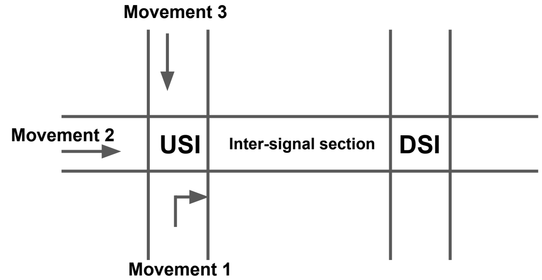


Fig. 1. Schematic signalized intersection pair.

The main idea is the following. For each vehicle that passed consecutively through both intersections in one particular direction, we store a data point containing:

(i) The crossing time of the first intersection (USI), denoted by t_{cross}, i.e. the time when the vehicle crossed the (estimated) stop-line.

(ii) The entering time into the second intersection (DSI), denoted by t_{enter}, i.e. the time when the vehicle joined the queue (or crossed if it did not stop) at the second intersection.

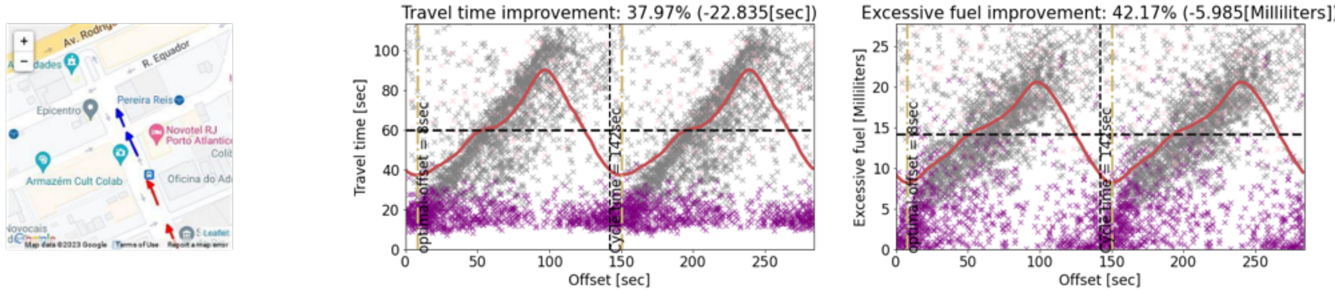
(iii) Various metrics we wish to optimize, such as travel time, fuel consumption, and whether it has stopped.

From the crossing and entering times of the vehicle, we are able to compute the offset. Given these data points, we can investigate our metrics as a function of the offset to find the optimal offset, predict its impact, and assess the sensitivity of our choice.

2) Fuel consumption estimation at signalized intersections using anonymized probe data: The actual trajectories of vehicles traveling through the intersections are extracted. Based on these trajectories, one can estimate the average travel times and fuel consumption. Estimating the average travel time is straightforward.

There are many software applications that can estimate fuel consumption or vehicle emissions in urban roads. Some of these software applications are based on microscopic and macroscopic traffic flow models, see e.g. [21]–[24]. In this paper, a proxy model of the National Renewable Energy Laboratory's Fast Simulation (NREL FASTsim) model [25] is utilized. The NREL FASTsim is a microscopic vehicle dynamic model that can be used to estimate fuel consumption from vehicle trajectories (speed values per time). This model and other like it have been well-established and calibrated for high accuracy.

3) Determining the offset: First, from the crossing and entering times of the vehicle (t_{cross} and t_{enter}), we are able to compute when each intersection plan has started, i.e. the crossing plan start at USI, denoted by t_1, and the entering



(a) (b)

Fig. 2. Offset effect SIP at Av. Pereira Reis in Rio de Janeiro. Purple “x” markers: vehicles traveling in free-flow conditions; grey “x” markers: vehicles that stopped once between the DSI and USI intersections; and pink “x” markers: vehicles that stopped more than once (i.e. experienced split failures). Red curve presents the moving average of the metric. Travel time and excessive fuel improvements are relative to the corresponding total average of the metrics (shown in the horizontal dashed lines).

plan start at DSI, denoted by t_2, as follows

$$t_1 = t_{\text{bps,USI}} + \lfloor \frac{t_{\text{cross}} - t_{\text{bps,USI}}}{c_{\text{USI}}} \rfloor \cdot c_{\text{USI}} \,, \tag{1}$$

$$t_2 = t_{\text{bps,DSI}} + \lfloor \frac{t_{\text{enter}} - t_{\text{bps,DSI}}}{c_{\text{DSI}}} \rfloor \cdot c_{\text{DSI}} \,, \tag{2}$$

where $t_{\text{bps,USI}}$ and $t_{\text{bps,DSI}}$ are respectively the base plan starts, i.e. the time when the traffic signal at USI and DSI start; c_{USI} and c_{DSI} are respectively the cycles of USI and DSI; and $\lfloor \, \rfloor$ is the floor operator.

Second, subtracting those times gives the “effective offset” which the vehicle experienced, which means that for first order approximation (neglecting the effect of the cycle change), if the offset of the signal plans was equal to the effective offset, this vehicle should have experienced the same “coordination timing”.

Third, for each sample, let t_1, t_2 be the relevant plan start times of SIP, and let c be the new cycle time that we want the new plans to operate with (in practice we take it to be one of the existing cycles). A naive guess offset corresponding to this sample is the remainder of $(t_2 - t_1)$ divided by c, i.e. $(t_2 - t_1) \mod c$. However, as the original plans are periodic the beginnings of the plans are arbitrary (this corresponds to which phase starts the plan), choosing a different point of time as the start of the plans may change t_1 to $t_1 \pm c_1$. As c should be close to c_1, this changes the offset by $c - c_1$ which should be small.

To counter this issue, we try all different plan beginnings and see if the optimal offset is stable. Thus, we will need that the dependence of the offset on our metrics will not be sensitive to changes of order $|c_1 - c_2|$.

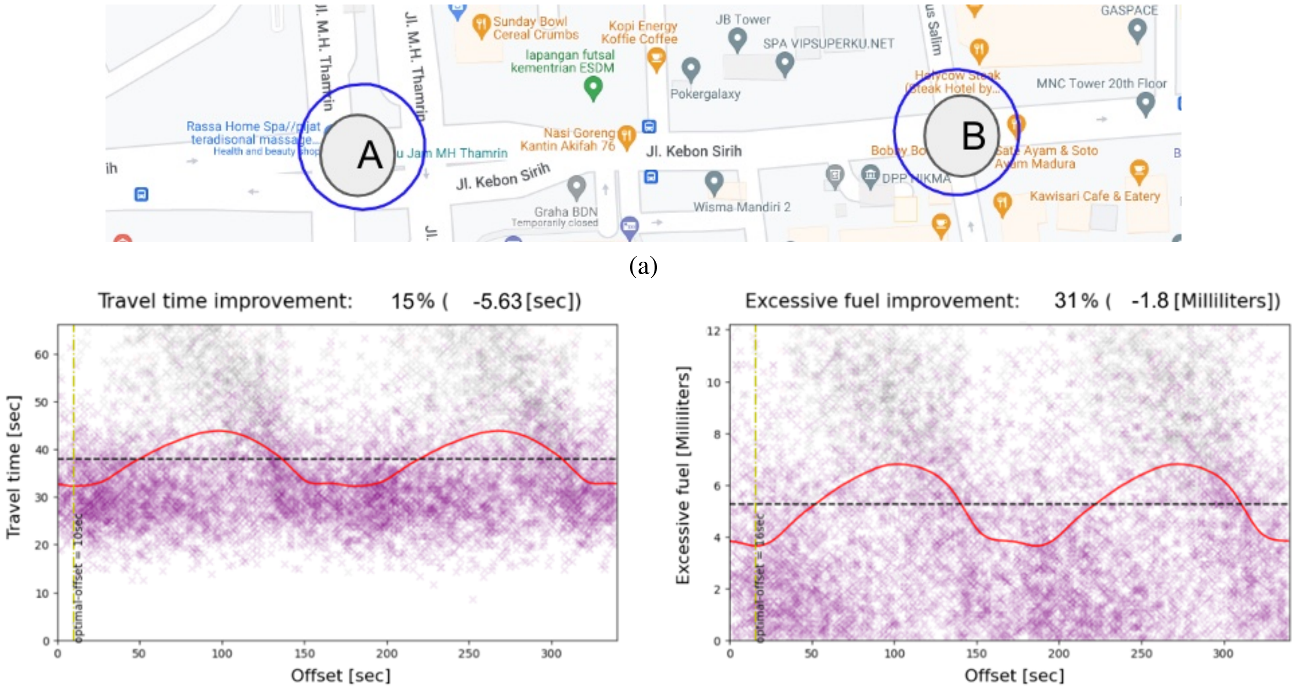
Furthermore, in practice, in many cases, the green starts of the major traffic with optimal coordination are close (as their difference is roughly the free-flow time which is usually smaller than the cycle time). In this case and when one of the cycles is equal to the new cycle, the offset “shift” will depend on whether the start of the plan will be between the two green starts, which will have a relatively small probability which makes our calculation even more stable to this ambiguity.

4) An example of the method’s output: Let us present from Rio de Janeiro an example of the method’s output for a real case study. We consider one movement (direction) in a SIP at Av. Pereira Reis, as shown in Fig. 2(a). The movement is shown in red arrows while passing the USI and blue arrows while passing the DSI. The results of the method are shown in Fig. 2(b), where

(i) We depict scatter plots of two metrics, travel time (left) and excessive fuel consumption[1] (right), as a function of the offset;
(ii) We replicate the data twice for two cycles, so it will be easier to visualize the results, the offset effect is periodic modulo the cycle time;
(iii) We color each data point according to the following color scheme: vehicles traveling in free-flow conditions are shown in purple “x” markers, vehicles that stopped once between the DSI and USI intersections (i.e. in the inter-signal section) are shown in grey “x” markers, and vehicles that stopped more than once (i.e. experienced split failures) are shown in pink “x” markers;
(iv) We plot a red curve that presents the moving average of the metric over a window of 10 seconds;
(v) We draw a horizontal dashed line to represent the total average of the metric; a vertical dashed line to represent the optimal offset, which minimizes the corresponding moving average; and a vertical dashed line to represent the common cycle time.

The results show that the travel time is almost constant for vehicles traveling in free-flow conditions, see the low scatter in purple “x” markers; while the travel time is linear as a function of the offset for stopping vehicles, as it includes the waiting time at the queue. On the other hand, the results show that the fuel consumption depends on the offset even for vehicles traveling in free-flow conditions, as queuing vehicles in the downstream might affect them, e.g. slowing down and then accelerating again. For stopping vehicles, the fuel consumption includes two terms: accelerating from fully stop conditions, and waiting in the queue.

[1]The additional fuel used in comparison to the fuel consumption during free-flow cruising conditions.



(a)

(b) (c)

Fig. 3. Case study 1 (Jakarta) – Offset effect on performance metrics: (a) SIP at Jl. Kebon Sirih road; and offset effect on (b) average travel times, and (c) excessive fuel. Purple "x" markers: vehicles traveling in free-flow conditions; grey "x" markers: vehicles that stopped once between the DSI and USI intersections; and pink "x" markers: vehicles that stopped more than once (i.e. experienced split failures). Red curve presents the moving average of the metric. Travel time and excessive fuel improvements are relative to the corresponding total average of the metrics (shown in the horizontal dashed lines).

III. Real case studies analysis

We have conducted several real-world case studies to investigate various issues related to SIP utilizing the new method: (i) offset effect on performance metrics, (ii) competition among movements, and (iii) distance between intersections.

A. Case study 1 – Offset effect on performance metrics

In this case study, we examine the effect of the offset on the performance metrics - average travel times and excessive fuel. A SIP at Jl. Kebon Sirih road in Jakarta is considered, see Fig. 3(a). The analyzed movement travels from intersection A to intersection B. The cycle time of intersection A is 166 $[\mathrm{sec}]$ and intersection B is 170 $[\mathrm{sec}]$. The distance between the intersections is approximately 200 $[\mathrm{m}]$.

The estimation results of average travel times and excessive fuel for the analyzed movement by the proposed method are shown in Fig. 3(b) and (c), respectively. The results are shown for two cycles, where the "x" markers in the figure present the results for individual vehicles, while the red curve is a moving average of the points. It can be observed that the average movement travel time and fuel consumption vary in a range of offsets. Choosing an appropriate offset may decrease the movement travel time and fuel consumption. For example, as shown in Fig. 3(b), by changing the offset from 100 to 10 $[\mathrm{sec}]$ the travel time of the movement decreases by 50%. Similarly, the fuel consumption of the analyzed movement decreases as the curves of the travel time and fuel consumption have same trend in this case study. It means that for offsets where the average travel time of a movement is high, the fuel consumption will be also high. Hence, the optimal offset is in range of 10 [sec] to 16 [sec], as all have similar minimum metric values. In the figure, the optimal offset of 10 [sec] is shown.

B. Case study 2 – Metric competition among movements

In case study 2, SIP at Av. Pereira Reis in Rio de Janeiro is considered. The results of average travel time and fuel consumption versus offset are shown for six movement pairs in Fig. 4, where in each row the movement pair appears in Fig. 4(a), shown in red arrows while passing the USI and blue arrows while passing the DSI. Recall, the average time and fuel consumption results in Fig. 4(b) are shown for two cycles, where the purple "x" markers present vehicles traveling in free-flow conditions, the grey "x" markers present stopping vehicles, the pink "x" markers present stopping vehicles with split failures; while the red curve presents a moving average of the metric.

Case study 2 demonstrates the effect of competing movements on the performance metrics. Different optimal offsets are gained for different movements. E.g., movement pairs 2 and 3 (same USI movement, but different destinations at DSI) share similar trends in both metrics, with similar optimal offset ($68-76$ [sec] for travel time, and $68-70$ [sec] for fuel consumption). While movements 2 and 4 (different origins at USI, but same destination at DSI) have

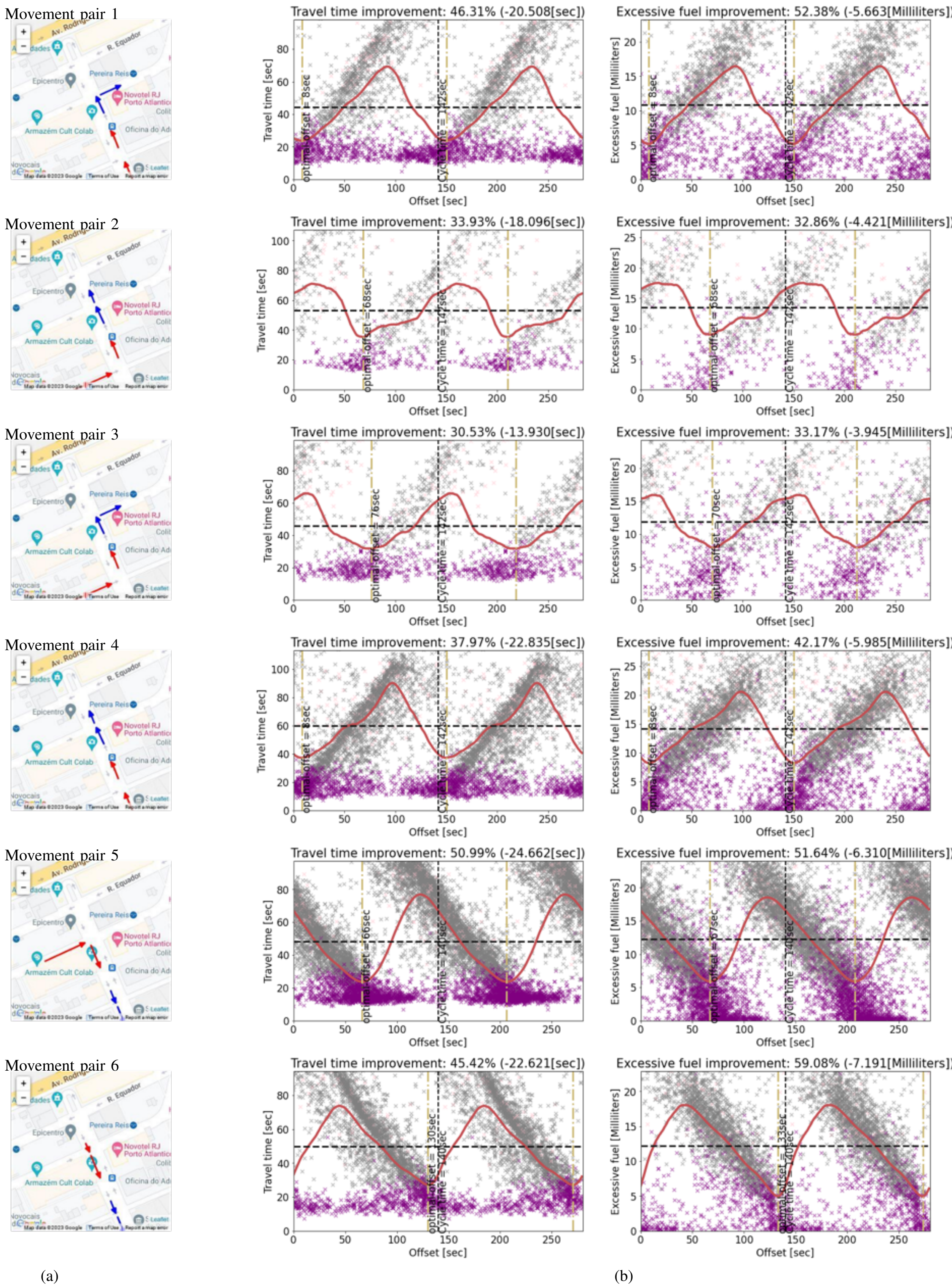


Fig. 4. Case study 2 (Rio de Janeiro) – Metric competition among movements: (a) movements and (b) offset effect at Av. Pereira Reis. Purple “x” markers: vehicles traveling in free-flow conditions; grey “x” markers: vehicles that stopped once between the DSI and USI intersections; and pink “x” markers: vehicles that stopped more than once (i.e. experienced split failures). Red curve presents the moving average of the metric. Travel time and excessive fuel improvements are relative to the corresponding total average of the metrics (shown in the horizontal dashed lines).

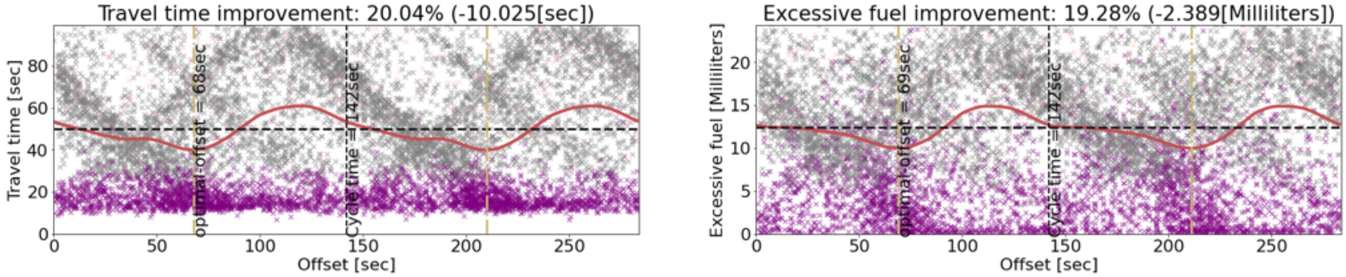


Fig. 5. Case study 2 (Rio de Janeiro) – Metric competition among movements: weighted (by flow) average travel time and excessive fuel for all six movement pairs.

reverse trends of metrics. It means that for offsets where the metric values of movement 2 are high the metric values of movement 4 are low, and vice versa. The optimal offset for movement 2 is 68 [sec], while for movement 4 the optimal offset is 8 [sec]. This shows the competition between the two upstream movements on the metric values.

Hence, one needs to determine the optimal offset that can maximize the weighted (by flow) average benefit for all six movement pairs. The results of weighted average travel times and fuel consumption are shown in Fig. 5. The optimal offset for both metrics is $68-69$ [sec].

C. Case study 3 – Inter-signal distance effect on movement metrics

Case study 3 examines how inter-signal distance affects movement metrics. In case study 1, the distance between the intersections was 200 [m], which is relatively small, guaranteeing interactions between intersections. In case study 3, three SIP with similar distance ($827-948$ [m]) are considered to examine the effect of relatively large distance, as shown in Fig. 6. The average travel time and fuel consumption results versus offset for three SIP in Haifa, Jakarta, and Rio de Jeneiro are respectively shown in Fig. 6(a), (b), and (c).

The results obtained from real data show that coordinating SIP with large inter-signal distance can still gain improvements and benefits in travel times and excessive fuel. Clearly, the level of improvements in traffic metrics varies among the different cases: minor improvements of 3.98% and 4.28% in travel times and excessive fuel (i.e. difference between minimum and maximum values) are obtained in Haifa, see Fig. 6(a), moderate improvements of 6.75% and 12.92% in travel times and excessive fuel are obtained in Jakarta, see Fig. 6(b), and significant improvements of 14.69% and 14.2% in travel times and excessive fuel are obtained in Rio de Jeneiro. Our results are in alignment with previous studies, including transport engineering guidelines. E.g., according to HCM, intersections which typically spaced within half mile (804.7 meters) of each other should be coordinated as they will benefit from coordination. Interactions spaced one mile or more may still benefit from coordination if there are flow-oriented interactions (coupling) between them.

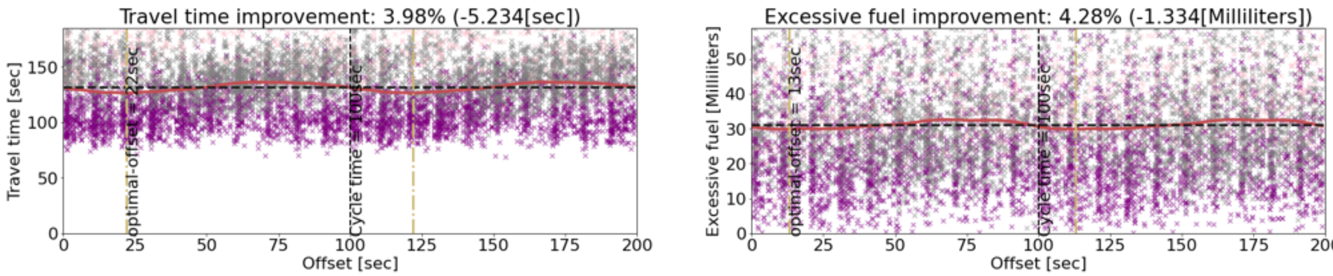
IV. Real Experimental Results

The proposed coordination method for SIP is examined by case study 1, as real implementation in Jakarta has been conducted in collaboration with the traffic control center by comparing before and after results. The city implemented the following change, recommended by the method presented in this paper. Between 9:00 to 14:30, the cycle times of both intersections (Jl. MH. Thamrin - Jl. Kebon Sirih) were set to 170 [sec] (i.e. intersection B was increased from 166 to 170). The relative offset was adjusted to a close value of the recommended offset. The predicted improvements in travel time and excessive fuel were 5.6 [sec] and 1.8 [mL], as shown in Fig. 3(b) and (c).

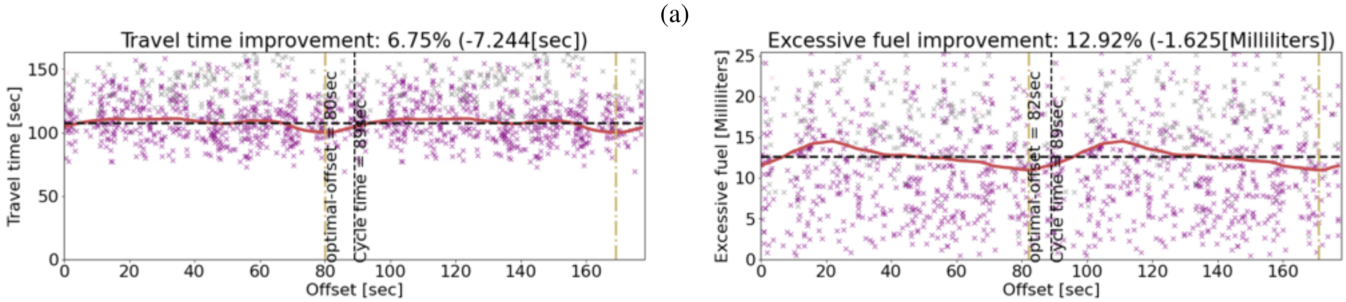
The recommendation was implemented on 29.3.2023. The analysis is based on $31,106$ total crossings (a single vehicle crossing a single intersection) of the affected movement along the corridor during the affected hours, on 11 days (2.8K crossings per day). We did not observe any meaningful change in demand between the compared periods. Average results of the coordinated movement are shown in Fig. 7. The average is per vehicle per intersection. The average travel time delay decreased by 34.8% from 14.6 seconds to 9.5 seconds, the fuel consumption decreased by 34.4% from 4.8 [mL] to 3.1 [mL], and the percentage of stops decreased by 65% from 24.6% to 8.6%. It should be stressed that the predicted improvements were 5.6 [sec] and 1.8 [mL], which are very similar to the obtained improvement values after implementation (5.1 [sec] and 1.7 [mL]). This highlights the accuracy of the method. This implemented coordination at Jakarta results in an expected yearly saving of $10,886$ engine hours, and 30 tons of CO2.

V. Conclusions and Future Work

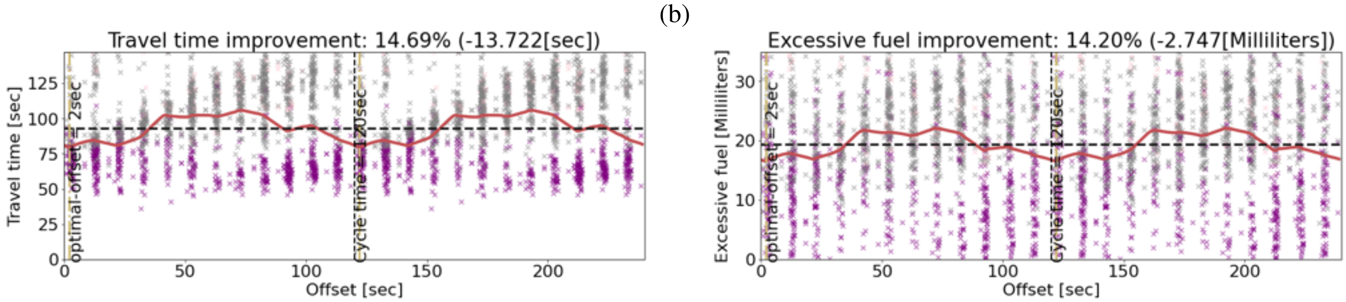
Signalized intersection pairs can have their own consideration regarding operational characteristics that are different from isolated intersections, e.g. SIP has a strong interaction between downstream queue and traffic flow discharging from upstream intersection. Hence, timing plans coordination between upstream and downstream interactions can increase the performances of SIP. However, choosing an appropriate value of offset is not a trivial task due to several issues. The current paper introduces a quantitative method which can determine the optimal offset without the need of explicit modeling of traffic-oriented issues such as queue spillback. The introduced method was tested and validated by real experimental results.



(a)



(b)



(c)

Fig. 6. Case study 3 (Haifa) – Inter-signal distance effect on movement metrics: (a) SIP at Hertzl St. with a distance of 945 meters between the intersections; (b) SIP at Jl. Pejompongan Raya in Jakarta with a distance of 948 meters between the intersections; and (c) SIP at Av. Mal Rondon in Rio de Janeiro with a distance of 827 meters between the intersections. Purple "x" markers: vehicles traveling in free-flow conditions; grey "x" markers: vehicles that stopped once between the DSI and USI intersections; and pink "x" markers: vehicles that stopped more than once (i.e. experienced split failures). Red curve presents the moving average of the metric. Travel time and excessive fuel improvements are relative to the corresponding total average of the metrics (shown in the horizontal dashed lines).

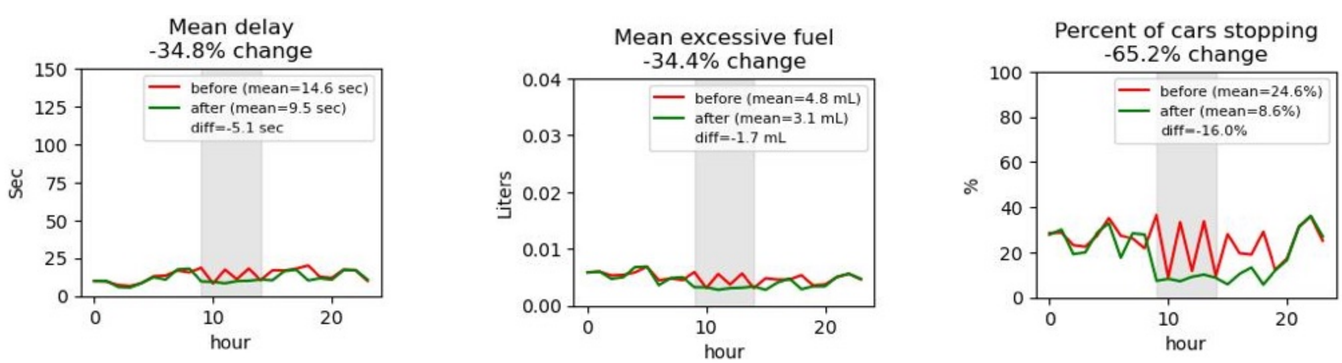


Fig. 7. Results and impacts of implemented coordination at Jakarta.

The importance of offset has been demonstrated through various analyses. The travel times and excessive fuel of USI movements vary significantly in relation to offset values. As the movements at USI compete among themselves for performance metrics, the offset values allocate the given metrics among the movements. For the same timing plans, travel times or excessive fuel of a movement may be largely decreased by simply changing the offset. A future research would be to utilize this method to study the optimal phase orders of coordinated intersections, as clearly some arrangements are better than others and minimize competition between movements. This can be carried out quantitatively.

In this paper, we followed a quantitative approach that considers the smallest system size of intersection pair. This approach can enable us to easily implement our solution method at scale. The new method enables studying and analyzing local properties of network intersection pairs, such as showing that under certain conditions coordination may still be effective across large distances or even when split failures are present.

Current research efforts are dedicated to implement the introduced method in this paper on arterials or networks, where we can overlap several SIPs among other to cover all the arterial or network. The potential benefits of coordinating many intersections at scale will be evaluated for different cities.

ACKNOWLEDGMENT

This research has been conducted in collaboration with four cities: Jakarta, Rio de Janeiro, Kolkata, and Haifa. We would like to thank:

- the Traffic Control System Management Unit of the Jakarta Provincial Transportation Agency for implementing our recommendation for traffic signal coordination, especially Syafrin Liputo, Emanuel Kristanto, Yayat Sudrajat, and Andi.
- the Traffic Management Control Center (TMCC) in Haifa, especially Anat Gilad and Sharona Kohn.
- the CET-RIO Traffic Engineering Company City of Rio de Janeiro for collaboration, especially Catia Nunes Poyares and Silvia D'Andrea Araujo.
- the Traffic Department in Kolkata, especially Shri Ramen Roy Chowdhery, Shri Debashis Ghosh, Shri Suman Basu, Shri Debayan Sarkar, Kaushik Pal, and Amit Das.

REFERENCES

[1] J. Haddad and D. Mahalel, "Offset effects on the capacity of paired signalised intersections during oversaturated conditions," *Transportmetrica A: Transport Science*, vol. 10, no. 8, pp. 740–758, 2014.

[2] J. Little, "The synchronization of traffic signals by mixed-integer linear programming," *Operations Research*, vol. 14, no. 4, pp. 568–594, 1966.

[3] J. D. C. Little, M. D. Kelson, and N. H. Gartner, "MAXBAND: A program for setting signals on arteries and triangular networks," *Transportation Research Record*, vol. 795, 1981.

[4] N. Gartner, "OPAC: A demand-responsive strategy for traffic signal control," *Transportation Research Record Journal of the Transportation Research Board*, vol. No. 906, pp. 75–81, 01 1983.

[5] C. Zhang, Y. Xie, N. H. Gartner, C. Stamatiadis, and T. Arsava, "Am-band: an asymmetrical multi-band model for arterial traffic signal coordination," *Transportation Research Part C: Emerging Technologies*, vol. 58, pp. 515–531, 2015.

[6] L. Zhang, Z. Song, X. Tang, and D. Wang, "Signal coordination models for long arterials and grid networks," *Transportation Research Part C: Emerging Technologies*, vol. 71, pp. 215–230, 2016.

[7] W. Ma, L. Zou, K. An, N. H. Gartner, and M. Wang, "A partition-enabled multi-mode band approach to arterial traffic signal optimization," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 1, pp. 313–322, 2018.

[8] H. Yan, F. He, X. Lin, J. Yu, M. Li, and Y. Wang, "Network-level multiband signal coordination scheme based on vehicle trajectory data," *Transportation Research Part C: Emerging Technologies*, vol. 107, pp. 266–286, 2019.

[9] J. Yao, C. Tan, and K. Tang, "An optimization model for arterial coordination control based on sampled vehicle trajectories: The stream model," *Transportation Research Part C: Emerging Technologies*, vol. 109, pp. 211–232, 2019.

[10] C. M. Day and D. M. Bullock, "Optimization of traffic signal offsets with high resolution event data," *Journal of Transportation Engineering, Part A: Systems*, vol. 146, no. 3, p. 04019076, 2020.

[11] S. L. Paulson, "Managing traffic flow through signal timing." *Public roads*, vol. 65, no. 4, pp. 6–9, 2002.

[12] K. Han, H. Liu, V. Gayah, T. Friesz, and T. Yao, "A robust optimization approach for dynamic traffic signal control with emission considerations," *Transportation Research Part C: Emerging Technologies*, vol. 70, pp. 3–26, 2016.

[13] S. Lin, B. De Schutter, Y. Xi, and H. Hellendoorn, "Integrated urban traffic control for the reduction of travel delays and emissions," *IEEE Transactions on Intelligent Transportation Systems*, vol. 14, no. 4, pp. 1609–1619, 2013.

[14] J. Lv and Y. Zhang, "Effect of signal coordination on traffic emission," *Transportation Research Part D: Transport and Environment*, vol. 17, no. 2, pp. 149–153, 2012.

[15] S. Zhou, H. Li, Q. Zhang, M. Gao, and B. Ran, "Traffic signal coordination control optimization considering vehicle emissions on urban arterial road," *Journal of Computational Methods in Sciences and Engineering*, vol. 21, no. 1, pp. 233–239, 2021.

[16] S. Alshayeb, A. Stevanovic, J. Stevanovic, and N. Dobrota, "Optimizing of traffic-signal timing based on the FCIC-PI — a surrogate measure for fuel consumption," *Future Transportation*, vol. 3, no. 2, pp. 663–683, 2023.

[17] L. Zheng, M. Feng, X. Yang, and X. Xue, "Stochastic simulation-based optimization method for arterial traffic signal coordination with equity and efficiency consideration," *IET Intelligent Transport Systems*, vol. 17, no. 2, pp. 373–385, 2023.

[18] K. M. Lum and C. Lee, "Actuated traffic signal control at diamond interchange," *Journal of Transportation Engineering*, vol. 118, no. 3, pp. 410–429, Jan/Feb 1992.

[19] N. Prosser and M. Dunne, "An analytical model for the estimation of capacities and delays of movements subject to blocking," in *Combined 18th ARRB Transport Research Conference and Transit New Zealand Land Transport Symposium*, vol. 7. Christchurch, New Zealand, September 1996, pp. 51–66.

[20] C. J. Messer, "Simulation studies of traffic operations at oversaturated, closely spaced signalized intersections," *Transportation Research Record*, vol. 1646, pp. 115–123, 1998.

[21] D. Gkatzoflias, C. Kouridis, L. Ntziachristos, and Z. Samaras, "COPERT 4: Computer programme to calculate emissions from road transport," *European Environment Agency*, 2007.

[22] H. Rakha, A. Kyoungha, and A. Trani, "Development of VT-micro model for estimating hot stabilized light duty vehicle and truck emissions," *Transportation Research Part D*, vol. 9, pp. 49–74, 2004.

[23] G. Scora and M. Barth, *Comprehensive Modal Emissions Model (CMEM), version 3.01, User's Guide*, Center for Environmental Research and Technology, University of California, Riverside, June 2006.

[24] D. Lejri, A. Can, N. Schiper, and L. Leclercq, "Accounting for traffic speed dynamics when calculating COPERT and PHEM pollutant emissions at the urban scale," *Transportation Research Part D: Transport and Environment*, vol. 63, pp. 588–603, 2018.

[25] A. Brooker, J. Gonder, L. Wang, E. Wood, S. Lopp, and L. Ramroth, "FASTSim: A model to estimate vehicle efficiency, cost and performance," SAE Technical Paper, Tech. Rep., 2015.