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Research Paper

Assessing the impact of bicycle infrastructure on safety and operations using microsimulation and surrogate safety measures: A case study in Downtown Atlanta

Katherine Lee [a], Amirarsalan Mehrara Molan [b,*], Anurag Pande [a], Uijeong Hwang [c], Subhrajit Guhathakurta [c], Mirabel Nkanor [b], Benedetta Sergio [d]

[a] Department of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA 93407, United States
[b] Department of Civil Engineering, University of Mississippi, University, MS 38677, United States
[c] School of City and Regional Planning, Georgia Institute of Technology, Atlanta, GA 30332, United States
[d] Department of Civil Engineering, University of Naples, Naples, Italy

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ABSTRACT

This research assessed the impact of efficiently expanding the biking network in Atlanta, Georgia, using dedicated lanes for bicycles. A total of three different conditions, i.e., existing, proposed (by the authors), and alternative (suggested by the City of Atlanta) conditions, were modeled to see the effectiveness of bike infrastructure design improvement and expansion. Trajectory data collected from the VISSIM simulation model were used in the Federal Highway Administration (FHWA)'s surrogate safety assessment model (SSAM) to analyze the safety effect on the bike infrastructure improvement and expansion. Based on the results, both the proposed and alternative conditions resulted in safer travel through the network during the peak hour period without any apparent deterioration in delays. For instance, compared to the existing condition, the average stop delays decreased from 190 s to 164 s for the proposed and the alternative conditions. These findings showed that the introduction of bicycle lanes and narrower lanes for automobiles may not adversely affect the peak hour congestion. Also, fewer conflicts were observed in the simulated network of proposed and alternative conditions compared to existing conditions. Conflicts involving bicyclists were also reduced since the bicyclists can use their own lanes and do not have to interact with automobile traffic in the sharrows.
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1. Introduction

The transportation system in the United States has traditionally prioritized the mobility of private automobiles, resulting in pollution, congestion, socioeconomic disparities, and inefficient use of scarce resources such as land and energy. Besides, vehicle-centric designs have created obstacles for pedestrians, bicyclists, and public transportation users, thereby restricting opportunities for active transportation. Streets will need to be made safe and convenient for all people, including children,

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* Corresponding author.
E-mail address: amehrara@olemiss.edu (A. Mehrara Molan).

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the elderly, and the disabled. Given that a significant portion of highway infrastructure in the United States, including streets, intersections, and interchanges, was constructed over 60 years ago under outdated policies with minimal consideration for pedestrians and bicyclists, there persist notable operational and safety issues related to pedestrian and bicycle facilities (Mehrara Molan and Hummer, 2018; Molan et al., 2019; Liu et al., 2021). Approximate 1 000 bicyclists lose their lives, and more than 130 000 sustain injuries in crashes on United States' roads each year (U.S. Centers for Disease Control and Prevention, 2023). While bicycle trips constitute just 1% of all journeys in the United States, bicyclists represent over 2% of individuals who lose their lives in motor vehicle-related crashes on the nation's roads (U.S. Centers for Disease Control and Prevention, 2023). According to a survey, 66% of Americans want more transportation options, so they have the freedom to choose how to get from one place to another, as 73% feel like they do not have a choice but to drive as their main mode of transportation, and 53% would like to spend less time in the car (Transportation For America, 2023). In addition to the automobile focus, economies and populations of major cities continue to increase, rendering city streets that focus on single-occupancy vehicles unable to support the travel needs of businesses, tourists, and residents.

A sustainable solution for enhancing the efficiency and livability of growing cities like Atlanta must incorporate an urban transport system that safely and effectively accommodates all modes of travel, such as walking, biking, and transit. The implementation of the "complete streets" policy will deemphasize the dominance of automobiles and transform streets to accommodate multimodal travel like biking and walking. One method to achieve this is to implement the "complete streets" policy to transform streets right-of-way (ROW) to accommodate multiple active modes of travel such as walking and biking. The policy on "complete streets", i.e., streets designed to enable safety and mobility to all users, plays a crucial part in transforming streets to accommodate multiple modes of transportation, especially active modes like biking and walking. One strategy to achieve complete street transformation is to connect isolated street segments to form a complete network that improves active mobility and public transit ridership. Such network-conscious implementation of the complete streets policy will deemphasize the dominance of automobiles and transform streets to accommodate multimodal travel like biking and walking.

Based on past studies (Carter et al., 2013; Chen et al., 2018; Elias, 2011; Karpinski, 2021), the anticipation is that an improved bike lane network will boost the safety and comfort for cyclists, leading to increased participation in biking. However, adding new bike lanes in urban areas comes with its own set of challenges, including limited space, safety concerns, and possible traffic congestion (as a result of converting traffic lanes to bike lanes). Reviewing the literature, there is limited knowledge regarding the impact of new bike lanes on vehicular traffic operation and safety, especially in growing cities like Atlanta, GA. Therefore, this research aims to provide new insights into the literature by examining the impact of new bicycle infrastructure in urban areas, not only on cyclists but also on vehicular traffic.

There are two main objectives of this study. Firstly, a microsimulation model will be used to assess the operational impacts of efficiently and equitably connected proposed bicycle networks compared to the existing network designs. Secondly, the potential safety impacts of the changes to the network will be assessed. Both operational and safety evaluations will also be conducted on two possible modal shift scenarios described later in the paper. In other words, a microsimulation model will support the evaluation of the operational and safety effectiveness of street network design changes at varying demand scenarios.

This study encompassed a simulation environment, with an approximate size of 4.015 square miles, to assess bicycle infrastructure within an urban network, Downtown Atlanta. The authors hope that the findings will assist transportation professionals in the decision-making process related to bicycle infrastructure in urban networks experiencing high demands and growth rates for various transportation modes.

The following sections provide a literature review of past relevant works, a description of the network's modeling procedure, an analysis of bicyclist/vehicular traffic behavior, and conclusions. The literature review will provide information on traffic simulation (PTV VISSIM), complete streets, and how bike users are affected by complete streets transformations. The next section of the paper will outline the development of the model, detailing the data collection process, calibration, and validation for the base (existing) conditions. Subsequent sections will describe the evaluation of the effectiveness of street design changes at varying demand scenarios and then summarize the safety effects of bike infrastructure improvements along with potential shifts in mode choices. The last section will summarize the conclusions and provide recommendations for future work.

2. Literature review

Roads that are built for everyone are defined as "complete streets". They are streets designed and operated to prioritize safety, comfort, and accessibility to various designations for all people who utilize the streets, especially those with disabilities, older adults, and young children. They typically include sidewalks, bike lanes, bus lanes, comfortable and accessible public transportation stops, frequent and safe crossing opportunities, median islands, accessible pedestrian signals, curb extensions, narrower travel lanes, roundabouts, and more (Smart Growth America, 2023). USDOT has reported that complete street conversion promotes a safer place for transportation-related physical activities like walking and bicycling, reducing the number of motor vehicle-related crashes (US Department of Transportation, 2023). Another study reported a 37% increase in pedestrian safety and a 26% decrease in emission-weighted traffic volume due to complete street implementation (US Department of Transportation, 2023). Overall, complete street networks bring a wide variety of direct and indirect ben-

efits, such as more livable communities, fewer energy consumptions, improvement in equity, safety, public health, and lower greenhouse gas emissions.

As this study focuses on the bike network in Atlanta, it is important to understand how biking and pedestrian infrastructures make the streets more "complete". In Atlanta, biking and shared micro-mobility are rapidly growing modes of travel throughout the city, and both travel modes will benefit from dedicated bike lanes. According to the USDOT, improving bicycle and pedestrian infrastructure means ensuring that a network of infrastructure is in place to make bicycling or walking viable, safe, and comfortable modes of travel. Complete street transformations to include bicycle infrastructure physically separate bicyclists from vehicles, thus helping to increase bicyclists' safety, increase bicycle use, and support safe bicycle travel (Pucher and Buehler, 2012). Additionally, Carter et al. (2013) compared the level of service (LOS) of each type of road user after complete street interventions. They showed that bicycle LOS improved more than any other mode. A similar analysis indicated that designated bike lanes significantly improved bike LOS while the LOS of pedestrians who have already had sidewalks was not much affected by complete street elements (Elias, 2011). A recent study (Karpinski, 2021) investigated the impact of the installation of a protected bike lane, in Boston, Massachusetts, on the proximate ridership of 'BlueBikes', a local bicycle-sharing system (bikeshare). Based on the results, the impact of the bike lane was most pronounced when trip origins and destinations were within a short distance (less than one mile) from the bike lane.

While bicycle LOS and connectivity were used for the evaluation of bike networks, few studies have considered the aspects of transit access, equity, and overall network performance. Furthermore, while there have been studies documenting reduced conflicts and delays resulting from adding bicycle lanes on individual streets (Chen et al., 2018), overall network effects have not been documented. Furthermore, the popular media articles still fuel the perception that adding bicycle lanes and complete infrastructure necessarily means increased automobile delays (e.g., (Collins, 2023)). Hence, research that quantifies network-wide safety and operational effects of the complete networks is still needed.

Simulation modeling is an increasingly popular and effective tool used to analyze the behavior and interactions of traffic systems via dynamic representations using computer models. Azlan et al. (2018) explained that these models optimize the use of resources to organize the effective functioning of the transportation system and accurately recreate traffic as observed and measured on the street and can be applied to plan and manage the traffic within a road network. Modern simulation models are based on random vehicular movements that aim to mimic driver behaviors. Therefore, simulation models can provide an answer to "what-if" questions to aid system designers in assessing the impact of various changes on existing systems in a cost-effective way (Yang et al., 2000). There are three classifications of traffic simulation models: microscopic (high fidelity), macroscopic (low fidelity), and mesoscopic (mixed fidelity) modeling. This study used PTV VISSIM (Version 2020), which is a well-known microsimulation package globally. Microscopic modeling is based on characteristics of various vehicle movements, such as cars, buses, and motorcycles, in the traffic flow and describes how traffic states evolve (Authors et al., 2015). Rathi et al. (1986) describe macroscopic modeling as the intersections at a low level of detail. It takes place on a section-by-section basis rather than by tracking individual vehicles. Here, the traffic stream is measured in terms of characteristics like speed, flow, and density (HWA Operations, 2023). For this study, VISSIM was chosen due to the software's ability to analyze multimodal traffic, such as bicycles, automobiles, and pedestrians, as well as transit operations under constraints such as lane configuration, traffic composition, traffic signals, transit stops, and other similar criteria (PTV AG, 2018).

3. Case study area and network modeling

The location of interest, Atlanta, Georgia, is home to more than 500 000 people according to the United States Census Bureau (U.S. Census Bureau, 2023). Atlanta attracts many new residents, businesses, and tourists, resulting in tremendous growth. For a city, the size of Atlanta to be efficient and livable, urban transport systems should be able to accommodate all modes of travel, such as walking, biking, and transit, more effectively. The study area in Fig. 1 consists of the entirety of downtown Atlanta (4.015 square miles).

The study focuses on the bike network in the Atlanta metropolitan region due to multiple factors. The first is that biking and shared micro-mobility modes are rapidly growing as modes of travel in Atlanta, and users of both modes benefit from dedicated bike lanes. The second is that having dedicated bike lanes will ensure safety and comfort for all road users, not just bicyclists. Third, cycling infrastructure is typically the least well-developed among other facilities and services dedicated to various modes of transportation. The last factor would be improving cycling infrastructure to encourage people to ride a bike, which promotes clean energy, better public health, and a cleaner environment.

The research team worked with various stakeholders to obtain the base network of midtown and downtown Atlanta. Shapefiles and other data sets were collected to build a base map in ArcMap. The street network of downtown Atlanta and most of midtown Atlanta was modeled using PTV VISSIM. The City of Atlanta provided signal timing and traffic volumes based on an existing Synchro (version 11) model for the street network. Synchro is a traffic signal optimization software developed by Trafficware, which is widely used for traffic engineering analysis and signal timing optimization (Molan and Hummer, 2018; Cubic Transportation Systems, 2023). The network was modeled with weekday PM peak hour travel demand to replicate the most congested period within Atlanta, Georgia. Fig. 2 shows the location of all signalized intersections within the study area. This section explains the network modeling, calibration, and validation procedures.

Within the network, signal timing, lane geometry, speed limits, and traffic counts were embedded within the base network. The general lane geometrics included both automobiles and bike lanes. Still, there was no clear differentiation between

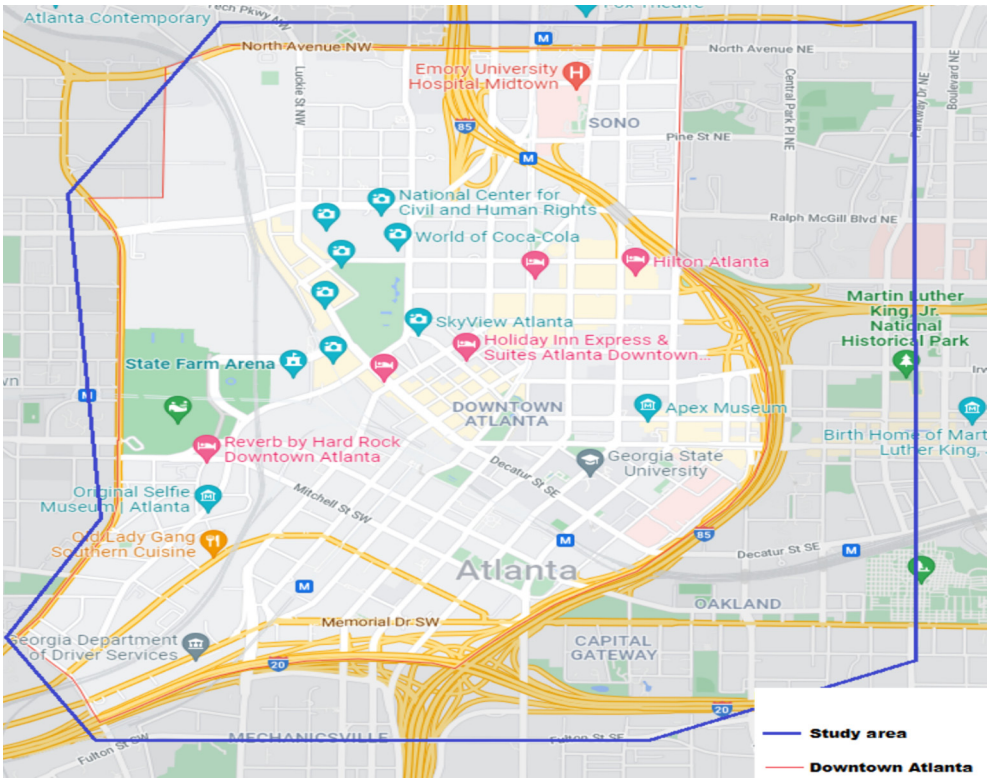

Fig. 1. Study area map (Google Maps).

vehicle and bike counts, nor did the Synchro network classify the existing bike lanes within the existing network. The complete network consisted of 214 intersections and 3 700 links resulting in a total length of 757 361 feet (143.5 miles) in the network shown in Fig. 3. Fig. 3 displays a downtown model and a midtown model in both Synchro 11 and VISSIM (version 2020).

As the model's primary focus is to evaluate biking infrastructure expansion and improvements within downtown and midtown, freeway mainline segments were not included in the model. However, it should be noted that there were freeways (defined as divided arterial highways with full control of access and with grade separations at intersections) that connected with the simulated network of urban streets. While the research team have not modeled these freeways, they do act as source and sink for the traffic that enters (and exists) the modeled network. In other words, we are referring to the freeway off-ramps that feed traffic to simulated network as origins and on-ramps that take traffic out of the network as destination since the freeways themselves are not modeled. In addition to parking lots, off-ramps and on-ramps to the area freeways connected to the downtown street network serve as origins and destinations in the VISSIM model. A visualization of the existing bike infrastructure modeled in VISSIM on ArcGIS ArcMap 10.8 is shown in Fig. 4.

As the last step of simulation modeling, trajectory (trj) files were extracted from PTV VISSIM models to identify simulated conflicts (also known as near misses) utilizing surrogate safety assessment model (SSAM). SSAM is a software application developed to automatically identify, classify, and evaluate traffic conflicts in the vehicle trajectory data output from microscopic traffic simulation models (Gettman et al., 2008). Safety performance can be examined through analysis of surrogate measures of safety, such as conflicts identified using post-encroachment (PET) or time-to-collision (TTC). Overall, SSAM is a promising approach to assessing the safety of new facilities, innovative designs, or traffic regulation schemes. SSAM was used in this study to analyze and estimate the number of potential conflicts within the whole study network. There are three categories of conflicts based on the type of crash each conflict correlates with, i.e., crossing, rear-end, and lane-change collisions. Fig. 5 illustrates the thresholds considered by SSAM to identify various types of simulated conflicts (Gettman et al., 2008).

SSAM-generated outputs were divided by the total simulated number of vehicles within the entire network to estimate a normalized measure of crash risk. This study considered a TTC equal to 1.5 for identifying simulated conflicts, as suggested in past studies (Fan et al., 2013; Haq et al., 2022; Huang et al., 2013; Luo et al., 2024; Molan et al., 2021).

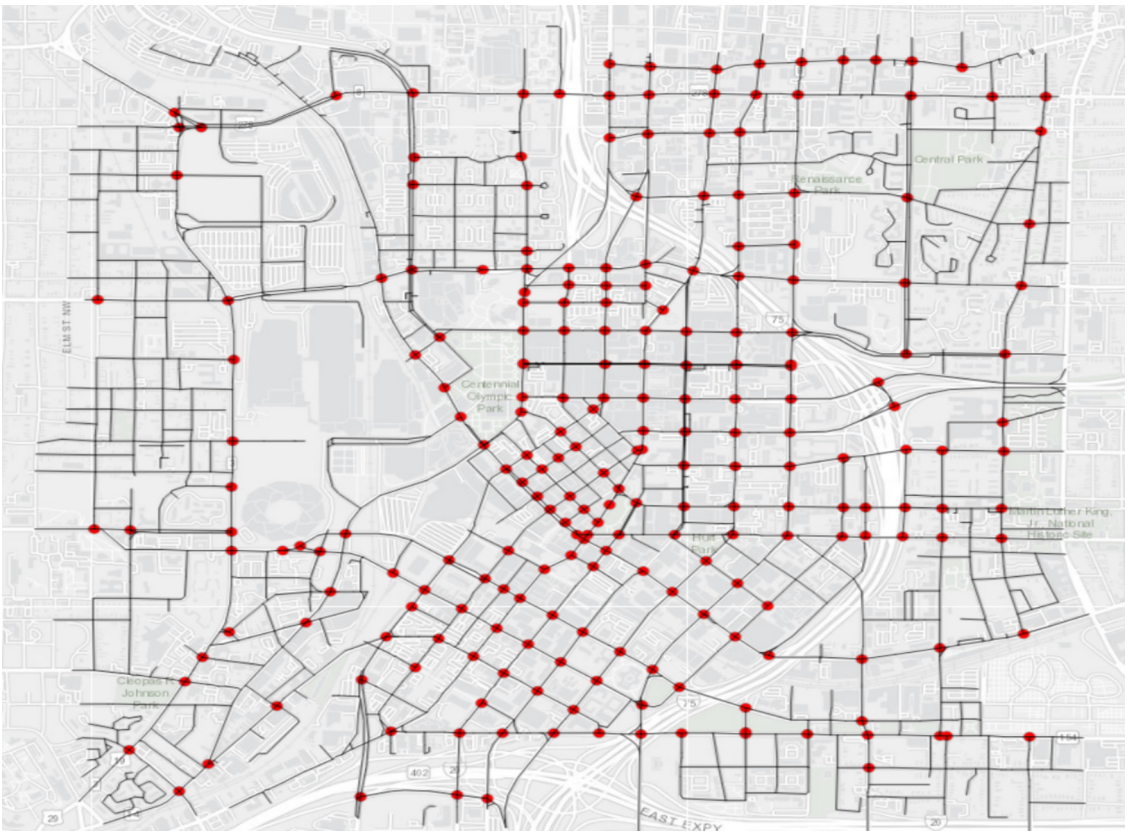

Fig. 2. Signalized intersections within study area.

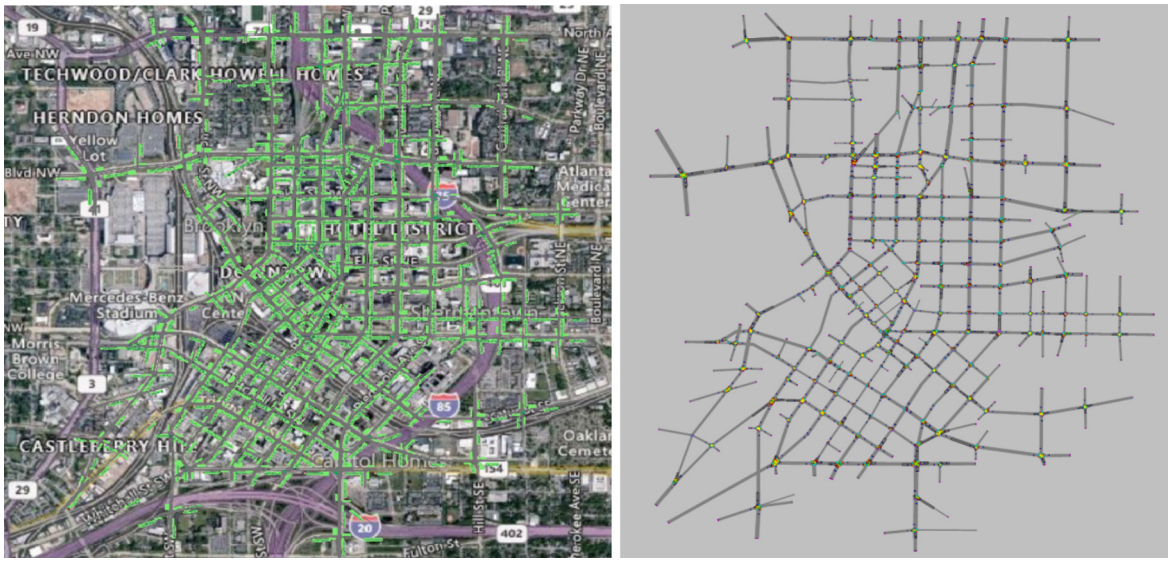

Fig. 3. Synchro 11 (left) vs VISSIM 2020 (right) models for downtown and midtown.

4. Input data collection

Input data were collected from various sources. With regard to the speed data, speed distributions are required to be defined for all vehicle classes. The vehicle speed distributions were set based on speed limit signs and the synchro model

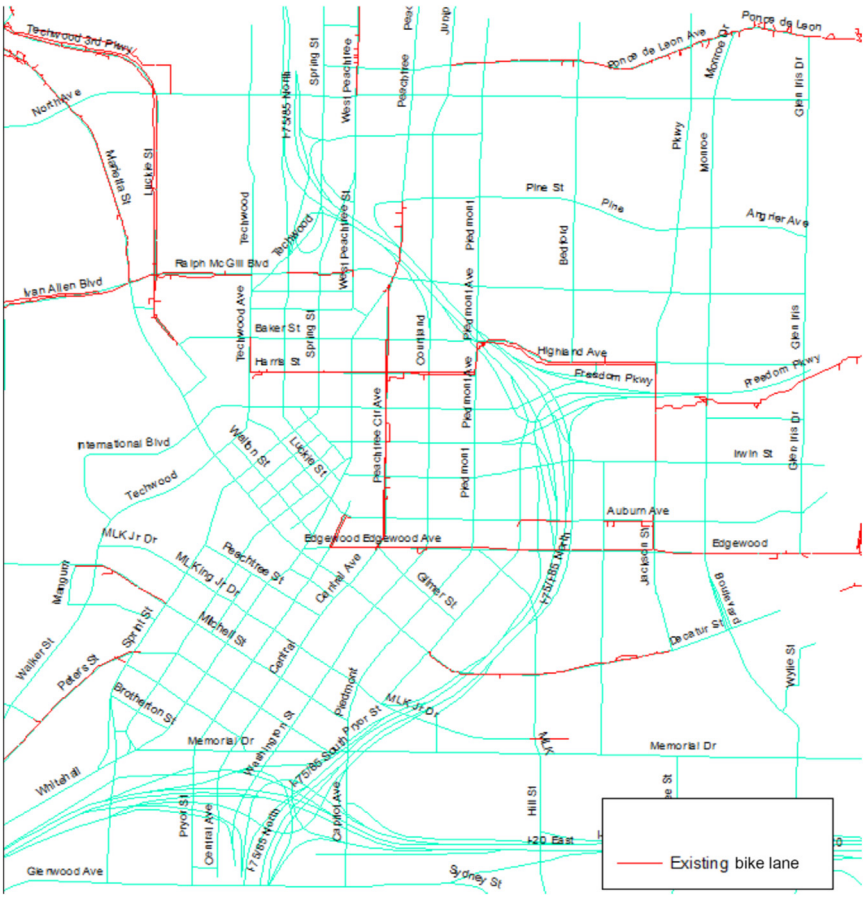

Fig. 4. Existing bike lanes within study area

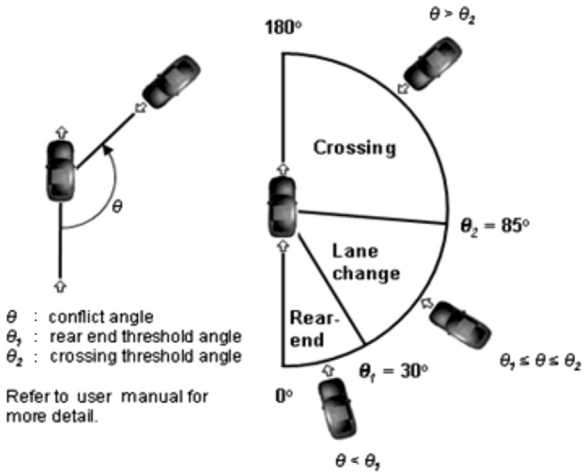

Fig. 5. Conflict angle diagram in SSAM (Gettman et al., 2008).

provided by the City of Atlanta. The bike speed distribution used for VISSIM was set to be 8 mph for the minimum and 25 mph for the maximum. Speeds were determined according to the average speeds of bike riding comfort level found in the *Guide for Development of Bicycle Facilities* (American Association of State Highway and Transportation Officials, 2012).

All signals were modeled as a ring barrier controller (RBC) in VISSIM, which modeled actuated signal timing patterns as well as coordination. A total of 668 signal controllers were identified in this model. Each signal head and controller were

assigned to each other through the RBC interface of VISSIM, which fulfills our needs to protect left turns and vehicle detection. Bicyclists were coded in VISSIM as their vehicle class and routed through corridors. An estimate of five (5) bicyclists per hour in each corridor was coded into the network based on the existing demand data available from the city.

5. VIISSIM network calibration and validation

Calibration and validation are necessary to ensure the model's accuracy and reliability. Calibration consisted of updating and adding any missing behavioral parameters. Validation was done on the existing condition (Scenario 0) by comparing the model's average speed and travel time data to real-world data. As a result of the calibration and validation process, the existing condition model is sufficient to assist in evaluating other alternative conditions. PTV VISSIM is a leading microscopic traffic simulation software that has been validated in multiple studies (Monfort et al., 2021; Mehrara Molan, 2017; PTV AG, 2018; Schroeder et al., 2014). In the current study, the research team also calibrated and validated the VISSIM model based on real data collected to increase accuracy of the final outcomes. The processes of network creation, calibration, and validation are discussed below.

5.1. Calibration

The network is calibrated using automobile driving behavior and parameters. A well-calibrated model is essential to the system that is being modeled as it increases the reliability of the predicted traffic patterns and scenarios. The simulation period is set to be 3 600 s (one hour) with a 15-minute start (warm-up) time. This means that VISSIM will start analyzing the trajectories and travel time after 15 min into the run time. User behavior parameters were adjusted to reflect urban bike behavior to make sure that the model's data closely resembled the actual data.

Calibration of traffic signals is one of the key parameters to ensure that the simulated traffic closely mirrors the observed behavior in the field. In this study, the research team received the signal timings and a synchro model directly from the City of Atlanta. Then, the traffic signal data were imported into PTV VISSIM model to obtain the simulation outcomes.

Due to the stochastic nature of the simulation, random fluctuations occur in the results of the individual runs based on a random seed assigned for each run. These seeds influence the arrival times of the vehicles within the network and the variability of the driving behaviors. If the same seed number was used for each simulation run, the output data, such as the volumes, speeds, and travel times, would be the same. According to the VISSIM user manual (PTV AG, 2018), a more reliable assertion is reached by averaging the results of a sufficient number of simulation runs with different random seeds (PTV AG, 2018). Therefore, the validation of each network is based on output averaged over ten (10) simulation runs. Fries et al. (2017) have suggested that models evaluating system-wide metrics such as average vehicle speeds or vehicle hours traveled need at least five (5) runs, and models measuring arterial travel times or total delays require at least 10 runs.

5.2. Validation

The validation process involved running multiple runs of the calibrated network and comparing the output data to the real world for accuracy. Below are the measurements used to validate the microsimulation model in VISSIM. The traffic counts recorded in simulation models were from a PM peak hour data collection period between 4:00 PM to 5:00 PM. Therefore, the real-world speed and travel time estimation was done by utilizing Google Maps for the same time interval. While the other resources might also offer estimates of travel times and delays, it is important to note that utilizing alternative resources instead of Google Maps could not guarantee a significantly higher accuracy in validation. Given that Google Maps travel time is readily available and uncertainty about the additional accuracy of the sources, the choice made for using Google Maps was the most appropriate in this study based on the scope. It should be mentioned that our approach to validation using Google Maps is consistent with past studies. For example, Bedogni et al. (2015) validated synthetic road traffic datasets using easily accessible real-world information from Google Maps. Similarly, Wang and Xu (2011) also used the Google Maps information for estimating travel time between two points on a network.

A part of the validation was based on the traffic output data from the VISSIM model using the elements of travel time measurements and vehicle network performance. Travel times were measured as the average travel time for vehicles to cross the origin and destination specified for the simulated travel time measurement placed on key corridors. Delay time measurements were obtained for any selected segment where travel time is measured. Delay time determines the average time delay calculated from all vehicles observed on a single or several link sections.

Key corridors were selected within the network to perform speed validation based on stakeholder input. The following segments were selected since they either have existing biking infrastructure along the route or intersect with other biking infrastructure. Real-life estimated average speed range and time were collected on a Friday, 4:00 PM – 5:00 PM (the period that highest automobile travel demand is expected) from Google Maps. This information was compared and matched with speed data from VISSIM to ensure the effects of road users' behavior on network traffic conditions are adequately captured. The average speed along the corridor recorded by VISSIM must fall within the range of speed obtained by Google Maps.

Table 1 summarizes the average speed data from the 10 runs of the existing network compared to the corridor average speed range from Google Maps, which provides a range based on historical data from real-world conditions. All key corridors

Table 1
Existing baseline speed and travel time summary.

Street name	Length/ miles	Existing baseline travel time/min	Model average speed/mph	Google Maps speed range/mph	Posted speed limit/mph	Google Maps travel time range/min
North Ave (WB)	1.4	5.85	14.44	7–21	30	4–12
Ivan Allen Jr Blvd toRalph McGill Blvd (EB)	1.7	9.91	10.29	6–18	30	6–16
Marietta St toDecatur St (EB)	2	12.05	9.95	7–20	30	6–18
Piedmont Ave toCapitol Ave (NB)	2.2	10.07	13.11	6–19	30	7–20
Juniper St toWashington St (SB)	1.9	15.22	7.49	10–23	25	5–12
Peachtree St (SB)	1.3	4.24	18.41	6–16	25	5–14

had the average speed within the distribution range of historical data other than Peachtree Street, which was just outside the range. Overall, 83% of the travel times of the selected key corridors fall within Google Maps' estimated travel time range.

6. Modeled demand scenarios and network conditions

Three sets of demand scenarios were considered in this study in order to see what the impact would be in terms of measures of effectiveness and conflicts within the study area. Scenario 0 is the baseline scenario where no adjustments in modal demand are made. The first scenario, Scenario 1, is the 5% adjustment, meaning that 5% of automobile demand was switched to bicycle mode. The second scenario, Scenario 2, is the 15% adjustment, which means that 15% of automobile demand was switched to bicycle mode.

The research team proposed bike lanes along some streets, which will be considered the Proposed Condition, which is essentially an ideal bike network through midtown and downtown Atlanta that enables the most equitable connectivity of destinations. The proposed condition was recommended by the research team based on evaluations done regarding origins and destinations of bicyclists in the study area. The details of the process to identify the proposed network has been outlined in another article (Hwang and Guhathakurta, 2023). The city has also proposed its bike lane implementation and extension plans, a simulation model for which is referred to as an alternative condition. A total of 3 scenarios were analyzed for each condition (existing, proposed, and alternative). Each combination of alternative design and demand scenario was modeled in VISSIM, leading to a total of nine combinations for which safety and operational MOEs were estimated. Fig. 6

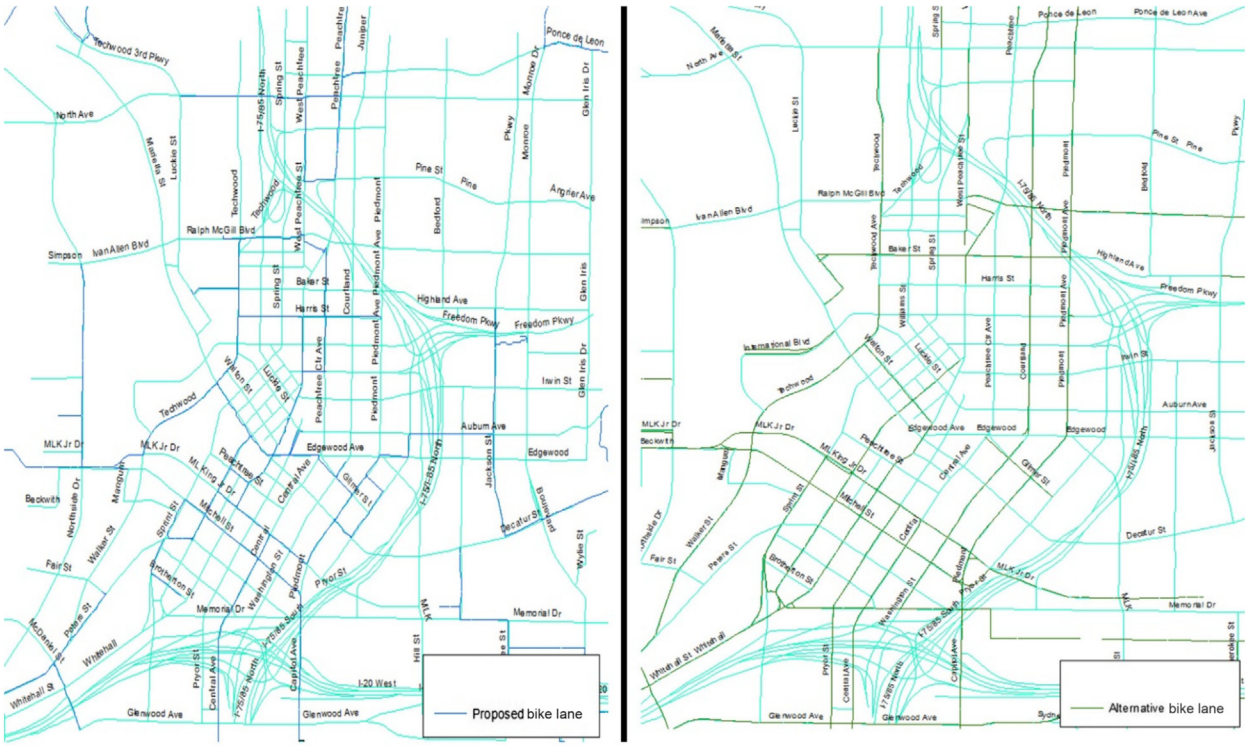

Fig. 6. Visualization of the proposed bike lane (left) and the alternative bike lane (right) within study area in ArcGIS.

shows the proposed and alternative conditions considered in this study. It should be mentioned that the existing bike lanes were also shown in Fig. 4.

Regarding MOEs, this study included five operational and safety MOEs described as follows.

1- Average speed (mph): The mean speed of vehicles within the analyzed traffic scenario over the simulation period (one hour).
2- Average delay (s): The average delay experienced by vehicles within the analyzed area, measured in seconds. Delay refers to the additional time vehicles spend in the traffic network compared to their ideal travel time.
3- Average number of stops: The average count of complete stops made by vehicles within the traffic scenario during the simulation period.
4- Average stop delay (s): The average delay experienced by vehicles during stops, measured in seconds.
5- Average Number of simulated conflicts per vehicle: The average count of simulated conflicts encountered by each vehicle within the traffic simulation scenario. In the context of SSAM, a simulated conflict refers to potential interactions or situations that could lead to safety-related issues.

7. Results and discussions

7.1. MOEs (speed, delay, number of stops, and stop delays)

Table 2 shows the comparison of the MOEs of all the conditions and their respective scenarios in the three networks included in this study. For all the conditions (existing, proposed, and alternative), the MOEs are summarized for the baseline (Scenario 0), 5% modal demand adjustment (Scenario 1), and 15% modal demand adjustment (Scenario 2).

For the existing condition (shown in Fig. 4), there is a decrease in average delay, stop delay and the average number of stops as we move from existing to potential demand scenarios with as much as 15% of automobile travel demand shifting to bicycles. This shows how fewer automobiles on the road and more bicycle riders will positively impact traffic operations on the roads.

For the proposed condition displayed in Fig. 6 (left), there was a significant drop in the total travel time compared to the existing baseline condition. This shows that adding well-connected bicycle infrastructure positively impacts network operation. The average speed also increased due to the decreased delay and the number of stops, which means that traffic is flowing much more smoothly compared to the base condition, even without any modal shift. If there were to be a modal shift, there would be a further drop in the total delay, based on a comparison of results from Scenario 0 to Scenario 2.

The alternative condition displayed in Fig. 6 (right) includes alternative bike lanes that are suggested by the City of Atlanta. While there is a large overlap between proposed and alternative network conditions, more alternative network bike lanes run in the northbound/southbound direction, connecting the north part of the city to the south compared to the proposed network.

Fig. 7 shows the average delay comparisons of all conditions and scenarios based on the results shown in Table 2. Based on Fig. 7, the average delays for the proposed and alternative conditions were very close, with the alternative condition delays being slightly lower than the proposed condition delays. These results clearly demonstrate that the network-level operational conditions for peak-hour travel are not adversely impacted, even for automobiles, by complete streets and networks.

7.2. Safety assessment

Table 3 summarizes the number of conflicts per vehicle type from each scenario (Scenario 0, Scenario 1, and Scenario 2) for all the conditions (existing, proposed, and alternative). Note that Table 3 includes three different conflicts (crossing, rear-end, and lane change) based on the angles identified during vehicle-vehicle interactions. The potential crash severity of crossing conflicts could be higher due to the sharper angle between vehicles, which could result in crashes such as left-turn head-on and angle crashes. On the other hand, rear-end and lane change conflicts should mostly result in possible rear-end and sideswipe crashes.

Table 2
MOEs for each combination of network condition and demand scenario.

	Existing condition			Proposed condition			Alternative condition		
Demand scenario	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**
Average speed/mph	7.57	7.77	8.18	8.21	8.49	9.06	8.22	8.48	9.07
Average delay/s	252.16	243.12	213.96	222.31	212.52	193.82	222.18	212.32	193.57
Average number of stops	7.62	7.43	6.42	7.12	6.93	6.35	7.12	6.94	6.34
Average stop delay/s	190.34	183.04	162.33	164.46	156.83	142.40	164.21	156.80	142.20

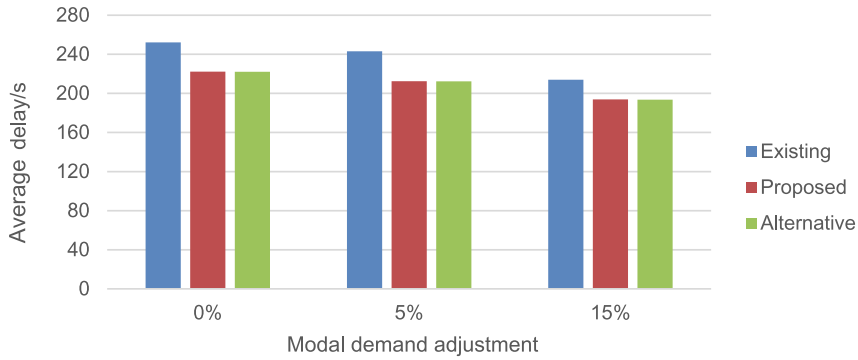

Fig. 7. Average delay comparisons of all conditions and scenarios.

Table 3
Safety MOEs for each combination of network condition and demand scenario.

Average number of conflicts per vehicle by type									
	Existing condition			**Proposed condition**			**Alternative condition**		
Scenario	0	1	2	0	1	2	0	1	2
Crossing	0.17	0.16	0.09	0.15	0.14	0.12	0.15	0.14	0.12
Rear-end	0.54	0.53	0.45	0.50	0.49	0.47	0.50	0.49	0.47
Lane change	0.14	0.13	0.12	0.13	0.13	0.12	0.13	0.13	0.12
Total	0.85	0.83	0.67	0.78	0.76	0.71	0.78	0.75	0.71

For the existing condition, with 5% and 15% modal demand adjustments, the model experiences a significant decrease in each type of conflict and the total conflicts. From Scenario 0 to Scenario 1, there was a 21% decrease in total conflicts and a 47% decrease in crossing conflicts.

For Scenario 0 in the proposed condition, results show that the number of conflicts per vehicle is lower than that in the existing condition. The decrease in the number of baseline conflicts may be a result of a more connected bike network, as modal demand adjustments have not been applied for Scenario 0. Similar to the existing condition scenarios, the biggest change is in the crossing and total conflicts. In Scenario 2 of the proposed condition, the crossing conflicts decreased by 20% while the total conflicts decreased by 8%.

To provide further detail on Table 3, Fig. 8 visually compares the total conflicts between all conditions and scenarios. When comparing SSAM results of all conditions and their scenarios, both alternative and proposed conditions, showed a decrease in conflicts per vehicle compared to existing condition.

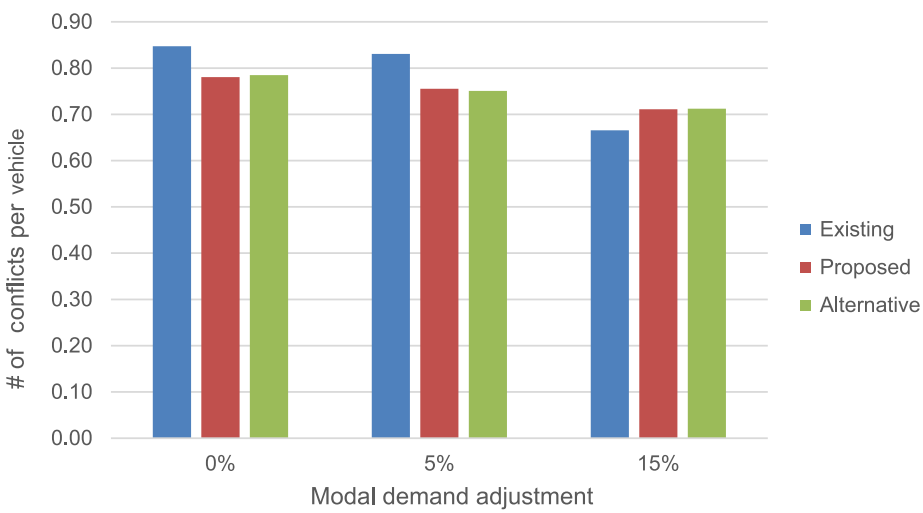

Fig. 8. Total conflicts comparison between all conditions.

The results show that with a more connected bike network, bicyclists have separated from automobile traffic, therefore, a connected bike network results in fewer collision-prone conflicts. These positive impacts are even more pronounced if the network changes are accompanied by a modal demand shift (moving from existing demand to Demand Scenario 2).

8. Conclusions

The paper examined the effects of complete streets by analyzing the existing bike networks and the potential connections and implementation of new bike infrastructure to form complete networks that improve active mobility. The simulation scenarios evaluated in this study demonstrated the impact of the existing, alternate, and potential bike infrastructure on the operations and safety within the study network.

Based on the output data from the microscopic traffic simulation models, the implementation and extension of bike networks throughout downtown Atlanta will improve safety and reduce average delays. According to VISSIM outcomes, the average speeds increased consistently from the base scenario (scenario 0) to proposed and alternative scenarios (scenarios 1 and 2; representing modal shift to bicycles) for all conditions. An increase in the peak-hour average speed represents an improvement in the flow of traffic. Similarly, for all the conditions, the average delay, number of stops, and stop delay continuously decreased from scenario 0 to scenario 2. The above-discussed changes in the MOEs show a positive impact of the modal shift in demand.

Based on the evaluation of SSAM using the number of conflicts, there was a significant decrease in the average number of conflicts per vehicle from existing condition to the proposed and alternative conditions. Interactions between vehicles and bicyclists were reduced, thus improving safety with the complete streets and bike infrastructure. Also, when comparing SSAM results of all conditions and the demand scenarios, a more connected network always resulted in fewer conflicts per vehicle. This may result from the more complete bike networks leading to fewer streets working as 'sharrows'. Reduction in sharrows means reduced interaction(s) between relatively faster automobiles and slower bicycles.

As a key conclusion, this study showed that providing bicycle infrastructure does not necessarily affect automobile operations adversely at the network level during peak automobile travel demand. Further improvements to this work would involve getting data on the actual future modal shifts within Atlanta instead of using our approach of somewhat arbitrary 5% and 15% traffic volume adjustments. We did not include bicycle conflicts in our study due to concerns regarding the applicability of using SSAM for cyclist safety analysis. As an additional recommendation, future studies should assess the accuracy of SSAM in identifying bicycle conflicts. Also, as a limitation in this study, a statistical test such as analysis of variances (ANOVA) could not be conducted due to the sample size needed in large networks. Based on past studies (Dattalo, 2008; Prajapati et al., 2010), a sample size of 30 runs in each group would be required to conduct a statistical test with appropriate statistical power.

CRediT authorship contribution statement

Katherine Lee: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amirarsalan Mehrara Molan:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Anurag Pande:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Formal analysis. **Uijeong Hwang:** Writing – review & editing, Methodology, Investigation, Data curation. **Subhrajit Guhathakurta:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition. **Mirabel Nkanor:** Writing – review & editing, Writing – original draft. **Benedetta Sergio:** Writing – review & editing, Writing – original draft, Data curation.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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