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A Bi-Objective Traffic Signal Optimization Model for Mixed Traffic Concerning Pedestrian Delays

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Abstract

Urban traffic networks suffer in numerous ways from traffic congestion. Some of these adverse effects are increased travel times of cars, buses, bicycle users, pedestrians etc., with the addition of excessive greenhouse gas emissions. Transportation engineers and policy makers try to improve the quality of urban transportation systems by developing projects to enhance the pedestrian experience, reduce private car usage, reduce total time spent in the network through different control strategies, and diminish the detrimental effects. In this context, this study takes Connected and Automated Vehicles (CAVs) and pedestrians into account at signal-controlled intersections. A novel intersection signal control optimization methodology that incorporates pedestrian delays and vehicular emissions from CAVs is presented. Non-dominated sorting genetic algorithm-II is utilized to solve the multiobjective optimization problem. For the emission calculations, the MOVES3 emission model is utilized. The proposed framework is tested on real-world case study. Simulation experiments showed major improvements in pedestrian delays and lower emissions.

1. Introduction

Properly managing signalized intersections in urban networks is essential to achieve less traffic congestion and air pollutants. There are numerous studies to try to optimize signal control settings (Papageorgiou et al. 2003). Although

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the optimization schemes may differ, the main objectives are the same for any traffic signal control problem: reducing excessive delays and minimizing vehicular emissions.

With the recent advances in communication and vehicle technology, the recent research trend on road traffic control concentrates on the performance of Connected and Automated Vehicles (CAVs) in mixed traffic flow conditions. In this context, traffic signal control approaches in the presence of CAVs are investigated in numerous publications (Guler et al. 2014; Chen and Englund, 2016; Yang et al. 2017; Rios-Torres and Malikopoulos, 2017; Xu et al. 2019; Zhou et al. 2020; Wu et al. 2021).

Although traffic signal control applications are used mainly for the regulation of conflicting vehicle movements, Central Business Districts (CBDs) also have high pedestrian demand. Conventionally, traffic signal control parameters are adjusted solely according to vehicular traffic characteristics and attributes. In traditional practice, satisfying minimum pedestrian green time in a signal control program is considered enough. Since these objectives (minimizing vehicular and pedestrian delay) contradict each other, a trade-off exists between them. We investigated the vehicle and pedestrian movement in CBDs in our previous works (Akyol et al. 2019; Silgu et al. 2019; Akyol et al. 2020; Akyol, 2021). Even though these studies investigate vehicle and pedestrian movement in conjunction, computationally efficient optimization algorithms and environmental effects of transportation, vehicular emissions are only exploited partially.

This work aims to address the trade-off between pedestrian delays and vehicular emissions and provide a thorough illustration. The novel contribution of this presented study is three-fold: i) proposing an optimization scheme for signalized intersections where instead of vehicular delays, the pedestrian delays and vehicular emissions are sought to be minimized, which, to the best of the authors' knowledge, is a first in this regard, ii) discuss the potential implications of prioritizing pedestrian delays and vehicular emissions instead of vehicular delays only, and iii) provide a detailed analysis of the trade-off between vehicular emissions and pedestrian delays through a real-world case study and extending it with CAVs.

2. Methodology

2.1. Problem Formulation

The problem at hand has two conflicting objectives. Pedestrian delay at signalized intersections is selected as the first and the second objective is vehicular emissions at signalized intersections. Red signal duration for pedestrians is proportional to the first objective and red signal duration for vehicles is proportional to the latter. A trade-off is needed to make in this situation since these two objectives are conflicting.

The formulation of the bi-objective optimization problem is given below.

$$\min \quad \{f_1(g_p), f_2(g_v)\} \tag{1}$$

$$\text{s.t} \quad g_{p,\min} \leq g_p \tag{2}$$

$$g_{v,\min} \leq g_v \tag{3}$$

$$C_{\min} \leq C \leq C_{\max} \tag{4}$$

$$\sum_{i=1}^{n} g_i + L_i = C \tag{5}$$

The objective function in Eq. (1) consists of two terms: $f_1(g_p)$ aims to minimize pedestrian delay, and the second term, $f_2(g_v)$, aims to minimize the total number of stops in one signal cycle. The first constraint in Eq. (2) assures that the green time for pedestrians is higher than or equal to the minimum pedestrian green time. As in Eq. (2), Eq. (3) assures that the green time allocated for vehicles must be greater than or equal to minimum vehicle green time. By the constraint in Eq. (4), boundaries of cycle length durations are given. In Eq. (5), components of one signal cycle are given. $g_{p,min}$ represents the minimum pedestrian green time, $g_{v,min}$ represents the minimum vehicle green time, the minimum cycle length is denoted by C_{min}, C_{max} denotes the maximum cycle length and L_i is the lost time occurs at each phase i. Decision variables are chosen as g_p and g_v. g_p stands for pedestrian green time and g_v represents vehicle green time. In our methodology, minimum pedestrian green time is determined as 24 seconds, minimum green time for vehicles is selected as 40 seconds, minimum cycle length is selected as 84 seconds and maximum cycle length is selected as 160 seconds.

The first objective function includes pedestrian delay at signalized intersections is adopted from Highway Capacity Manual (TRB, 2010) and is given in Eq. (6).

$$f_1(g_p) = q_p * \frac{(C - g_p)^2}{2C} \tag{6}$$

In Eq. (6), q_p stands for pedestrian volume in one cycle and other parameters are defined previously. For the second objective function which is represented in Eq. (7), Akcelik's (1981) number of stops function is utilized. In Eq. (7), s_i represents saturation flow rate, q_v is the mean arrival rate of vehicles and λ_i is the green time ratio of phase i.

$$f_2(g_v) = \sum_{i=1}^{n} \frac{q_v(1-\lambda_i) * (\sum_{i=1}^{n} g_i + L_i)}{(\sum_{i=1}^{n} g_i + L_i) * (1 - \frac{q_v}{s_i})} \tag{7}$$

Under uniform vehicle arrivals, if pedestrian green time (g_p) is increased, the pedestrian delay would be decreased at the expense of increasing the total number of stops. Therefore, a trade-off exists between these two objectives and our goal is to illustrate the trade-off. In the subsequent sections, we show the non-dominated solutions to the problem by using a non-dominated sorting genetic algorithm (NSGA-II) (Deb et al. 2002).

2.2. Modeling Framework

We present the utilized framework for modeling vehicular and pedestrian traffic and the employed emission model. In addition, integration between emission models and traffic simulation environment is given.

PTV Vissim (PTV, 2020) microsimulation software simulates CAVs, human-driven vehicles, and pedestrians. With their recent project, CoExist (Olstam et al. 2020), Vissim enables us to model CAVs. Three different driving behaviors are defined for CAVs in Vissim: i) cautious, ii) normal, and iii) aggressive. Olstam et al. (2020) suggested that cautious AV driving behavior is selected since our case study area is an arterial road. For human-driven vehicles, Wiedemann's car following model for urban traffic is chosen (Wiedemann, 1974). The pedestrian simulation model adopts the Social Force Model, first proposed by Helbing and Molnar (1995). Vissim has a built-in Component Object Model (COM) feature to access and change many utilities. COM interface enables us to dynamically alter the capabilities of Vissim and integrate various signal control programs. Moreover, we can interfere with vehicle routes, trajectories of vehicles, and pedestrians. COM interface is also used for Vissim-MATLAB connection. Therefore, optimization can be done in MATLAB and solutions can be implemented in Vissim.

We utilized MOVES3 (USEPA, 2020) emission model to estimate vehicular emissions, a state-of-the-art emission estimation tool with an open-source code. There are three different scales defined in MOVES3 to model emissions: i) national, ii) county, iii) project. We used the project (microscopic) scale to estimate emissions since we have the second-by-second speed and acceleration data of all vehicles in the network by the Vissim-COM interface.

A general architecture of proposed framework is presented in Fig. 1. In this context; we utilized MATLAB for two main objectives: i) optimization of signal control settings, and ii) interfering with the Vissim through COM interface.

Furthermore, since we have conflicting objectives in our objective function, more than one solution is obtained after the optimization process. Using the COM interface, we can obtain the number of vehicles and pedestrians on certain links in our network and adapt the signal control program accordingly through our dynamic structure. This feedback loop is repeated every 10 minutes, and after the simulation experiments are completed, vehicle trajectories are obtained from Vissim and fed into the MOVES3 emission tool. In addition, to reflect the stochastic nature of traffic demand, simulation experiments are repeated 10 times with varying random seeds.

2.3. Solution Methodology

An evolutionary algorithm NSGA-II (Deb et al. 2002) is adopted for our solution method. The Pareto optimal solutions are initially obtained using the NSGA-II algorithm, and results are fed into the signal control program. Although the solutions obtained from evolutionary algorithms are near-optimal compared to classical methods, the proposed approach provides less computational time, and most importantly, using evolutionary algorithms enables us to use unbiased weights.
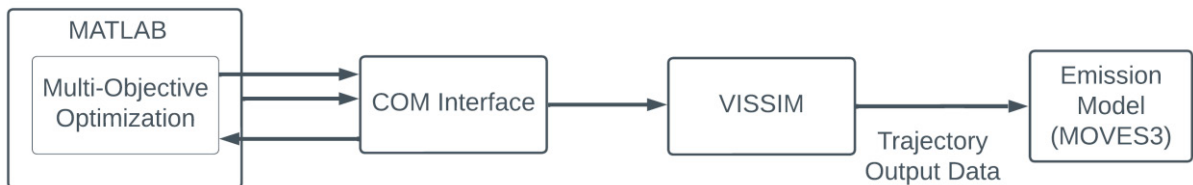
Fig. 1. Proposed framework.

Values of selected parameters for NSGA-II are given below. The number of generations is limited to 200. The crossover rate is chosen as 0.5. The mutation probability is selected as 0.03. The convergence threshold is set to 0.001. These parameters are chosen because of their common usage in literature (Yang and Benekohal, 2011; Stevanovic et al., 2007; Stevanovic et al., 2009; Yun and Park, 2012).

3. Case Study

3.1. Calibration of Simulation Model

Calibration of a simulation model is needed before the simulation experiments are performed. The aim of the calibration is to minimize the difference between the reality and the simulation model. GEH statistic (Daamen et al. 2014) is selected as the measure considered for calibration and given in Eq. (8).

$$GEH = \sqrt{\frac{2(y-x)^2}{y+x}} \qquad (8)$$

In Eq. (8), x and y represent the traffic flow obtained from the data collected in the field and the traffic flow produced from the simulation model, respectively. The field measurements consist of camera footage from two high-rise buildings, which we have utilized to extract pedestrian and vehicular flows between 12:00-14:00 and 17:30-19:30. Traffic flow data from two signalized intersections are obtained. For each intersection, vehicle counts generated from the simulation model are compared with the observed vehicle counts from the field survey for 2-min intervals. Next, the GEH statistic is calculated for the interested intersections. The differences between the observed vehicle counts and simulated flows are presented in Fig. 2.
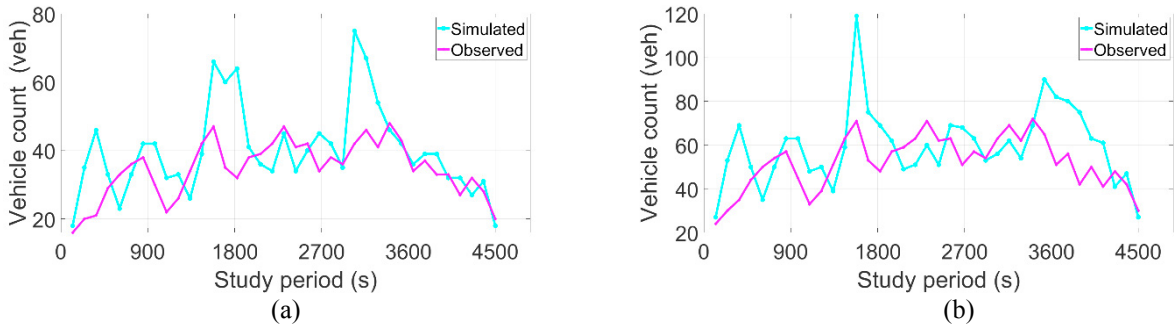
Fig. 2. Observed and simulated traffic flow profile through calibration at (a) City Center Intersection; (b) Ferry Intersection.

Fig. 3 shows the temporal variations of GEH statistics at two intersections that we are interested in. As can be seen from Fig. 3, calculated GEH values for each intersection are lower than the predefined value, approximately over 90% of the time.
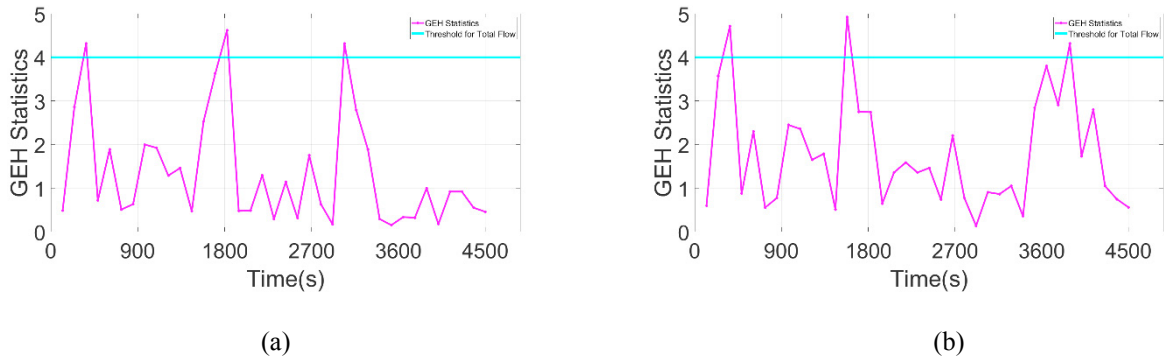

Fig. 3. Variation of GEH statistics obtained through calibration at (a) City Center Intersection; (b) Ferry Intersection.

3.2. Real-word Case Study

We have selected the Kadikoy district of Istanbul for the real-world case study. Kadikoy was chosen because it is one of the Central Business Districts in the polycentric form of the city. Citizens can use private cars, buses, minibuses, metrobus (bus rapid transit), metro and ferry from several locations in addition to walking and cycling to reach the case study area. Vehicles using the ferry intersection come from either the state road D-100 freeway -one of the most densely used urban freeways connecting Europe and Asia- or the arterial roads (Demiral and Celikoglu, 2011; Celikoglu and Silgu, 2016). City center intersection enables vehicles to access to D-100 freeway or residential areas within the Asian side of the city. Kadikoy also accommodates a historical tram line that travels from the inner parts of Kadikoy to the coastline.

The case study area is illustrated in Fig. 4. Red polygons represent the pedestrians' free walking space. Yellow arrows show the location of ferry stations. The light blue polyline represents the historical tram line. The two-headed green arrow indicates the traffic lights and crosswalks interested in this study. The northern bound of green arrow is the crosswalk closer to the central area of Kadikoy. The intersection at the northern end of the green arrow is referred to as ferry intersection while the southern bound of the green arrow is referred to as city center intersection. Ferry and city center intersections have identical signal control parameters and consist of four phases. The first phase is 75 seconds green signal for vehicles where pedestrians wait at the red phase. The second phase is 10 seconds all-red for

all traffic units. The third phase is 15 seconds green signal for pedestrians and last phase is 10 seconds of all-red for all traffic units. The cycle length is, therefore, 110 seconds.

Fig. 4. Case study area.

3.3. Scenarios

We designed two main scenarios for our real-world case study. First, vehicle flows are changed from low, medium and high. High vehicular flow (3000 vehicles per hour (vph)) is the base case scenario that is observed in the field survey. As the second main scenario, the prioritization of traffic units (vehicles and pedestrians) is implemented by changing signal control dynamically via the COM interface. The second scenario has three sub-scenarios i) pedestrian priority signal control, ii) balanced, and iii) vehicle priority signal control. For each sub-scenario, priorities are given by changing the split and cycle durations of each intersection in consideration. Pareto optimal solutions are found without giving any weight to the objective functions. The traffic flow composition is 100% of CAVs.

Table I shows the scenario properties explained above. Pedestrian volume is kept at the same level in all scenarios to investigate the effects of vehicle flow on intersection performance.

Table 1. Scenario properties.

Vph	Priority		
	Pedestrian Priority	Balanced	Vehicle Priority
High (3000 vph)	Pedestrian-High	Balanced-High	Vehicle-High
Medium (2000 vph)	Pedestrian-Medium	Balanced-Medium	Vehicle-Medium
Low (1000 vph)	Pedestrian-Low	Balanced-Low	Vehicle-Low

3.4. Results and Discussion

As we have explained in our methodology, we have two conflicting objectives, and a trade-off needs to be between them. Through the NSGA-II algorithm, we have obtained the Pareto optimal solutions for our cases. One of the assumptions of this study is that our optimization problem uses number of stops by vehicles as the objective function and number of stops is used as a proxy for vehicular emissions (Coelho et al., 2006).

In base case scenario, the cycle length is fixed at 110 seconds. Selected green signal durations after the optimization are tabulated in Table II. We chose the interval of split durations as narrow as possible to avert the negative impacts of significant changes in signal control parameters. Adaptive signal control algorithms e.g., SCOOT and SCATS perform in an analogous way while determining split duration changes after optimization.

The summary of results for our real-world case study is given in Fig. 5. For the low vph scenario, if the changes in signal control settings prioritize pedestrians, a 54.27% improvement can be achieved compared to the base case. On the other hand, vehicular emissions increased by 102%. In the balanced case, the pedestrian delay is reduced by

46.12%, while vehicular emissions increased by 127.35%. In the vehicle priority sub-scenario, the pedestrian delay is reduced by 12.78% as vehicular emissions are reduced by 9.81%.

For the medium vph scenario, pedestrian delay is decreased by 49.12% in the pedestrian priority sub-scenario while vehicular emissions are worsened by 82.12%. In the balanced sub-scenario, pedestrian delay is improved by 42.45% as vehicular emissions increased by 72.37%. In the vehicle priority sub-scenario, pedestrian delay is improved by 8.24% and emissions are reduced by 5.14%.

For the high vph scenario, pedestrian delay is improved by 52.71% compared to the base case and vehicular emissions are increased by 105.57%. In the balanced sub-scenario, a 39.25% improvement in the pedestrian delay is observed while emissions are increased by 102.65%. In vehicle priority sub-scenario, pedestrian delay is improved by 12.40% and emissions are increased by 82.51%.

Table II. Green signal duration for the real-world case study.

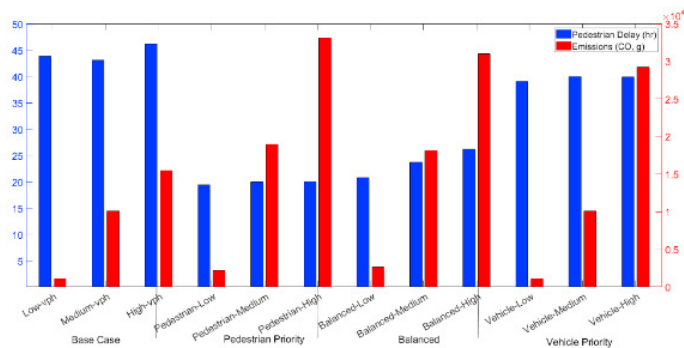| Scenario	Sub-Scenario	Vehicle Split(sec)	Pedestrian Split(sec)	All-Red(sec)	Cycle Length(sec)
Pedestrian Priority	High	50 - 55	55 - 70	10	125 - 145
	Medium	50 - 62	65 - 77	10	135 - 159
	Low	45 - 55	75 - 85	10	140 - 160
Balanced	High	50 - 55	45 - 50	10	115 - 125
	Medium	45 - 50	45 - 50	10	110 - 120
	Low	40 - 45	45 - 50	10	105 - 115
Vehicle Priority	High	80 -87	30 - 35	10	130 - 142
	Medium	75 - 80	30 - 35	10	125 - 135
	Low	70 - 75	35 - 45	10	125 - 140

Figure 5. Summary of results for our case study.

4. Conclusions

In this study, an integrated methodology for optimizing traffic signal control considering pedestrian delay and vehicular emissions is developed. VISSIM is selected for microscopic traffic simulator, NSGA-II is adopted to solve

multiobjective optimization problem and lastly, MOVES3 is selected to calculate vehicular emissions on the microscopic scale. In addition, a case study was conducted at Kadikoy, Istanbul to evaluate the proposed approach. Two main scenarios are developed to test the method in varying demand and different prioritization of traffic units. Results show that the proposed approach can reduce the pedestrian delay up to 57.28%. Emissions are reduced up to 6.04% compared to the base case. It can be derived from the results that pedestrian delay is improved in all scenarios while vehicular emissions fluctuate.

The method proposed in this paper does not optimize a single objective or a compound single objective which is produced by weighting the objectives. Despite this, a multiobjective problem is used. It means that after multiobjective optimization, multiple solutions were acquired instead of one. The weights or prioritization is used after the optimization, enabling perception of the problem handled.

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