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RESEARCH ARTICLE

New Approach for Estimating Intersection Control Delay From Passive Traffic Sensors at Network Level

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ABSTRACT In junction traffic operations, vehicle delay is one of the most essential performance measures of effectiveness. It allows traffic engineers to assess the performance of a traffic system component or the efficacy of a system-wide control plan. Real-time applications such as adaptive signal control, congestion management, and dynamic traffic assignment often use this technology. Obtaining real-time data on intersection performance, such as control delay, may be time-consuming and labor-intensive. This study presents a new approach for estimating network-level real-time delay from passive traffic counting. Total Travel Delay Estimation Technique (TTD) is proposed for signalized intersection delays that can be computed by examining real-time data from arrival and departure detectors upstream and downstream of a junction. The proposed estimation method mathematically manipulated equations that relate the input-output model and vehicle O–D data acquired from the Automatic Turning Movement Identification System (ATMIS). The developed methods utilize the obtained real-time traffic detection system as input data. The proposed methods are applied for three cases: simple, semi-generalized, and generalized networks, where any of them can be used as a building TTD estimation block for the whole actual network. Results from the TTD were compared to VISSIM output, and a statistical test was conducted under varying traffic conditions (low, medium, high, and saturated). The findings show that the proposed methodology can yield stable and reliable results in various traffic volumes and turning movement conditions. Future field implementation studies for the suggested methods are recommended to evaluate the model's reliability and efficacy in real-time traffic scenarios.

INDEX TERMS Delay estimation, signalized intersections, traffic counting, traffic simulation, Vissim.

I. INTRODUCTION

Increasing congestion on transportation networks has increased irritation for network users, particularly at major city crossroads where delays and poor service levels are regularly encountered. Unfortunately, this issue seems to be settled by adding new roads or making extra capacity, specifically which is needed in areas with an interface between the arterial streets and the freeways. It has been established that traffic congestion is impacting billions of individuals around the globe, specifically in the form of economic losses, elevated commuting times, and deteriorated ecological conditions. Among others, interrupting traffic flow facilities or arterial streets are found to be under a massive influence on traffic congestion problems. This indicates that traffic signals or traffic-controlling devices are the major contributors to this problem. Therefore, in light of a traffic engineering perspective, it is vital to reduce or control the delays that result from the traffic signals at the transportation network level [1].

Intersections of traffic might be regarded as the most intricate element of a transportation network. In a junction

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operation, cars traveling in opposing directions simultaneously seek to occupy the same place. At every junction, users are expected to make quick judgments based on the route, geometry, operation speed, and movement of other cars. Misjudgments may result in both delays and serious accidents. A transportation network is total efficacy mainly depends on the quality of its junctions. Typically, performance is quantified in terms of latency, which is an essential feature of intersection analysis [2], [3].

This indicates that delay measurement could help in solving the problem. However, several parameters are required to be considered for measuring the delays, like departure and arrival of specific automobiles, saturation flow rates, signal cycle, intersection types, traffic volume, intersection grade, vehicle composition, the queue length of traffic, and traffic control system. Some of the other factors that result in delays are non-stopped movement during the green time, stop and queue movement during the red time, and over-saturation flow of pedestrians or traffic [4].

The two most popular approaches to solving crossings are grade separation and at-grade solutions. The grade separation is regarded as the most significant approach since it eliminates all traffic conflicts and creates the fewest delays. Due to the high initial cost of this solution, it is not usually recommended as the first choice. An at-grade solution is the typical approach to solutions for network intersections. It can be divided into three categories: uncontrolled, sign-controlled, and signal-controlled (e.g., traffic light). However, the examination of signalized junctions has garnered a great deal of attention in the literature [5], [6], [7].

Although signalized junctions may be regarded as the most efficient and adaptable active traffic management owing to their advantages in arranging traffic flow and boosting capacity, the number of roundabouts in large cities has expanded dramatically over the last decade [8]. Unlike the signal control solution, they need no post-installation changes. However, signalized intersections are constantly proposed as a remedy or alternative to current roundabouts because of the belief that they reduce delays significantly at high traffic volumes [1]. However, they cause severe delays by cars waiting behind the stop line while the red signal is illuminated. The vehicle delay may indicate not only the severity of traffic flow obstruction, fuel consumption, and travel time loss but also the logic of the channelization design and signal timing plan. It has been selected as the most essential assessment indicator for defining the degree of service at the junction over a considerable amount of time [9].

Real-time road traffic parameter collection and accurate road congestion assessment are necessary for enhancing the effectiveness of traffic congestion avoidance solutions [10], [11]. The conventional traffic parameter detectors, such as the loop detector [12], [13], [14], the microwave detector [15], [16], and the magnetic detector [7], can only get the vehicle throughput, speed, and occupancy information in the location where the detectors are located, i.e., the transect detecting. These measurements obtained along a particular transect are unable to characterize the traffic condition of an entire road segment or junction. In addition, these parameters are only accessible when their data are gathered every 5 minutes, 30 minutes, or one hour, resulting in inadequate real-time estimations. Traditional traffic parameter collecting techniques have deficiencies in accuracy, real-time, and comprehensiveness, which have become the "bottleneck" for future applications, such as improving traffic signal management and road navigation [17].

Based on the above information, the main objectives of this research are to develop a system that can collect real-time traffic information such as turning movement, arrivals, and departures data. Later on, it involves their processing to estimate performance measures in traffic networks in urban areas. The primary objective of the proposed method is to make real-time calculations for measuring the effectiveness of the vehicle, specifically through "travel time and average delay". The system is prepared to collect traffic data, including turning movements and arrival and departure rates through detection systems. The structure of the remainder of this article is as follows. The next section gives a background of intersections delay analysis to draw the state of the art and highlight the potential contributions. Section III shows the related concepts to the problem statement. Section IV provides some details of the tools used and input data for the solution method. Section V outlines the mathematical techniques in the TTD solution framework. Section VI uses three case studies of different sizes to validate the research approach. The conclusion is drawn in the final section.

II. LITERATURE REVIEW

The highway capacity manual (HCM) has regarded traveling delays as the additional time that a pedestrian, passenger, or driver requires to travel. In other words, it can be affirmed that the delay is different between the actual traveling time and the estimated or ideal traveling. However, it is essential to note that it is difficult to directly measure the delay in the field since its measurement is based on hypothetical definitions. The delay in the transportation network could occur by the presence of intersections, hindrances, road bumps, speed breakers, crossing pedestrians, etc. These elements cause additional braking and deceleration, eventually consuming more time and leading to a considerable difference between estimated locations' arrival and actual arrival times. Since the ideal time period of traveling is regarded to be the off-peak travel time, measured delay can be termed as the difference between the actual measured travel time during off-peak hours and the actual measured travel time during the peak hours. In order to understand signalized intersection delay (SID), different delay components have to be understood to deal with its estimation method [18]. The formal definition and SID's components are listed in the subsequent section.

Conventionally, the primary approaches for estimating SID may be categorized into field study, analytical, and simulation methods [2]. The field inquiry approach gathers the traffic delay using fake statistics based on car license plate data, floating data, or video data gathered from the road field by human surveys or other devices, including onboard Global Positioning System (GPS) and traffic monitoring video equipment. In practical use, this sort of approach is with tremendous effort and poor efficiency. Although it is simple to execute in the field, employing this method for vehicle monitoring in circumstances with many lanes and heavy traffic flow is challenging. In addition, since sampling is the sole approach employed, the traffic delay cannot be gathered continually and automatically [19]. In the theoretical analytical techniques, academics have presented models derived from the deterministic queuing theory or the vehicle dynamic theory, such as the Miller Model [20], the Webster Model [21], and the HCM2000 Model [22]. In these models, the traffic delay is determined using mathematical modeling based on the characteristics of vehicles coming and departing. As inputs, the models get the fundamental parameters and signal timing plan for intersections, and the algorithm mechanism generally adheres to the deterministic queueing theory or the vehicle dynamic theory [23], [24]. Since the dependent fundamental parameters are readily obtainable and the delay value is calculable in a sustainable manner, the theoretical analytical technique has been a prominent study path in recent years, with several accomplishments. These models get the traffic delay value from the fundamental traffic metrics gathered by conventional detectors. The derivation findings are often erroneous because of the limited precision, low real-time, and comprehensiveness of the obtained fundamental data. The simulation technique uses microscopic traffic simulation tools such as VISSM and SimTraffic to construct junction simulation models and extract traffic characteristics. To a certain degree, traffic simulation models depart from the actual road situation, and some random traffic flow changes cannot be precisely represented. The obtained parameters are offline and unable to support real-time traffic applications [2], [25].

In a simple procedure, SID can be calculated by estimating the time difference between the green phase's start and arrival during the red phase. When it is in a red phase, then it must wait the rest of the red time to cross the intersection. However, if the car arrives during the green phase, the waiting time will be zero, assuming there is no queue when the vehicle arrives. This estimation method is based on the assumption of infinite intersection capacity. With this assumption, the proposed model can provide a reasonable estimate of signal delay - only under low traffic volumes. Furthermore, if traffic demand for the intersection approach is close to or at oversaturated conditions, then there is a high chance of an existing long queue at the beginning of the red phase. More accurately, SID can be measured in the field using three timestamps: the arrival time of vehicles to a point located upstream of the approach, beyond the point where a queue could typically form; the timestamp when the vehicle crosses the stop bar; and the timestamp at the start or end of the green phase of the signal [19]. This strategy is easier to perform accurately in the field than sampling procedures, which need more complicated data collection and processing. However, it cannot assess junction delays since the turning motions of cars entering and exiting the intersection are not recorded. Alternatively, extra detectors could be placed to cover each lane individually. Thus, the approach delay for each set of lanes may be determined. This method cannot be used to quantify junction control delay since it did not detect vehicle turning motions [26].

The most recent developments in detection and communication technology have significantly improved the capacity to gather real-time traffic data [27], [28]. This data helps intelligent transportation system (ITS) applications in traffic signal control and enables traffic engineers at traffic management centers (TMCs) to react proactively to traffic condition changes to reduce traffic congestion and boost throughput. For example, GPS data is used to capture the speed and position of sampled cars every second. However, the tiny sample size (as few vehicles were equipped with GPS devices) prevented significant data gathering [29]. SID is also estimated using video detection, and a delay estimate for all four approaches and lane groups at a junction was performed. This technique only permits the computation of approach delay, and it was reported to produce more precise and less biased delay estimates than HCM2010 [30]. In [31], an automated system was created for estimating traffic delays at an intersection in real-time. However, the delay prediction was restricted to through lanes, and this research did not address shared lanes. Another technique was introduced in [19] for real-time estimation of delay at a signalized intersection involving an estimated arrival rate procedure. One of the most significant advantages of this technique resides in its ability to self-adjust for arrival rate estimates, especially once the spillback occurs (when the queue is not visible). The method for arrival rate adjustment was built on using a power function to estimate the actual arrival rate. Besides, this method can estimate delay on each second. On the other hand, the disadvantage of this method lies in the lack of a stable theoretical relationship between the departure rate and the real arrival rate. Therefore, a huge error is expected, to the extent that the delay estimation is not realistic.

Recently, traffic simulation has been the preferred method for assessing traffic problems, such as modeling speed limits for highways [32], [33], examining ramp meter techniques [34], and analyzing the impacts of vehicle behavior on a traffic control facility [35]. In addition, modeling techniques are enhanced to estimate the movement of people [36] and even the anticipated traffic emissions [37], [38]. All areas of modeling pertinent to intersection operation, such as delays, queue length, capacity estimations, and other vital information, have been studied for intersections. Typically, calibration efforts are concentrated on producing findings that depart slightly from reality. The simulation tools provide validity in a broad context [36]. In [2], the "Antalya Muratpaşa Sampi" junctions were investigated at three different places using the microscale traffic simulation program VISSIM. The data was acquired via a camera over the course of five workdays at two intervals every day. The software evaluated the intersection's performance in terms of service class, latency, and saturation level. On the other hand, in [19], the simulation that relies on microscopic simulation through VISSIM was adapted to replicate real-time studies in attempted improvements for actual work on the roads. AVDET (Automated Vehicle Delay Estimation Technique) simulations are implemented in three dummy intersections. The only failure in the system analysis was the lack of consideration of the time lost as vehicles slowed down in intersections and queues. The proposed AVDET simultaneously collects information, stores data, and performs system analysis, and it best applies at a single intersection. Detectors are applied upstream and in the stop lines to determine the needed data, such as arrivals, departures and delays. The rationale for proposing this system is high adaptability to different isolated intersection geometric layouts.

In a variety of transportation applications, Machine Learning (ML) and Computer Vision (CV) have shown outstanding performance in traffic congestion [39], traffic flow prediction [40], incident detection [41], transportation network reliability analysis [42], [43], and pavement crack detection [44], [45], [46]. ML and CV techniques used image and video processing to estimate the vehicle delay. They intelligently tracked the input-output flows to predict the delay and maximum queue length at the signalized intersection. The difference between the departure and arrival profiles can help in estimating the total delay [47], [48], [49]. However, the method is not effective because of the limited processing power that restricts vehicle tracking at two strips only – i.e., one at the departure points and another at the arrival point. Besides that, the method is intolerant to the detection errors and assumes that no change in lane would be made. These unrealistic assumptions and processing limitations require more research to enhance this approach.

Other techniques have been explored for real-time delay estimation and integration with the online traffic signal control scheme. In [50], a designed optimization module has been complementarily introduced to the existing controller to minimize total traffic delay and improve the system performance at signalized intersections. The proposed algorithm optimizes the signal timing plan based on the estimated delay through vehicle reidentification technology. The system can estimate delay in real-time and utilize it directly for optimization purposes. The SID was estimated according to the vehicle reidentification technique, and an algorithm was used to match each vehicle's waveform obtained from advanced detectors. In reality, the proposed technique, specifically for vehicle delay estimation at the signalized intersections, is inaccurate because the algorithm for vehicle reidentification does not consider the signal time status, leading to a less accurate matching rate. Nevertheless, the algorithm for vehicle reidentification can capture more than 40% of vehicles and measure the travel time with less than 15% error. In [51], a model is proposed for the estimation of vehicle delay – specifically for an isolated intersection that operates actuated signal control (ASC). ASC uses a probability algorithm and works on the idea of green time discretization for control logic. It was assumed that the vehicle arrival type follows the Poisson distribution for the vehicle delay at the ASC intersection to simplify the calculation process. The proposed principle of the vehicle delay model divides vehicle delay into the stopped delay and the discharge delay. The average stopped time represents the stopped delay of the vehicle. On the other hand, the discharge delay can be calculated as the difference between the vehicle's time of passing the intersection (i.e., without signal control) as well as the discharged time of queued vehicles. In addition to this, vehicle delay estimation is presented in three conditions according to the actuated signal control types (Semi- ASC, Fully ASC, and Delay Generation Mechanism under ASC). However, since the vehicle arrival detection is based on the Poisson distribution, the full approach and intersection delays, which may result in the control delay, are not considered in detail or thoroughly measured to approximate reality.

In [52], a combined approach was proposed for delay estimation using simulation and analytical techniques. In this account, the researcher used information obtained from both sources: the ground truth (field) and the micro-simulation model "TRAF-NETSIM". The main objective behind the activity was to assess the developed generalized delay model for actuated signal control. The delay results obtained from NETSIM were compared with those estimated by the proposed delay model. In the same context, HCM (2000) proposed a delay estimation model that was in accordance with the Gamma statistics probabilities of signal phase states and traffic volume that relies on the maximum queue length occurring at the end of each group phase. Whereas, in [53], the probe data was used with the ASC for a real-time delay estimation technique. The results generated from the proposed algorithm have been validated using traffic simulation experiments. The limitation of this method was that the average control delay, which may result from the approach length and speed, was not captured.

To this end, rare studies have considered the SID estimation problem at the network level, where the majority have been directed to SID for isolated intersections [54]. However, researchers considered many strategies to mitigate the network delay. These strategies include SCOOT [55], SCATs [56], OPAC [57], PODE [58], and others. For example, the PODE (Piecewise Optimum Delay Estimation) relies on field detection to optimize signal operations within short-term intervals. It relies on the information regarding vehicle arrival, the queue at the system, and the stop line. It has two main features that make it stand out: flexible interval length and the ability to self-adjust.

In conclusion, all the above-discussed delay models that were used to calculate vehicle delays at isolated intersections using in-field, analytical, and simulation methods, or a combination of them, have certain limitations. Although the simulation method is more convenient, less expensive, and more adaptable, the greatest challenge is to ensure that the simulation platform is constructed to accurately represent the field environment and that the simulation model is fully calibrated and sufficiently sophisticated to replicate the individual behavior as well as the interactions of the vehicles at the intersection, so that the artificial process is not biased. Similarly, the efficiency of the application of analytical models to this sort of engineering issue is often constrained by assumptions and limits on the initial boundary conditions or oversimplifications to identify practical and comprehensible mathematical solutions. At the same time, it is difficult to establish an analytical model to calculate vehicle delays at a signalized intersection in real-time. Where analytical and simulation methods theoretically can estimate the ISD at the transportation network level, field studies miss this capability. This return that presented techniques depend primarily on human labor or are incapable of measuring collective junctions control delays properly for traffic management applications. This study contributes to the literature by designing a new approach for calculating the network delay without the need for active and intermediate intersection detectors. The proposed methodology can use the collected traffic data to estimate effectiveness measurements in real-time, including arrivals, departures, and turning movement vehicle data.

III. PROBLEM STATEMENT

A. INTERSECTION DELAY

The Highway Capacity Manual (HCM2010) of the Transportation Research Board defines control delay as the increased travel time incurred by a vehicle impacted by junction control [59]. Control delay may be broken down into many components, including deceleration, stop, acceleration, approach, and junction delays. The taxonomy related to the SID is as follows:

- Approach delay is the delay a vehicle experiences before approaching a junction.
- Intersection delay is the extra travel time that a vehicle experiences after entering an intersection and before reaching free-flow speed.
- Deceleration delay is the delay encountered by a vehicle when its speed is decreased.
- Stop delay is the time a vehicle must wait when its speed is zero (practically, we consider a vehicle as stopped when its speed is less than five mph).
- Acceleration delay is the extra travel time a vehicle experiences during the acceleration phase. Consequently, control delay equals deceleration delay plus stop delay plus acceleration delay.

Approach delay includes stopped time and adds the time consumption due to the deceleration of a vehicle from either approaching speed to stop or joining the queue at low speeds. It also includes the time consumed for re-acceleration to the desired speed to cross the junction. There could be two different circumstances that could affect the shape of the vehicle's trajectory. The first situation could be that a vehicle is approaching an intersection while the intersection is in its red phase and with an existing queue. Hence, that vehicle will decelerate to join the queue, resulting in a delay due to the deceleration. As depicted in Fig. 1, the vehicle delay, which results when a vehicle arrives on a red signal phase, could be represented by trajectory line "a". The second situation that could follow is when a vehicle arrives at an intersection while it is in its green phase, keeping the queue size to zero. Hence, the vehicle will approach the intersection without any approach delay, resulting from either acceleration, deceleration, or stoppage time. This is depicted in trajectory "b". However, there would still be a small quantity of delay involved due to the reduced speeds of vehicles that are going for turning movements. The "c" and "d" seen could be described as "c" to describe delays due to other vehicles involved in the turning process, while "d" indicates other practical delays. Stopped time delay could be described as the time consumed by a car to be at rest while waiting for the intersection to show a green signal and cross the junction. In particular, this delay is the measure of time when a vehicle comes to rest completely and is measured until it starts accelerating. It is important to note that the average stopped-time delay becomes average for all the vehicles during the specified period. However, it is worth noticing that the Federal Highway Administration [60] considered any velocity below 5 mph to be stopped and is counted in a stopped delay. An acceleration delay could be defined as the additional time consumed by the vehicle to accelerate and reach the desired velocity to cross the intersection while joining with other traffic vehicles. This happens because, firstly, the driver takes a few seconds to lag in pressing the gas, and then the engine takes a few milliseconds to get the power up. After implementing CVT-type engines for maximum fuel economy, acceleration delay has become a significant type of delay [61]. During a specified interval of the time period, the average approach delay is said to be the average for all the vehicles. It is regarded as the total difference between the drivers' or passengers' expected arrival time and the actual time they may require to arrive. Control delay is the entire delay that a vehicle experiences as a result of all the above SID components.

The SID at isolated intersections could be illustrated in either stochastic or deterministic manners considering both properties of traffic flow, the variability and randomness of vehicle arrivals. Therefore, the delay and travel time estimation models involve both components of traffic flow characterization: the deterministic and stochastic approaches. It is stated that traffic flow at signalized intersections indicates that the deterministic component is estimated with the following initial assumptions:

1. The initial queue size is zero at the start of the green phase.

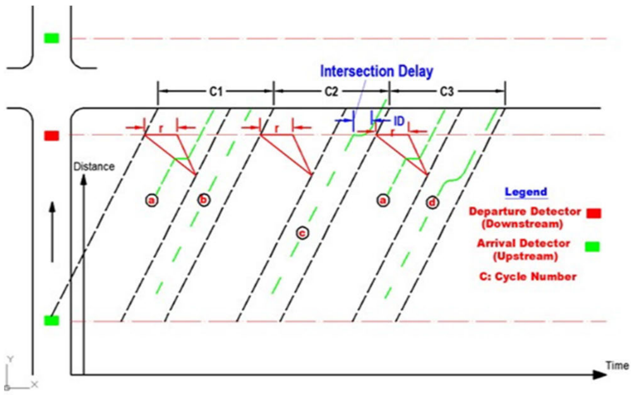

FIGURE 1. Signalized intersection control delay components.

2. The arrival pattern is assumed to be uniform at the flow rate during one cycle.
3. When the queue is at the saturation flow rate, the departure pattern is assumed to be uniform.
4. Arrivals will exceed the capacity of the traffic signal, which is obtained by multiplying the effective green-to-cycle ratio and approaching the saturation flow rate.

Fig. 2 shows the delay process by adopting the deterministic approach. The area covered below the queue line denotes the total approach delay in one cycle. Such a model can derive several performance measures, such as the average vehicle delay and the queue length. However, this model is only appropriate for intersections with low traffic volumes, and capacity-to-ratios do not exceed 0.5 to ensure the assumptions of initial and end queues are not violated, as these are hard to measure in most cases. Moreover, this model only applies when the vehicle arrival rate type is constant in the same cycle, and the vehicle delays due to the decelerations and accelerations are discontinued. The vehicle arrival rate in a real road traffic situation is stochastically changeable. The influencing variables include the signal timing plan of both the present and upstream junctions, traffic incidents, the make-up of cars, and distinctive driving behavior, among others. During the red-light time, there is a large disparity between the actual and projected arrival rates. Similarly, cars are not discharged according to the saturation flow rate when the green light starts. Let denote $\mu(t)$ as the actual vehicle arrival rate function and $\gamma(t)$ as the actual flow rate function. In a given signal control time c, the entire delay of the cars may be represented as the region between the actual vehicle arrival cumulative line and the releasing line, as follows:

$$D = \int_{0}^{c} \mu(t)\,dt - \int_{0}^{c} \gamma(t)dt \tag{1}$$

B. NETWORK DELAY

Network delay is a crucial indicator of the efficiency of traffic operations. When drivers encounter traffic congestion on the

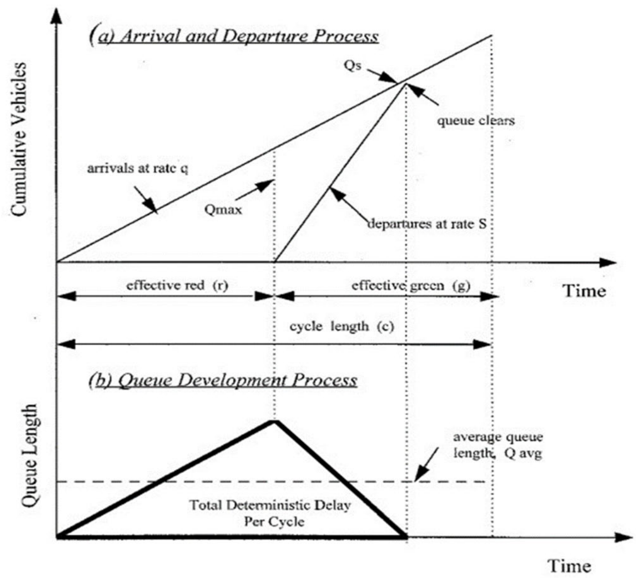

FIGURE 2. Delay models using deterministic components of arrivals and departures.

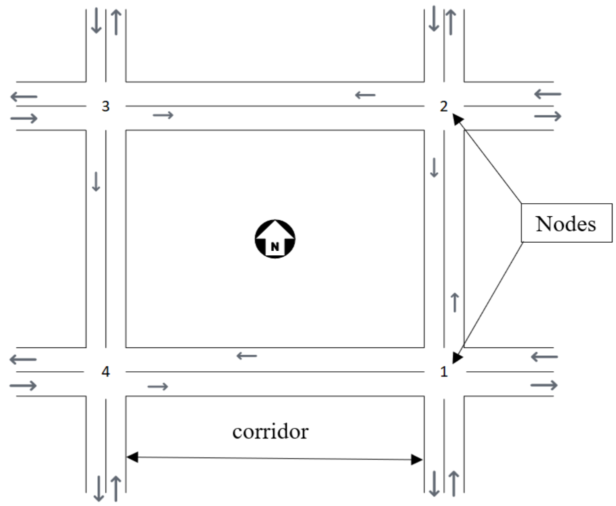

FIGURE 3. Simple traffic network components.

network, they immediately return it to intersection performance. In the same sense, we can define network delays as the delays produced by intersection traffic control additions that create a difference between travel time before and after implementation. Fig. 3 shows an example of a simple traffic network that has four boundary nodes (intersections) and eight corridors (links). The delay is the additional time a vehicle takes to pass through the intersections without pauses. It might alternatively be understood as the average difference between the departure and arrival timings of cars at the network entrance and exiting intersections. Consequently, the SID could be treated as the previous section for each kind of junction. Notably, the network delay is more difficult to quantify in the field than the isolated SID since it requires advanced monitoring equipment to track each vehicle delay through a number of consecutive intersections. However, network delay estimation is still more important than isolated intersection delay estimation. It might be utilized as a performance metric to determine the level of service of the whole network [19], [62].

IV. EQUIPMENT AND REQUIRED INPUT DATA

A. DETECTION SYSTEM

Efficient and optimal traffic control operation at signalized intersections needs a reliable vehicle detection system to be able to estimate performance measures and respond automatically to various changes in traffic conditions. The quality of intersection performance measures highly relies on the communication part of the detection system and the signal controller. The processing of traffic signal information, including signal timing plans and turning movements data, is highly dependent on the infrastructure for signal and traffic detection systems. Detection systems are used to collect information on traffic conditions at signalized intersections and analyze the data to get the performance measures and give the optimal timing plans. A typical infrastructure with hardware components for a signal system is shown in Fig. 4.

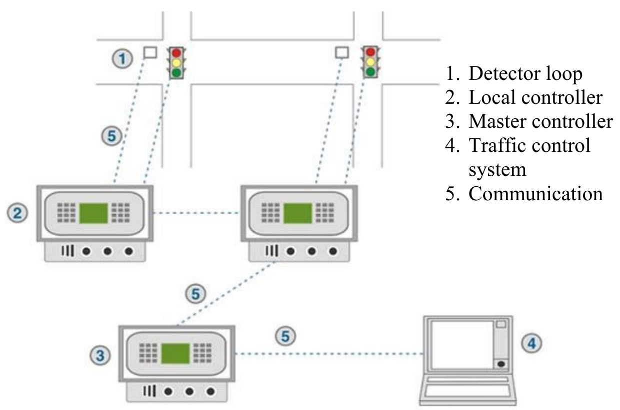

FIGURE 4. Physical components of a signal system.

B. DETECTOR INFORMATION

From a technical standpoint, it is also challenging to obtain field measurements of approach delay, which includes the delay experienced by vehicles decelerating toward a queue or red light, the delay experienced by vehicles stopped at the intersection or in a queue, and the delay experienced by departing vehicles as they accelerate through the intersection and depart. Recent technological evolution, specifically advancements in computer technology, has facilitated real-time and efficient data collection. This capability has eventually helped optimize traffic operations, enhancing the ability to accurately estimate signal performance measures like travel time and average control delay of the vehicles. In such models, the information related to vehicle arrival is acquired from the detectors deployed upstream of the intersection. The main idea behind this model revolves around obtaining the vehicle travel time between the intersection stop line and the upstream detector. To optimize the systems, it is essential to optimize the traffic conditions. This is because geometric uncertainties and constraints in the arrival of the vehicles result in a trade-off between the data accuracy and duration estimation. Fig. 5 shows the geometric layout for estimating the travel time.

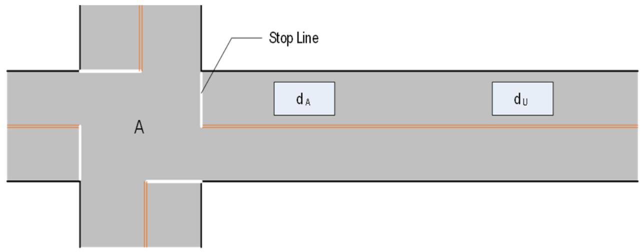

FIGURE 5. Geometric layout for estimating the arrival time of the vehicle.

The vehicle's travel time can be split into two parts. The division was conducted between arrival time d_A and upstream detector d_U and time to intersection (A) from d_A. Here, it is essential to note that d_U is placed at a distance of hundred feet upstream of A to provide sufficient 'reaction time' to the system for adjusting the signals. Conventionally, the distance between d_A and d_U ranges from 250 feet to 300 feet. However, in the case of heavy traffic, the time of travel to intersection A from d_A is not easily determinable since it is significantly affected by the signal status and existing queues – present at the intersection (A). Fig 6. Shows the two possible cases of a vehicle arriving where the estimated arrival time a vehicle is estimated as follows:

$$\mu_i = \delta_i + \tau_i \tag{2}$$

where; i is the index for incoming vehicles at intersection (A), μ_i and δ_i denote the estimated arrival time of the vehicle i at intersection (A) and detector d_A, respectively. Whereas τ_i is the estimated traveling time between intersection (A) and d_A.

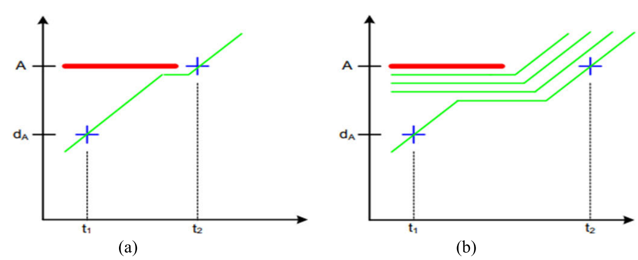

FIGURE 6. Travel time between intersection (A) and d_A with different Sizes of the queue: (*a*) Vehicle arrival without existing queue, and (b) Vehicle arrival with existing queue.

While assessing Eq. (2), it has been established that d_U and d_A affect the δ_i. However, it is also found that there are errors in the determination of δ_i and τ_i (travel time), which is not the total time that is traveled between intersection A and d_A. It is important to note that different queue length impacts τ_i. On the other hand, there is also a possibility that the approaching speed is likely to be changed when the incoming vehicle gets close to the queue. This phenomenon also impacts the estimation of the vehicle's travel time to the intersection. In this account, the travel time could be described as the one that is covered by the vehicle between the downstream and upstream signals. However, this model is not deemed efficient in accurately estimating the travel time, specifically in congested traffic. This issue prevails in the optimization of all available adaptive control systems. There is also a literature gap in identifying the effects of different queue lengths on estimating the vehicle's arrival time.

C. TURNING MOVEMENTS INFORMATION

Turning movement information (TMI) is vital for various applications at signalized intersections. These include advanced signal control, travel demand estimation, traffic safety analysis, and other applications. In addition, TMI is also required to analyze the system, specifically for estimating delay, congestion, travel time, and levels of services. Therefore, research on turning movement estimation at signalized intersections in urban areas has been widely explored. Many studies have been conducted on obtaining TMI through mathematical models, especially statistical models. Several practical methods have been proposed for obtaining TMI in real time using the detector data directly. The time and place system method was developed by tracking each turning movement's signal phasing and detection information [63], [64]. The proposed system can separate the right and left turning movements from the through traffic by using special lane detectors to capture the turned vehicles for the left-handed driving platforms. The estimation errors generated in the right lanes with shared through movements are not significant, but the error increases and varies from 5% to 70% for the vehicles making left turns in a shared lane. However, the method is restricted by requiring a dedicated right-turn detector and no shared lanes for left-turning movements. The limitations did not address the identification of left-turning movements in shared lane scenarios. Furthermore, the difficulty of identifying turning movements in the cases of left-turning vehicles approaching from the opposite direction and through vehicles approaching from the cross street requires a dedicated right-turn detector and careful calibration for its position. This study used a framework called the Automatic Turning Movement Identification System (ATMIS) [65]. The operations of ATMIS are based on matching the characteristics of the individual outgoing and incoming vehicles with the traffic signals. This calculation also helps in managing the mistakes that occur due to flawed discoveries and shared paths. It is significant to bring to the notice that the lab trials and field tests gave promising results.

V. METHODOLOGY

This paper presents a novel method for evaluating vehicle delay at a signalized crossing. This technique employs the input-output model and vehicle origin-destination (O-D) data acquired from the ATMIS. Using this paradigm, approach delays may be computed by examining real-time data from arrival and departure detectors situated upstream and downstream of a junction. In addition, intersection delay is computed by measuring the time spent inside the intersection by comparing the time it takes a vehicle to travel between the paired detectors that define the origin and destination of each turning action. Simulations conducted in the laboratory using the proposed method demonstrate that it is feasible, effective, and reliable in dealing with varying traffic conditions (low, medium, high, and saturated); however, oversaturated conditions that may cause street gridlock to have not been taken into account in this study. The principles of the suggested concept and its implementation are presented.

In a simple sense, the concept of the Total Travel Delay (TTD) estimation technique is based on two components that include Actual Travel Time (ATT) and Default Travel Time (DTT). These principal components are connected with the number of detected vehicles ($\sum n$) as follows:

$$TTD = \sum n(ATT - -DTT) \tag{3}$$

The Input-Output principle of TTD is based on using and turning movement data in real-time. Some of the existing systems had required detectors for each in and out for intersection inside the network while tracking each vehicle that goes through intersections. However, TTD does not require detectors for each inter and exit of intersections inside the network and just needs timestamp detectors for inter and exit for boundary network intersections (nodes).

The proposed TTD system is based on simultaneous operations in terms of collecting traffic information (including data about vehicle arrivals, departures, and turning movements), storing data, and performing system analysis. The system has the flexibility to be modeled into different grid networks. TTD utilizes turning movement data, vehicle input, and vehicle output, relying on detectors placed at the arrival and departure points. The following section profoundly discusses the simple and intermediate intersection traffic network. Each simulation's input parameters are used to run the test under different traffic conditions. The outputs of each case study are presented, and results were validated using different statistical techniques.

A. ATT ESTIMATION METHOD

ATT is one of the crucial facts that help in effectively assessing the overall performance of traffic networks. Although there may be changes in the lanes, passing activities, or direction changes between the arrival and departure detectors, the total value of vehicle travel time (summation of all vehicles) will not be affected by any change in the order of detection sequence because an overestimation of one vehicle delay will result in an underestimation of another. In other words, since output and input are not dependent on the order of the individual detection (timestamp), their values will not be affected by any change in the order of detection due to lane changing, passing activities, or direction change. The ATT for one vehicle (i) is different from time out ($t_{out,i}$) and time in ($t_{in,i}$), and if there is more than one vehicle using the following equation:

$$ATT = \sum_{\mathrm{i}} (\mathrm{t_{out,i}} - \mathrm{t_{in,i}}) / \sum_{\mathrm{i}} n_i \tag{4}$$

Eq. (4) illustrates that there is no need to know and track the vehicle path or route. To illustrate the concept, two scenarios were applied to estimate ATT. The first scenario was the one when the vehicle path was known. On the other hand, the second scenario was associated with the situation where there was no tracking of the vehicle path; instead, it only required a timestamp for input and out.

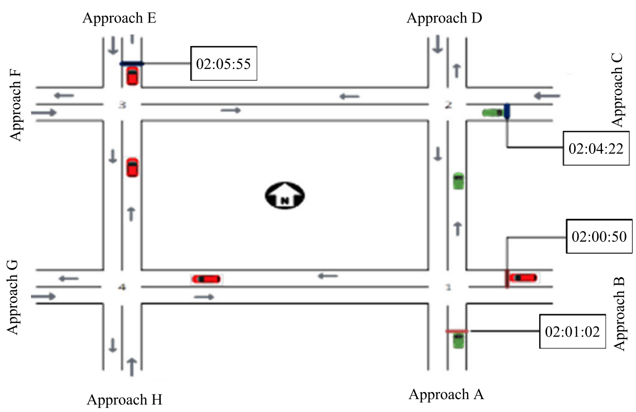

FIGURE 7. The concept model of the ATT estimation method.

To prove the ATT concept theoretically, Fig. 7 illustrates an example of two vehicles entering the system at different time periods for the example network in Fig. 3. It is assumed that the red vehicle enters the system from approach B (Bin) at 02:00:50 pm and the green vehicle enters from approach A (Ain) at the time of 02:01:02 pm. After that, the green vehicle exits the system from approach C (C out) at 02:04:22 pm, and the red vehicle exits the system from approach E (E out) at 02:05:55 pm. If the average time stamp for the two vehicles is taken, the average travel time will be 252.5 sec, which is the same as the average of time stamps – specifically if the vehicle's path is unknown. It also indicates different summations of output and input timestamps over the number of vehicles. The output time stamp collected from exit detectors is 617 sec, and the input time stamp collected from entrance detectors is 112 sec. Moreover, the average travel time is found to be 252.5 sec, which is the same result of travel time (in the case of a known vehicle route). It is also important to note that two vehicles were selected for this case. Based on these findings, it can be stated that there is no need to track each vehicle to calculate total travel time in a gird traffic network.

B. DTT ESTIMATION METHOD

DTT is regarded as the time that the vehicle takes to move from one place to another place. In other words, it is the time that is necessary to traverse a route between any two points of interest. Following Eq. 5 shows how to calculate the DTT in general. For the traffic network presented in Fig. 7, Eq. 6 used the general equation for multiple vehicles involved in the network system. For example, D_{1-2} is the distance between Node 1 and Node 2, and its equal distance for D_{2-1} is the distance between Node 2 and Node 1 ($\mathrm{D}_{1-2} = \mathrm{D}_{2-1}$). However, the numbers of vehicles are not equal ($\mathrm{N}_{1-2} \neq \mathrm{N}_{2-1}$). It is important to note that the same procedure can be followed for semi-generalized and generalized networks, as will be seen in the numerical section with larger network cases.

$$\mathrm{DTT} = \frac{Travel\ Distance\ (D)}{Velocity\ (U)} \tag{5}$$

$$DTT_{t_i} = \frac{1}{V} \begin{pmatrix} 0 & 0 & 0 & D_{4-1} & 0 & 0 & 0 & 0 \\ D_{1-2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & D_{3-4} & 0 & 0 & 0 & 0 & 0 \\ 0 & D_{2-3} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & D_{1-4} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{2-1} \\ 0 & 0 & 0 & 0 & 0 & D_{4-3} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & D_{3-2} & 0 \end{pmatrix} \cdot \begin{pmatrix} N_{1-2} \\ N_{2-3} \\ N_{3-4} \\ N_{4-1} \\ N_{1-4} \\ N_{4-3} \\ N_{3-2} \\ N_{2-1\_} \end{pmatrix} \tag{6}$$

C. TRAFFIC DATA PROCESSING FOR OBTAINING THE TMI

To accurately analyze the system performance measures, important information such as traffic volume at each approach, turning movements for each lane, and vehicle arrivals and departures should be obtained and processed in real time. As a part of this traffic information, the intersection turning movements on each lane at each approach is the most challenging task to be done. It has been established that the turning movement is estimated by keeping track of each detector's status and the traffic signal phase's status at each instant. For the sake of explaining the core concept of this method, a four-leg intersection has been taken as an example.

For estimating the TM at a signalized intersection, an approach is vital that uses data gathered by the ATMIS obtained by the detector. ATMIS matches individual incoming and outgoing vehicle characteristics and coordinates with traffic signals. Detectors are placed at enter and exit of intersection approaches. Two types of detectors are there: 1) input detectors counting vehicle entry and 2) output detectors detecting leaving intersections of vehicles.

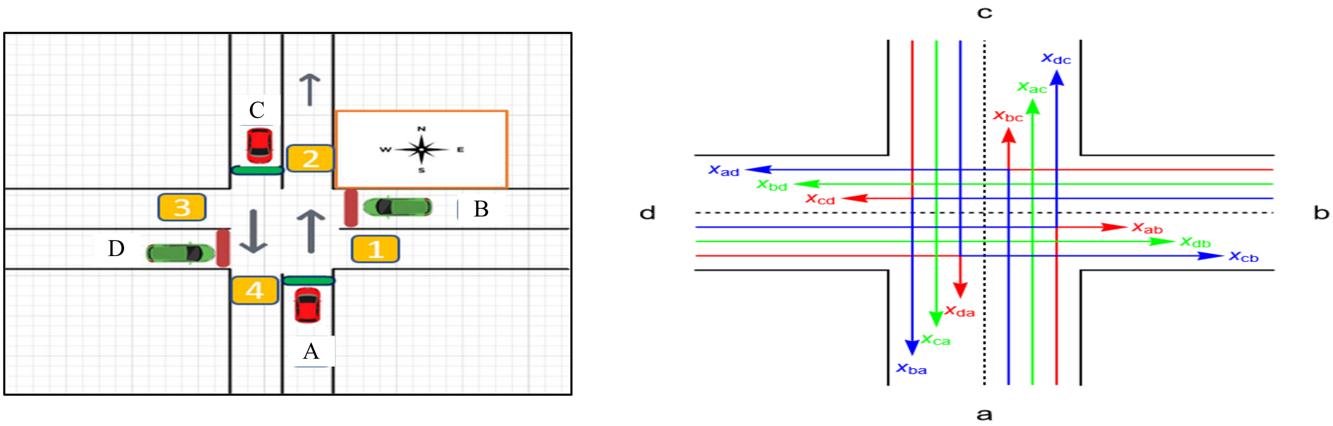

FIGURE 8. Detectors layout for intersection and general intersection geometric layout.

Fig. 8 shows more details of the layout intersection during phase 1 (north-south bound). A, B, C, and D represent input volume entering the intersection, whereas 1, 2, 3, and 4 represent output volume exiting from the intersection. Right turning is available from B and D. At volume 1 (V_1), it allows the volume to come from the green phase. In particular, it considered the volume at D that takes the north right turn (V_{NR}) and the volume at B that takes the south left turn (V_{SL}). The following system of equations represents all components in the Fig. 8:

$$\begin{aligned} V_1 &= V_{NR} + V_{SL} \\ V_2 &= V_{NT} + V_{WR} \\ V_3 &= V_{SR} + V_{NL} \\ V_4 &= V_{ST} + V_{ER} \\ V_A &= V_{WR} \\ V_B &= V_{ST} + V_{SR} + V_{SL} \\ V_C &= V_{ER} \\ V_D &= V_{NT} + V_{NR} + V_{NL} \end{aligned} \tag{7}$$

Note that the Eq.s (7) system has eight equations and eight unknowns. Where V_1, V_2, V_3, V_4, V_A, V_B, V_C, V_D are known traffic volumes. Also, the following system can be realized during phase 1. So, volume at A is just allowed to turn right (V_{WR}) and cannot go through and left during the red phase. Likewise, the same procedure can happen at volume C as follows:

$$\begin{aligned} V_{WR} &= V_A \\ V_{ER} &= V_C \\ V_{NT} &= V_2 - V_{WR} = V_2 - V_A \\ V_{ST} &= V_4 - V_{ER} = V_4 - V_C \end{aligned} \tag{8}$$

The system of Eq.s (8) helps in solving four (4) unknown volumes that include North-Through volume (V_{NT}), South-Through volume (V_{ST}), West-Right volume (V_{WR}), and East-Right volume (V_{ER}). Hence, Eq. (7) still has four unknown volumes that include: V_{NR}, V_{SL}, V_{SR}, V_{NL}, which helps in forming the following system of equations:

$$\begin{aligned} V_1 &= V_{NR} + V_{SL} \\ V_3 &= V_{SR} + V_{NL} \\ V_B &= V_{ST} + V_{SR} + V_{SL} \\ V_D &= V_{NT} + V_{NR} + V_{NL} \end{aligned} \tag{9}$$

In order to ease the determination of the number of independent equations in the system (9), the formulation is written in the following matrix form:

$$M \cdot X = Q, \tag{10}$$

where;

$$M = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix}, \tag{11}$$

$$X = \begin{pmatrix} V_{NR} \\ V_{SL} \\ V_{SR} \\ V_{NL} \end{pmatrix}, \tag{12}$$

$$Q = \begin{pmatrix} V_1 \\ V_3 \\ V_B - V_{ST} \\ V_D - V_{NT} \end{pmatrix} \tag{13}$$

It is obvious that matrix M is of $rank\ (M) = 3$. The above work indicates that out of 4 rows of the matrix M, only three rows are independent. Therefore, only three unknowns out of 4 (V_{NR}, V_{SL}, V_{SR}, V_{NL}) can be found using Eq. (9), and the remaining 1 unknown must be specified. As a result, it has been established that by solving Eq. (7). The volumes can be found, i.e., V_{WR}, V_{ER}, V_{NT}, V_{ST} – specifically by formulas that are used from Eq.s 8 to 13 and any three volumes from the list V_{NR}, V_{SL}, V_{SR}, V_{NL}, considering the fourth volume as given.

Further, Fig. 8 shows that the approach assumes that all 8 volume links are known, meaning all vehicle input and output flows are known. Eq. (14) shows that the summation of output flows is equivalent to the input flows of vehicles:

$$A_i + B_i + C_i + D_i + E_i + F_i + G_i + H_i = A_o + B_o + C_o + D_o + E_o + F_o + G_o + H_o \quad (14)$$

where:

Y_i – the flow of vehicles at the entrance Y
Y_o – the flow of vehicles at the exit Y
N_{ab} – the flow of vehicles in the link $Na - b$
R_{ab} – the flow of vehicles moving along the $Na - b$ link and turning right
L_{ab} – the flow of vehicles moving along the $Na - b$ link and turning left
T_{ab} – the flow of vehicles moving along the $Na - b$ link and passing through the intersection without turning
$Y = A, B, \ldots, H$ and $a, b = 1, 2, \ldots, 4$ or $A, B, \ldots, H$

Compose a system of equations for each of the intersections in the network in Fig. 7 with the four intersections (1, 2, 3, and 4), where each system is concerned with one intersection:

$$\begin{cases} R_{A1} + T_{A1} + L_{A1} = A_i \\ R_{41} + T_{21} + L_{B1} = A_o \\ R_{B1} + T_{B1} + L_{B1} = B_i \\ R_{A1} + T_{41} + L_{21} = B_o \\ R_{21} + T_{21} + L_{21} = N_{21} \\ R_{B1} + T_{A1} + L_{41} = N_{12} \\ R_{41} + T_{41} + L_{41} = N_{41} \\ R_{21} + T_{B1} + L_{A1} = N_{14} \end{cases} \quad (15)$$

$$\begin{cases} R_{C2} + T_{C2} + L_{C2} = C_i \\ R_{12} + T_{32} + L_{D2} = C_o \\ R_{D2} + T_{D2} + L_{D2} = D_i \\ R_{C2} + T_{12} + L_{32} = D_o \\ R_{32} + T_{32} + L_{32} = N_{32} \\ R_{D2} + T_{C2} + L_{12} = N_{23} \\ R_{12} + T_{12} + L_{12} = N_{12} \\ R_{32} + T_{D2} + L_{C2} = N_{21} \end{cases} \quad (16)$$

$$\begin{cases} R_{E3} + T_{E3} + L_{E3} = E_i \\ R_{23} + T_{43} + L_{F3} = E_o \\ R_{F3} + T_{F3} + L_{F3} = F_i \\ R_{E3} + T_{23} + L_{43} = F_o \\ R_{43} + T_{43} + L_{43} = N_{43} \\ R_{F3} + T_{E3} + L_{23} = N_{34} \\ R_{23} + T_{23} + L_{23} = N_{23} \\ R_{73} + T_{F3} + L_{E3} = N_{32} \end{cases} \quad (17)$$

$$\begin{cases} R_{G4} + T_{G4} + L_{G4} = G_i \\ R_{34} + T_{14} + L_{H4} = G_o \\ R_{H4} + T_{H4} + L_{H4} = H_i \\ R_{G4} + T_{34} + L_{14} = H_o \\ R_{14} + T_{14} + L_{14} = N_{14} \\ R_{H4} + T_{G4} + L_{34} = N_{41} \\ R_{34} + T_{34} + L_{34} = N_{34} \\ R_{14} + T_{H4} + L_{G4} = N_{43} \end{cases} \quad (18)$$

If we combine all systems for Eq.s (15) to (18), we get 32 equations and 48 unknowns (each intersection corresponds to 8 equations and 12 unknowns). All these equation systems are arranged according to the same template. It is considered an arbitrary (one of four) intersection. It can be denoted by letters a, b, c, d – the number of four intersections (or entrances and exits) connected to this intersection. Let x_{ab} be the flow of vehicles passing (turning) from point a through the intersection towards point b. Then, the general template according to which the systems are composed can be represented in the following form:

$$\begin{aligned} x_{ab} + x_{ac} + x_{ad} &= a_i \\ x_{da} + x_{ca} + x_{ba} &= a_o \\ x_{bc} + x_{bd} + x_{ba} &= b_i \\ x_{ab} + x_{db} + x_{cb} &= b_o \\ x_{cd} + x_{ca} + x_{cb} &= c_i \\ x_{bc} + x_{ac} + x_{dc} &= c_o \\ x_{da} + x_{db} + x_{dc} &= d_i \\ x_{cd} + x_{bd} + x_{ad} &= d_o \end{aligned} \quad (19)$$

where a_i, b_i, c_i, d_i – input vehicles flow to this intersection, a_o, b_o, c_o, d_o – output vehicle flows, x_{ab}, x_{ac}, x_{ad}, x_{ba}, x_{bc}, x_{bd}, x_{ca}, x_{cb}, x_{cd}, x_{da}, x_{db}, x_{dc} – unknown flows. For example, if we set $a = H, b = 1, c = 3, d = G$, then we get the system of Eq.(18) which is Intersection 4, where $a_i = H_i$, $a_o = H_o$, $b_i = N_{14}$, $b_o = N_{41}$, $c_i = N_{34}$, $c_o = N_{43}$, $d_i = G_i$, $d_o = N_o$, $x_{ab} = R_{H4}$, $x_{ac} = T_{H4}$, $x_{ad} = L_{H4}$, $x_{ba} = L_{14}$, $x_{bc} = R_{14}$, $x_{bd} = T_{14}$, $x_{ca} = T_{34}$, $x_{cb} = L_{34}$, $x_{cd} = R_{34}$, $x_{da} = R_{G4}$, $x_{db} = T_{G4}$, $x_{dc} = L_{G4}$.

Thus, it suffices to find a solution to Eq. (19), and then it will be possible to solve Eq.s (15)-(18), which has 8 equations and 12 unknowns. To determine the number of independent equations for this, we rewrite Eq. (10) with the following information:

$$\begin{pmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \end{pmatrix}$$

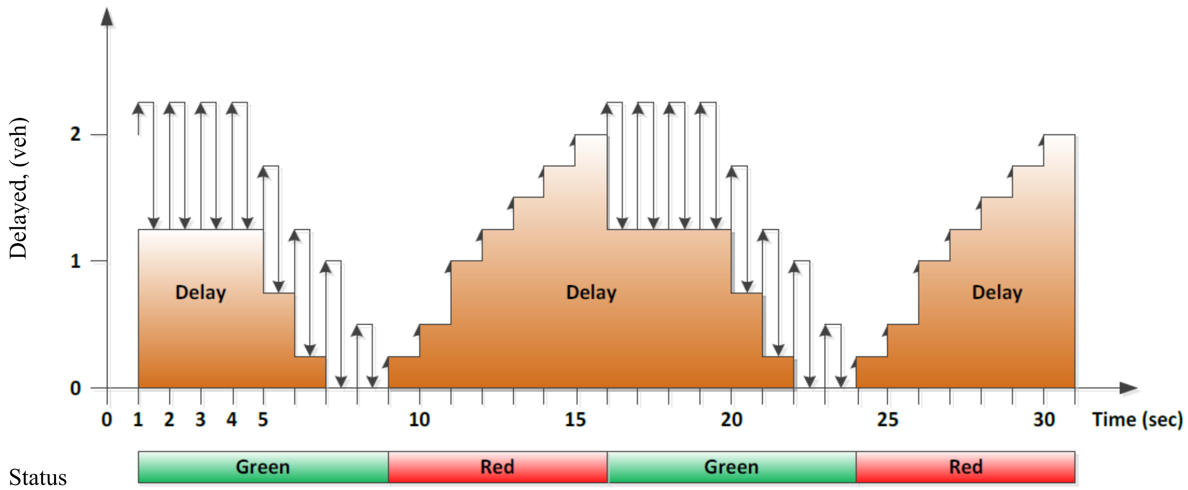

FIGURE 9. **Process of delay calculation.**

$$\times \begin{pmatrix} x_{ab} \\ x_{ac} \\ x_{ad} \\ x_{ba} \\ x_{bc} \\ x_{bd} \\ x_{ca} \\ x_{cb} \\ x_{cd} \\ x_{da} \\ x_{db} \\ x_{dc} \end{pmatrix} = \begin{pmatrix} a_i \\ a_o \\ b_i \\ b_o \\ c_i \\ c_o \\ d_i \\ d_o \end{pmatrix} \quad (20)$$

As $rank\ (M) = 7$, out of 8 rows of the matrix M, only 7 rows are independent. Therefore, only 7 unknowns can be found from Eq. (19), and the remaining 5 unknowns will have to be specified. Of the 12 unknowns, 792 sets of 5 unknowns can be made. For example, $\{x_{ab}, x_{ba}, x_{ca}, x_{db}, x_{dc}\}$, $\{x_{bc}, x_{ca}, x_{cb}, x_{db}, x_{dc}\}$,..., etc. However, this does not mean that any of these 792 sets can be selected as specified values. For example, if we choose the quantities $\{x_{ab}, x_{ba}, x_{ca}, x_{db}, x_{dc}\}$ as given (known), then Eq. (19) can be rewritten in the following form:

$$\begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} x_{ac} \\ x_{ad} \\ x_{bc} \\ x_{bd} \\ x_{cb} \\ x_{cd} \\ x_{da} \end{pmatrix} = \begin{pmatrix} a_i - x_{ab} \\ a_o - x_{ca} - x_{ba} \\ b_i - x_{ba} \\ b_o - x_{ab} - x_{db} \\ c_i - x_{ca} \\ c_o - x_{dc} \\ d_i - x_{db} - x_{dc} \\ d_o \end{pmatrix} \quad (21)$$

In the reformulation in Eq. (20), the rank of the matrix (M) is reduced to 6.This means that out of 8 matrix rows, only six are independent. Therefore, only 6 unknowns from 7 unknowns can be found in the system (21). This means that setting five values $\{x_{ab}, x_{ba}, x_{ca}, x_{db}, x_{dc}\}$ is not enough to find all unknowns.

Summing up, it can be said that out of 792 sets, only 384 sets allow finding all unknowns in our case. For all these 384 sets, the rank of the corresponding matrices M will be 7. For example, set $\{x_{bc}, x_{ca}, x_{cb}, x_{db}, x_{dc}\}$ can be used as 5 known values. As mentioned earlier, since all four intersections are constructed according to the same pattern, the result calculations above are valid for any of the four intersections. The TMI calculation that has been developed for four intersections can be applied extended to nine and sixteen intersections network scale.

D. MESOSCOPIC INTERNAL EVALUATOR

An embedded mesoscopic algorithm is used to facilitate the evaluation of the proposed performance measure system under different signal cycle lengths. This algorithm helps in estimating vehicle delay in a grid system. The algorithm calculates vehicle delay using the input-output method using phase codes to represent each phase's minimum and maximum green time. It has already been discussed that the total system delay is the average of all vehicle delays in each lane of each intersection approach. To increase the accuracy of calculating the overall system delay, the arrival vehicles, departure vehicles, and the vehicles turning movement information were tracked - second by second - and at each intersection. The arrival flow represents the number of vehicles arriving each second, and the upstream detectors measure it. Since the input detectors are placed at a sufficient distance from the intersection, the arrival flow will not be influenced by the queue buildup in each lane. The vehicle departure flow represents the number of vehicles released at each second. Moreover, various factors, such as signal timing and lane capacity, can influence the departure flow profile. The vehicle departure flow can be calculated every second in the simulation by obtaining the precise time for vehicle

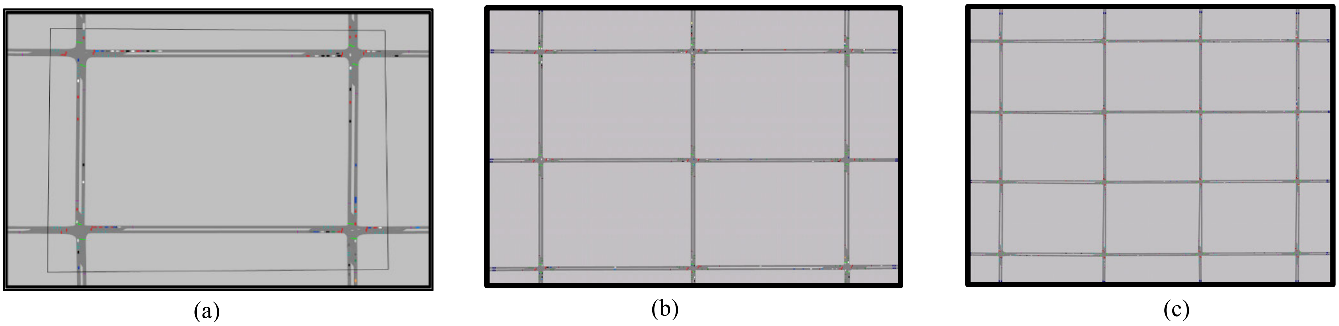

FIGURE 10. Build grid networks in VISSIM: (a) four intersections, (b) Nine intersections, and (c) Sixteen intersections.

arrival, vehicle departure, and signal timing - including the phase status. From these variables, delayed vehicles are determined, which are the vehicles decelerated by buildup queues or red phase time at each second. Fig. 9 shows the calculation process of total delayed vehicles in each phase.

VI. NUMERICAL STUDY

This section uses the results of three different network sizes to validate the proposed approach. It is worth noting that each of the presented networks could be used as a building block to analyze large-scale networks where the output flow from each block is the input to the other, and the designer can accumulate the total delay over the network under study. The capacity of the networks being simulated is dependent on the constituent streets, which we assumed all as two way – two lanes streets with theoretical/ideal practical capacity of 2200 pc/hr/lane and ideal saturation flow of 1900 pc/hr/lane recommended by the HCM. Traffic volume was used for three different levels: low, medium, and high. There were three levels of turning movements. The first level is 90% of traffic volume goes through, and 10% will be divided between left and right equally. The other two levels, which are 80% and 70%, go through, and the remaining percentage for the level is divided equally between left and right. The speed parameter is assumed to be a constant average for the network. The corridor's length was also assumed to be of the same length for vertical and horizontal network alignment. The cycle length was set up to be optimized through the simulation program. As the study intended to estimate the delay and not control it, we did not direct the software to synchronize the intersections.

A microscopic simulation platform (VISSIM) and Python programming language were adopted as an evaluation platform for lab experiments to evaluate the performance and effectiveness of the approach performance measurement system. VISSIM was used to simulate the experimented grid systems. Moreover, it was used to estimate ATT and extract input and output timestamps to be used to estimate DTT. It is worth noticing that MATLAB was also used to solve the stated systems of equations and calculate the DTT. The proposed methods were implemented and run at the same time as the micro-simulation platform. VISSIM was used to build the grid networks for the three study cases (i.e., four, nine, and sixteen nodes network), as shown in Fig. 10. VISSIM calls the code during the simulation, which is created and implemented in the Python script file. This file has a code to detect each vehicle that enters and exits the network and collect the timestamps and numbers of vehicles. Therefore, detectors were placed in the entrance and exit traffic network system. VISSIM can set up a different level of volumes. Additionally, VISSIM could set up turning movement boundary conditions for traffic speed for the entire network and control traffic signals. The simulation time step was set up for 12 intervals; each interval has 300 sec (5 minutes), which is a 1-hour simulation time and 15 minutes warm-up.

The proposed TTD system evaluation was implemented for three cases of the numerical study. Each intersection in the networks has two lanes on each approach - with a configuration of one lane for a left turn and one lane shared for through movement and a right turn. The traffic volume includes different levels, depending on the number of vehicles, which were low, mid, and high. Table 1 shows more details about traffic volumes. The turning movement percentages - as mentioned before, are 70%, 80%, and 90% of the through volume. The speed limit for the intersection approach was 35 mph. Table 1 also shows the details for each demand level scenario for the turning movement.

A. CASE (1): FOUR NODES NETWORK

This network information is presented in section V. A validation test is processed to ensure that the output results obtained from the proposed TTD method meet acceptable quality measures when compared to "ground truth". This subsection describes the general statistical validation methods used for simulation data. The distance between the intersections is about 800 ft from North to South and 1000 ft from East to West. Fig. 11 depicts an example of the model performance during the simulation analysis at the worst traffic case: the heights of TM percent with the highest traffic volume condition. The figure clearly showed that the VISSIM and TTD methods produced comparable results.

B. CASE (2): NINE NODES NETWORK

The system performance measure, which has been developed for the four nodes, can be readily extended to a grid system of more than four nodes (i.e., a semi-generalized grid network).

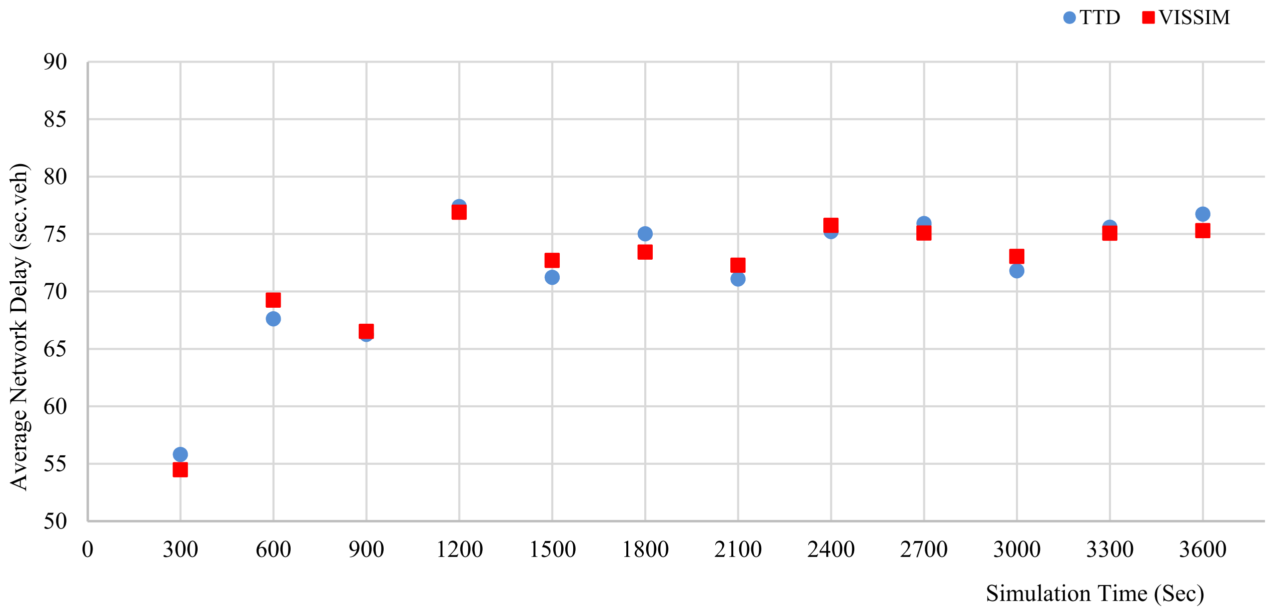

FIGURE 11. Delay results of through turning movement 90% at high level approach volume.

TABLE 1. Volume level and TMI for grid network.

Level	Volume (Veh/hr)	TM% Through	TM% Left	TM% Right	Speed (mph)
Low	400-600	90	5	5	35
		80	10	10	
		70	15	15	
Meduim	800-1000	90	5	5	35
		80	10	10	
		70	15	15	
High	1200-1400	90	5	5	35
		80	10	10	
		70	15	15	

The performance of the TTD method has been quantitatively evaluated using VISSIM, in which a 3×3 grid traffic network having nine signalized intersections is made and adjusted to reflect real-world traffic and geometric parameters. The layout of this grid system is shown in Fig. 12.

Before presenting the results, It is beneficial here to show how to generalize the methodology shown in the previous section. The approach's main idea was to utilize boundary intersections' (Nodes: 5, 6, 7, and 8) traffic volume data to estimate the intermediate intersection (Node: 9) data mathematically. The basic equation is the summation of entrance vehicles (N_{in}) equal to the summation of exit vehicles (N_{out}). Therefore, this basic equation was applied to boundary intersections such as (N_{1-2}) means the number of vehicles that travel from node 1 to node 2, as depicted in the following system:

$$N_{9-5}+N_{2-5}+N_{1-5}+N_{5in} = N_{5-9}+N_{5-2}+N_{5-1}+N_{5out}$$
$$N_{9-5} = N_{5-9}+N_{5-2}+N_{5-1}+N_{5out} - N_{2-5} - N_{1-5} - N_{5in}$$
$$N_{9-6} = N_{6-9}+N_{6-2}+N_{6-3}+N_{6out} - N_{2-6} - N_{3-6} - N_{6in}$$
$$N_{9-7} = N_{7-9}+N_{7-3}+N_{7-4}+N_{7out} - N_{3-7} - N_{4-7} - N_{7in}$$
$$N_{9-8} = N_{8-9}+N_{8-1}+N_{8-4}+N_{8out} - N_{1-8} - N_{4-8} - N_{8in} \tag{22}$$

As a result, intersection nine (i.e., intermediate) did not need detectors and can be figured out from boundary intersection as shown in previous equations. Moreover, this approach aims to minimize the number of detectors at boundary intersections, such as links 9-5, which did not need a detector. The next step is associated with applying Eq. 6 to calculate network DTT as follows: (23), as shown at the bottom of the next page.

The accuracy of the nine-node network matches with the previous case with no significant differences. The full summary of the results of the three cases of study is presented in Table 2. The coefficient of determination (R^2) as a measure of goodness of fit is used to evaluate this case. The worst value of the R^2 was 0.916 at the highest of TM percent with the highest traffic volume condition.

C. CASE (3): SIXTEEN NODES NETWORK

This network is used as the generalized case of our study. The augmentation of the TTD calculation method is similar to the previous case. Table 2 depicts the results of the average delay for all runs comparing the three cases of study, including varying flow rates and turning movement percentages. The results clearly show that the TTD performance is comparable to those attained from VISSIM. The table shows that the geometric configuration of the simple simulated network has different traffic volumes, which affects the performance of delay estimation for the grid network. When the volume increases, the average delay will also increase. Table 2 result also shows that the shared lanes for right-through movements affect the performance of delay estimation for turning movements increasingly, as in the through vehicle stream, there is an increase in the percentage of right-turning vehicles.

A frequently used validation method that is considered for comparing one data series with another is called the chi-square method, referred to as χ^2 test. This test will assess whether a significant difference between the anticipated output produced by the TTD method and VISSIM exists or not in one or more than one interval. This method will also indicate whether a significant difference between observed and anticipated results occurs due to sampling variation. This will be indicated if a significant difference is present in the number of individuals anticipated from the number of individuals falling in each interval. The chi-square is explained as follows:

$$x^2 = \sum_{s=1}^{S} \frac{(O-E)^2}{E} \tag{24}$$

where; x^2 is the value for chi-square. S and s are the total interval number and the interval index, respectively. Whereas S and $\boldsymbol{s}$ are the observed and the expected frequencies, respectively.

A chi-square test examined whether significant differences exist among VISSIM and TTD out delays under varying traffic conditions. The chi-square test results are depicted in Table 3. The level of significance ($\alpha = 0.05$) was used in the chi-square test to test the null hypothesis. The degree of freedom is written as df = 12-1 = 11, as the simulation test contained 12 intervals of categories. Analyzing the χ^2 value from the distribution table with df = 11 and α =0.05 showed that $\chi^2{}_{11,0.05} = 19.675$. The null hypothesis Ho cannot be rejected as the chi-square tabulated value is more than the calculated chi-square values. This shows that estimated delays from VISSIM and TTD have no significant difference.

The null hypothesis (H_0) said there is no difference between TTD and VISSIM outputs, and the Alternative

$$DTT_{ti} = \frac{1}{V}\begin{bmatrix}
D_{5-1} & D_{8-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & D_{5-2} & D_{6-2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & D_{6-3} & D_{7-3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & D_{7-4} & D_{8-4} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{1-5} & D_{2-5} & D_{9-5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{2-6} & D_{3-6} & D_{9-6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{3-7} & D_{4-7} & D_{9-7} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{1-8} & D_{2-8} & D_{9-8} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & D_{5-9} & D_{6-9} & D_{7-9} & D_{8-9}
\end{bmatrix} \times \begin{bmatrix}
N^{5-1} \\ N^{8-1} \\ N^{5-2} \\ N^{6-2} \\ N^{6-3} \\ N^{7-3} \\ N^{7-4} \\ N^{8-4} \\ N^{1-5} \\ N^{2-5} \\ N^{9-5} \\ N^{2-6} \\ N^{3-6} \\ N^{9-6} \\ N^{3-7} \\ N^{4-7} \\ N^{9-7} \\ N^{1-8} \\ N^{4-8} \\ N^{9-8} \\ N^{5-9} \\ N^{6-9} \\ N^{7-9} \\ N^{8-9}
\end{bmatrix} \tag{23}$$

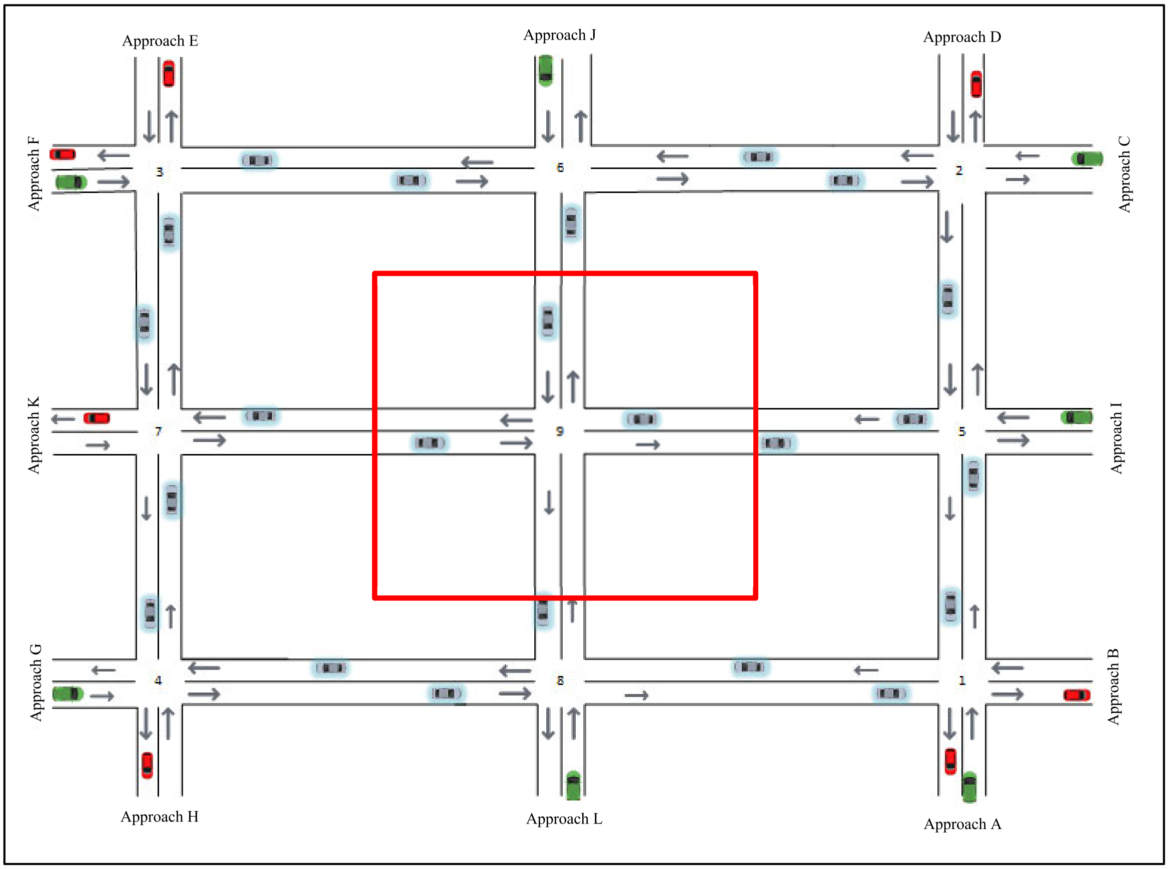

FIGURE 12. Nine network analysis with one intermediate intersection.

TABLE 2. The estimated TTD and VISSIM result of average delay.

Volume level	Estimated TTD (Sec)									VISSIM results (Sec)								
	Case (1)			Case (2)			Case (3)			Case (1)			Case (2)			Case (3)		
	TM%																	
	70%	80%	90%	70%	80%	90%	70%	80%	90%	70%	80%	90%	70%	80%	90%	70%	80%	90%
Low	32.28	33.1	34.57	53.43	55.16	60.79	60.83	64.11	67.35	32.44	33.54	34.69	53.12	55.37	60.16	60.82	64.40	67.78
Medium	40.66	43.14	46.17	75.86	81.94	94.12	68.35	72.19	76.59	40.74	43.51	46.47	76.22	81.85	93.73	68.06	71.76	76.81
High	61.95	64.84	71.64	141.41	146.59	152.20	93.66	97.90	97.53	61.85	65.22	71.66	141.98	146.48	151.73	92.79	98.12	97.70

Hypothesis (H_1) said there is a significant difference between TTD and VISSIM outputs. The result from the chi-square test and the value of this test is (0.11, 0.22, and 0.25) for different traffic volume levels < the critical value (19.68). Thus, we concluded that there is no significant difference between the outputs. The same procedure was done for other TM percentages; in all cases, the H0 is accepted. Also, the method has achieved Mean Square Error (MSE) and Mean Absolute Error (MAE) values of 1.25% and 2.45%, respectively, by which the proposed method's efficiency could be proved.

Interestingly, the proposed method is a generalization of delay estimation at individual intersections, which simply places the detector upstream and downstream of an intersection. Although fine-tuning individual signal timings is a well-established topic in the literature, tracking network delays resulted from intersection timings deemed missing. In management scenarios, it is essential to have granular information on delays at specific intersections. However, the aggregate intersection delays manage to judge timing synchronization plans. Therefore, this study makes an essential contribution to the literature.

VII. CONCLUSION

This study proposes a novel methodology that can use the collected traffic data to estimate real-time network control delay. These include arrivals, departures, and turning movement vehicle data. Moreover, the study also evaluated the proposed methodology's efficiency under different traffic situations. At signalized intersections, the most essential measures of effectiveness are vehicle delay and travel time, which allow traffic engineers to assess the performance of a traffic engineering component or system. The key to estimating

TABLE 3. Generalized network chi-square analysis at 70% varying traffic volume and TM approach.

Turning Movement Percentage (veh/hr)	70%Th, 15 % L, 15 %R					
Approach Demand	High Traffic		Med Traffic		Low Traffic	
Time Interval (Sec)	TTD	VISSIM	TTD	VISSIM	TTD	VISSIM
0~300	55.806	54.478	40.403	40.395	29.999	31.035
300~600	67.613	69.252	49.052	49.510	36.220	35.120
600~900	66.258	66.522	43.297	42.502	38.307	38.803
900~1200	77.395	76.899	45.915	47.044	34.221	35.709
1200~1500	71.228	72.706	43.564	44.252	32.862	32.927
1500~1800	75.013	73.430	45.391	45.390	33.967	34.426
1800~2100	71.092	72.289	49.159	49.704	35.685	34.836
2100~2400	75.208	75.764	43.994	44.240	32.409	33.134
2400~2700	75.918	75.082	47.286	47.071	33.036	33.128
2700~3000	71.799	73.049	49.421	49.848	33.929	34.770
3000~3300	75.592	75.076	46.665	48.033	35.360	34.509
3300~3600	76.732	75.304	49.932	49.749	38.881	37.908
df=(r-1)(k-1)	*df*=11	$\chi^2 11_{,0.05}$ = 0.25	*df*=11	$\chi^2 11_{,0.05}$ = 0.22	*df*=11	$\chi^2 11_{,0.05}$ = 0.11
Chi-square Test	0.25 < 19.675 α=0.05 , Accept *Ho*		0.22 < 19.675 α=0.05 , Accept *Ho*		0.11 < 19.675 α=0.05 , Accept *Ho*	

performance measures for a traffic system, such as travel time and delay, is to estimate intersection turning movements in real-time. This is mainly due to the fact that vehicle delay and travel time can be easily calculated from turning movement data by knowing the activation and deactivation timestamp for each detector. This study's models require data from detectors that record traffic volume and timestamps. As a result, the detectors are installed at the traffic network's entrances and exits. The traffic network model is expanded in this work to estimate the average delay and travel time in three case studies: simple, semi-generalized, and generalized networks. The TTD model introduces a new technique for determining the average delay time in each of the three case studies. This study investigated and implemented network strategies based on the TTD model. In establishing TTD for traffic networks, the limitations and problems of existing traffic performance measurement methodologies are addressed. The suggested methods' capability to estimate measures of effectiveness, such as vehicle delay and travel time, has been demonstrated through simulation-based evaluation findings. For the TTD, simulations have demonstrated the proposed method's ability to estimate vehicle delay by accurately utilizing real-time information from detectors. VISSIM was used to determine the performance of TTD and reliability in simple traffic networks under various traffic scenarios. The results of TTD are found to be highly encouraging. They show an interesting potential for expanding the methodology to large-scale data applications, such as a semi-generalized network (nine intersections) and a generalized network (sixteen intersections). It is worth noting that while the theoretically studied examples are idealized grid networks, the solution method does not demand any special geometrization for the studied network. TTD results acquired from the suggested methods were compared to VISSIM, and statistical tests were performed under different traffic conditions. The results demonstrate that both techniques can produce reliable findings under varying traffic conditions, and outputs are very stable. This work has highlighted several areas that might help improve network traffic delay estimation, and this article is simply the first step in developing performance measurement models. Since the simulation findings are so limited, more scenarios should be investigated for each system. Future studies should include specific severe scenarios, such as traffic accidents or oversaturated environments. Furthermore, the study opens the gate for applying artificial intelligence techniques (e.g., reinforced learning to optimize traffic signals in real-time as the network delays are estimated in real-time.

RESEARCH DATA AND CODES

The codes are available upon request from the corresponding author, Dr. Mahmoud Owais, maowais@aun.edu.eg.

REFERENCES

[1] M. Owais, O. Abulwafa, and Y. A. Abbas, "When to decide to convert a roundabout to a signalized intersection: Simulation approach for case studies in Jeddah and Al-Madinah," *Arabian J. Sci. Eng.*, vol. 45, no. 10, pp. 7897–7914, Oct. 2020.

[2] H. Liu, L. Rai, J. Wang, and C. Ren, "A new approach for real-time traffic delay estimation based on cooperative vehicle-infrastructure systems at the signal intersection," *Arabian J. Sci. Eng.*, vol. 44, no. 3, pp. 2613–2625, Mar. 2019.

[3] X. Li, "The symmetric intersection design and traffic control optimization," *Transp. Res. C, Emerg. Technol.*, vol. 92, pp. 176–190, Jul. 2018.

[4] Z. Wang, S. Chen, H. Yang, B. Wu, and Y. Wang, "Comparison of delay estimation models for signalised intersections using field observations in Shanghai," *IET Intell. Transp. Syst.*, vol. 10, no. 3, pp. 165–174, Apr. 2016.

[5] A. S. Mane and S. S. Pulugurtha, "Applicability of unconventional intersection designs over pretimed signalized intersection design along a coordinated corridor," *Transp. Res.*, vol. 45, pp. 503–516, Oct. 2019.

[6] E. Hauer, J. C. Ng, and J. Lovell, "Estimation of safety at signalized intersections," *Transp. Res. Rec.*, vol. 1185, pp. 48–61, 1988.

[7] C. A. Quiroga and D. Bullock, "Measuring control delay at signalized intersections," *J. Transp. Eng.*, vol. 125, no. 4, pp. 271–280, Jul. 1999.

[8] B. W. Robinson, L. Rodegerdts, W. Scarborough, W. Kittelson, R. Troutbeck, W. Brilon, L. Bondizio, K. Courage, M. Kyte, and J. Mason, *Roundabouts: An Informational Guide*. Washington, DC, USA: Federal Highway Administration, 2000.

[9] H. Lin, Y. Han, W. Cai, and B. Jin, "Traffic signal optimization based on fuzzy control and differential evolution algorithm," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 8, pp. 8555–8566, 2022.

[10] J. Sanguesa, J. Barrachina, M. Fogue, P. Garrido, F. Martinez, J.-C. Cano, C. Calafate, and P. Manzoni, "Sensing traffic density combining V2V and V2I wireless communications," *Sensors*, vol. 15, no. 12, pp. 31794–31810, Dec. 2015.

[11] M. Owais and A. Alshehri, "Pareto optimal path generation algorithm in stochastic transportation networks," *IEEE Access*, vol. 8, pp. 58970–58981, 2020.

[12] M. Owais, G. S. Moussa, and K. F. Hussain, "Sensor location model for O/D estimation: Multi-criteria meta-heuristics approach," *Oper. Res. Perspect.*, vol. 6, Feb. 2019, Art. no. 100100.

[13] M. Owais, "Deep learning for integrated origin-destination estimation and traffic sensor location problems," *IEEE Trans. Intell. Transp. Syst.*, early access, 2024. [Online]. Available: https://doi.org/10.1109/TITS.2023.3344533

[14] M. Owais and A. I. Shahin, "Exact and heuristics algorithms for screen line problem in large size networks: Shortest path-based column generation approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 12, pp. 24829–24840, Dec. 2022.

[15] T.-J. Ho and M.-J. Chung, "An approach to traffic flow detection improvements of non-contact microwave radar detectors," in *Proc. Int. Conf. Appl. Syst. Innov. (ICASI)*, May 2016, pp. 1–4.

[16] M. Owais, "Location strategy for traffic emission remote sensing monitors to capture the violated emissions," *J. Adv. Transp.*, vol. 2019, pp. 1–9, Mar. 2019.

[17] M. Owais, M. El Deeb, and Y. A. Abbas, "Distributing portable excess speed detectors in AL Riyadh City," *Int. J. Civil Eng.*, vol. 18, no. 11, pp. 1301–1314, Nov. 2020.

[18] R. Dowling, "Traffic analysis toolbox volume VI: Definition, interpretation, and calculation of traffic analysis tools measures of effectiveness," Office of Operations, Federal Highway Administration, Washington, DC, USA, Tech. Rep. FHWA-HOP-08-054, 2007.

[19] I. Shatnawi, P. Yi, and I. Khliefat, "Automated intersection delay estimation using the input–output principle and turning movement data," *Int. J. Transp. Sci. Technol.*, vol. 7, no. 2, pp. 137–150, Jun. 2018.

[20] A. J. Miller, "Settings for fixed-cycle traffic signals," *J. Oper. Res. Soc.*, vol. 14, no. 4, pp. 373–386, Dec. 1963.

[21] A. Verma, G. Nagaraja, C. S. Anusha, and S. K. Mayakuntla, "Traffic signal timing optimization for heterogeneous traffic conditions using modified Webster's delay model," *Transp. Developing Economies*, vol. 4, no. 2, Oct. 2018.

[22] R. Akçelik, "Progression factors in the HCM 2000 queue and delay models for traffic signals," Akcelik Associates Pty Ltd, Melbourne, VIC, Australia, Tech. Rep., 2001.

[23] M. Owais, A. S. Ahmed, G. S. Moussa, and A. A. Khalil, "Integrating underground line design with existing public transportation systems to increase transit network connectivity: Case study in greater Cairo," *Expert Syst. Appl.*, vol. 167, Apr. 2021, Art. no. 114183.

[24] M. Owais, A. S. Ahmed, G. S. Moussa, and A. A. Khalil, "An optimal metro design for transit networks in existing square cities based on non-demand criterion," *Sustainability*, vol. 12, no. 22, p. 9566, Nov. 2020.

[25] Z. Z. Tian, T. Urbanik, R. Engelbrecht, and K. Balke, "Variations in capacity and delay estimates from microscopic traffic simulation models," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 1802, no. 1, pp. 23–31, Jan. 2002.

[26] W. Kebab, M. P. Dixon, and A. Abdel-Rahim, "Field measurement of approach delay at signalized intersections using point data," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2027, no. 1, pp. 37–44, Jan. 2007.

[27] M. Owais, "Traffic sensor location problem: Three decades of research," *Expert Syst. Appl.*, vol. 208, Dec. 2022, Art. no. 118134.

[28] M. Owais, G. S. Moussa, and K. F. Hussain, "Robust deep learning architecture for traffic flow estimation from a subset of link sensors," *J. Transp. Eng., A, Syst.*, vol. 146, no. 1, Jan. 2020, Art. no. 04019055.

[29] J. Ko, M. Hunter, and R. Guensler, "Measuring control delay components using second-by-second GPS speed data," *J. Transp. Eng.*, vol. 134, no. 8, pp. 338–346, Aug. 2008.

[30] Y. Cai, W. Zhang, and H. Wang, "Measurement of vehicle queue length based on video processing in intelligent traffic signal control system," in *Proc. Int. Conf. Measuring Technol. Mechatronics Autom.*, vol. 2, Mar. 2010, pp. 615–618.

[31] M. Saito and T. Forbush, "Automated delay estimation at signalized intersections: Phase I concept and algorithm development," Utah Dept. Transp., Taylorsville, UT, USA, Tech. Rep. UT-11.05, 2011.

[32] M. Sadat and H. B. Celikoglu, "Simulation-based variable speed limit systems modelling: An overview and a case study on Istanbul freeways," *Transp. Res. Proc.*, vol. 22, pp. 607–614, Jan. 2017.

[33] M. Sadat, I. M. Abuamer, M. A. Silgu, and H. B. Celikoglu, "A comparative performance analysis of variable speed limit systems control methods using microsimulation: A case study on D100 Freeway, Istanbul," in *Proc. Int. Conf. Comput. Aided Syst. Theory*. Cham, Switzerland: Springer, 2017, pp. 462–469.

[34] I. M. Abuamer, M. A. Silgu, and H. B. Celikoglu, "Micro-simulation based ramp metering on Istanbul freeways: An evaluation adopting ALINEA," in *Proc. IEEE 19th Int. Conf. Intell. Transp. Syst. (ITSC)*, Nov. 2016, pp. 695–700.

[35] I. M. Abuamer, M. Sadat, M. A. Silgu, and H. B. Celikoglu, "Analyzing the effects of driver behavior within an adaptive ramp control scheme: A case-study with ALINEA," in *Proc. IEEE Int. Conf. Veh. Electron. Saf. (ICVES)*, Jun. 2017, pp. 109–114.

[36] R. Akçelik, "Roundabout model calibration issues and a case study," in *Proc. TRB Nat. Roundabout Conf.*, Vail, CO, USA, 2005, p. 25.

[37] M. A. Silgu, K. Muderrisoglu, A. H. Unsal, and H. B. Celikoglu, "Approximation of emission for heavy duty trucks in city traffic," in *Proc. IEEE Int. Conf. Veh. Electron. Saf. (ICVES)*, Sep. 2018, pp. 1–4.

[38] İ. G. Erdağı, M. A. Silgu, and H. B. Çelikoğlu, "Emission effects of cooperative adaptive cruise control: A simulation case using SUMO," *EPiC Ser. Comput.*, vol. 62, pp. 92–100, Aug. 2019.

[39] M. Owais and M. K. Osman, "Complete hierarchical multi-objective genetic algorithm for transit network design problem," *Expert Syst. Appl.*, vol. 114, pp. 143–154, Dec. 2018.

[40] A. Alshehri, M. Owais, J. Gyani, M. H. Aljarbou, and S. Alsulamy, "Residual neural networks for origin-destination trip matrix estimation from traffic sensor information," *Sustainability*, vol. 15, no. 13, p. 9881, Jun. 2023.

[41] G. S. Moussa, M. Owais, and E. Dabbour, "Variance-based global sensitivity analysis for rear-end crash investigation using deep learning," *Accident Anal. Prevention*, vol. 165, Feb. 2022, Art. no. 106514.

[42] M. Owais and T. Hassan, "Incorporating dynamic bus stop simulation into static transit assignment models," *Int. J. Civil Eng.*, vol. 16, no. 1, pp. 67–77, Jan. 2018.

[43] M. Owais, A. S. Ahmed, G. S. Moussa, and A. A. Khalil, "Design scheme of multiple-subway lines for minimizing passengers transfers in megacities transit networks," *Int. J. Rail Transp.*, vol. 9, no. 6, pp. 540–563, Nov. 2021.

[44] G. S. Moussa and M. Owais, "Pre-trained deep learning for hot-mix asphalt dynamic modulus prediction with laboratory effort reduction," *Construct. Building Mater.*, vol. 265, Dec. 2020, Art. no. 120239.

[45] G. S. Moussa and M. Owais, "Modeling hot-mix asphalt dynamic modulus using deep residual neural networks: Parametric and sensitivity analysis study," *Construct. Building Mater.*, vol. 294, Aug. 2021, Art. no. 123589.

[46] M. Owais, "Analysing Witczak 1–37A, Witczak 1–40D and modified Hirsch models for asphalt dynamic modulus prediction using global sensitivity analysis," *Int. J. Pavement Eng.*, vol. 24, no. 1, pp. 1–37, Dec. 2023, Art. no. 2268808.

[47] F. Guo, Y. Wang, and Y. Qian, "Computer vision-based approach for smart traffic condition assessment at the railroad grade crossing," *Adv. Eng. Informat.*, vol. 51, Jan. 2022, Art. no. 101456.

[48] L. K. Idriss and M. Owais, "Global sensitivity analysis for seismic performance of shear wall with high-strength steel bars and recycled aggregate concrete," *Construct. Building Mater.*, vol. 411, Jan. 2024, Art. no. 134498.

[49] V. Shepelev, A. Glushkov, Z. Almetova, and V. Mavrin, "A study of the travel time of intersections by vehicles using computer vision," in *Proc. 6th Int. Conf. Vehicle Technol. Intell. Transp. Syst.*, 2020, pp. 653–658.

[50] H. Liu, J.-S. Oh, and W. Recker, "Adaptive signal control system with online performance measure for a single intersection," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 1811, no. 1, pp. 131–138, Jan. 2002.

[51] S. Feng, Y. Ci, L. Wu, and F. Zhang, "Vehicle delay estimation for an isolated intersection under actuated signal control," *Math. Problems Eng.*, vol. 2014, pp. 1–7, Jan. 2014.

[52] H. Hanabusa, M. Iijima, and R. Horiguchi, "Development of delay estimation method using probe data for adaptive signal control algorithm," in *Knowledge-Based and Intelligent Information and Engineering Systems* (Lecture Notes in Computer Science), vol. 6279, R. Setchi, I. Jordanov, R. J. Howlett, and L. C. Jain, Eds. Berlin, Germany: Springer, 2010, doi: 10.1007/978-3-642-15384-6_33.

[53] A. Sharma, D. M. Bullock, and J. A. Bonneson, "Input–output and hybrid techniques for real-time prediction of delay and maximum queue length at signalized intersections," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2035, no. 1, pp. 69–80, Jan. 2007.

[54] C. Shao, *Adaptive Control Strategy for Isolated Intersection and Traffic Network*. Akron, OH, USA: Univ. Akron, 2009.

[55] P. Hunt, D. Robertson, R. Bretherton, and R. Winton, "SCOOT—A traffic responsive method of coordinating signals," Source Agency, Transp. Res. Lab., Tech. Rep. LR 1014 Monograph, 1981.

[56] U. Dutta, J. Lynch, B. Dara, and S. Bodke, "Safety evaluation of the scats control system," Geographical Coverage, Michigan, Tech. Rep. RC-1545, 2010.

[57] N. H. Gartner, F. J. Pooran, and C. M. Andrews, "Implementation of the OPAC adaptive control strategy in a traffic signal network," in *Proc. IEEE Intell. Transp. Syst. (ITSC)*, 2001, pp. 195–200.

[58] P. Yi, C. Shao, and Y. Wang, "Piecewise optimum delay estimation for improved signal control," *Transp. Res. Rec.*, vol. 2080, no. 1, pp. 57–66, Jan. 2008.

[59] *Highway Capacity Manual (HCM)*, Transp. Res. Board, Washington, DC, USA, 2010.

[60] *HS Series*, Federal Highway Admin., Washington, DC, USA, vol. 20, 1996.

[61] Q. A. Jawad and A. K. Ali, "Comparison of CVT performance with the manual and automatic transmission for evaluation the fuel consumption and exhaust emissions," *Basrah J. Eng. Sci.*, vol. 20, no. 1, pp. 15–22, Mar. 2020.

[62] C. Cheng, Y. Du, L. Sun, and Y. Ji, "Review on theoretical delay estimation model for signalized intersections," *Transp. Rev.*, vol. 36, no. 4, pp. 479–499, Jul. 2016.

[63] K. Xu, P. Yi, C. Shao, and J. Mao, "Development and testing of an automatic turning movement identification system at signalized intersections," *J. Transp. Technol.*, vol. 3, no. 4, pp. 241–246, 2013.

[64] I. M. Shatnawi, *Automated Vehicle Delay and Travel Time Estimation Techniques for Improved Performance Measures of Urban Network System*. Akron, OH, USA: Univ. Akron, 2015.

[65] A. Stevanovic, N. Dobrota, and N. Mitrovic, "Benefits of adaptive traffic control deployments—A review of evaluation studies," NCHRP, Washington, DC, USA, Tech. Rep. NCHRP 20-07/Task 414, 2019.

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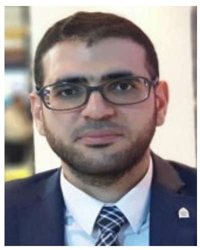

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