Impact of Buses, Taxis, Passenger Cars, and Traffic Infrastructure on Average Travel Speed

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1.Introduction

The main objective of the present study is to achieve a better understanding of low travel speed. We conducted all research in an area with compromised vehicle velocity. The zone under study possesses regular traffic infrastructure, such as speed bumps, traffic lights, and bus stops. It also has regular city traffic, i.e., buses, taxis, and passenger cars (hereafter just cars).

The appropriate combination of factors to sustain acceptable traffic speed (i.e., below but close to the speed limit) while avoiding undesirable traffic speed (i.e., far below the speed limit) is a functional problem under intense investigation in the field (e.g., references [1–8]). In the present investigation, we want to identify the variables that most affect the average travel speed. To do so, we will answer the following three questions:

(1) Are the buses’ arrival frequency and speed tendency, bus bay, and curbside bus stops the variables that influence the average travel speed of cars and buses?
(2) Are the taxis’ arrival frequency, stopping frequency, and speed tendency the variables that affect the average travel speed of cars, taxis, and buses?

(3) Are the number of speed bumps, cars’ arrival frequency, and cars’ speed conditions (homogeneous and heterogeneous) the variables influencing the cars’ average travel speed?

Developing countries face serious traffic problems [9] and some of these not count with field traffic data to conduct investigations, so that new technologies as traffic simulations are a suitable (economic) choice. We employed an in-house developed simulator to model the interaction between cars, buses, and taxis. Such smart interactions, and reactions to traffic infrastructure, allowed our simulator to show which variables have stronger effects on the average travel speed. Henceforth, we performed a set of simulations to answer our research questions.

Some variables are associated with driver behavior (e.g., the speed tendency—see definition below), while others are related to traffic infrastructure (e.g., speed bumps). By detecting the variables that impact speed and how they affect it, we gain further understanding about what causes detrimental effects. Hence, we gain further understanding that may lead to better public policies.

The literature review that follows presents several well-proven models that, unfortunately, fall short in answering our specific research questions, yet it proves that such a task is possible. In addition, it presents references that investigated the effect of buses, taxis, and traffic infrastructure such as speed bumps. In our work, we investigate the effect of several factors on the vehicles’ average travel speed that the literature suggests have an impact on traffic.

The rest of this work is organized as follows. In Section 2, we present the literature review. Section 3 deals with the method: avenue under study, design of the simulation tool, and experimental details. In Section 4, we present the statistical results of each experiment and compare the simulations’ outcome (the average travel speed, also called response or output) in order to gain insight of the variables that affect it. Finally, in Section 5, we summarize the conclusions of our work and state the contributions we made.

2. Literature Review

2.1. Buses. The implications of improper bus stop locations in New Delhi, India, were investigated in [10]. In India in 2001, the percentage of fatal crashes that occurred near a bus stop was 6.2%, and in 2009, it was 7.0% [11]. In this study, it was observed a deficiency of sufficient space to stop and perform maneuvers and also pedestrian activity outside regulations. The effect of bus stops on traffic is analyzed in [12]. This paper correlated the traffic flow stability with bus stops and normalized density. The finding in a two-lane-30 km-long highway, where vehicles cannot overtake during buses’ boarding/alighting periods, is that six or more bus stops affect the stability of traffic flow.

The relation between bus impact time and curb lane capacity of roadways in Beijing is presented in [13]. The bus impact time (without dwell time) is the amount of time since the bus starts to decelerate until it stops (in a bus bay stop), plus the time since accelerates to re-enter the road until it reaches another vehicle’s speed. With data from 15 bus bay stops, it was found that the relation between average bus arrival frequency and average bus impact time is best explained with a power model.

The work described in [14] deals with simulations of non-lane-based heterogeneous traffic. Distinct flow measurements of the vehicles’ average speed for a 400 m road length (200 m on each side of a bus stop) were done. The simulation considered curbside and bus bay bus stops and dwell times of 10 s, 20 s, and 30 s. The investigation in [15] analyzes the relationship between volume and speed in the presence of bus bay or curbside stops (using midblock location) with a bus arrival frequency of 10 min. In the case of vehicles per hour per lane = 480 and curbside stops, the speed difference between dwell times (20 s, 40 s, and 60 s) is quite small (about 2.5 mph between each other). Moreover, there is no significant speed difference for the bus bay stop case regardless of the dwell time.

In [16], simulations are used to establish the impact of the bus occupancy ratio (number of buses/number of vehicles) on traffic flow capacity. It was observed that traffic flow decreases as the occupancy ratio increases. The variables studied were speed and brake response time of cars and buses, safety following-distance, deceleration capabilities, and occupancy ratio. Reference [17] also utilizes simulations that consider the space occupation rate of buses (the sum of all circulating buses’ length divided by the sum of the lanes’ length) and the space occupation rate of cars, in order to analyze the influence of buses on other vehicles.

2.2. Taxis. Taxis have a significant effect on traffic, as shown in the following references. In [18], a study in Nanjing, China, identifies the percentage of taxis and cars that were involved in one of the following risk-taking behaviors: failure to yield the right-of-way, sudden lane change, inadequate stop, unnecessary passing, and failure to stay in lane. In these five situations, taxis’ percentage was greater than that of cars.

In [19], the presence of taxis in a road section and its impact on vehicle dynamics was studied. Employing simulations, three taxi behaviors were explored: (1) a taxi makes a stop to pick up or drop off passengers, (2) a taxi slows down to inquire destination information, and (3) a taxi circulates at low speed seeking for customers. In another study [20], the time that taxis utilize to pick up or drop off passengers (blockage time) is investigated. Measurements were made in outlet legs of signalized intersections in Rasht City, Iran. From the observations of four intersections, the average parking maneuver was 7.37 s, and the average blockage time was 11.31 s (ranging from 8.85 s to 12.56 s).

Passenger car units per hour (PCU/h) and speed range regions were measured in the center of Patras, Greece [21]. An augmented Naïve Bayesian network was developed to associate variables. The results determine the order of importance of the relevant variables: travel speed, volume, taxis...
2. Materials and Methods

3.1. Avenue Selection. We were interested in a place with low speed (see [28]). The selected avenue was Miguel Hidalgo, in Lerma (Mexico state), since its geometry (two lanes, same direction both), its traffic infrastructure, and the vehicle speed on it are common in Mexico state. Thus, the results in this work could apply to places with similar characteristics. Following [24], the avenue was divided into four segments, each of ~ 500 m length. Specific traffic conditions occur in each segment because each has different traffic infrastructure (see Table 1). The observations mentioned in this work were extracted from video recordings made in October 2017. Additionally, the traffic lights’ cycle times were set in the simulator to match the real timings closely. The speed bumps on segments $S_1$, $S_2$, and $S_3$ force the vehicles to reduce the speed to ~10.8 km/h, a similar value as reported in [25].

Segment $S_1$ has two speed bumps at location 141 m (measured from the start of the segment) and 397 m. $S_2$ has two speed bumps at 85 m and 260 m, one curbside bus stop at 99 m, and one bus bay bus stop at 488 m. $S_3$ has one traffic light at 163 m and one bus bay bus stop at 220 m. $S_4$ has three speed bumps at 137 m, 211 m, and 440 m, two traffic lights at 46 m and 87 m, one bus bay bus stop at 65 m, and one curbside bus stop at 445 m.

3.2. Simulation Tool. We choose Unity Engine (used for traffic analysis in [29, 30]) to develop a simulation tool (scripts and scenario). In the simulator, variables related to vehicles can be set, such as the taxis’ stopping frequency and the buses’ dwell time. Also, it measures the vehicles’ travel speed to traverse an avenue segment. The C# scripts to regulate the vehicles’ behavior are presented as algorithms. For overtaking, see Algorithm 1. For accelerating, decelerating, and follow another vehicle, see Algorithm 2.

The overtaking algorithm was designed to be consistent with expected human behavior. The need for overtaking is triggered when a vehicle desires to attain a higher speed than the vehicle in front, which for some reason circulates slowly, or when in the proximity there is a static obstacle, as it can be a bus or a taxi that is completely stationary. Additionally, a vehicle overtakes only when it is safe to do so. In Algorithm 1, the Overtaking() function allows a vehicle to overtake if there is no collision risk, which depends on the speed of the vehicles located ahead and behind in the other lane of the current vehicle, and if there is no vehicle at its side. The first IF detects the need to overtake comparing the speed of the current vehicle (and the speed tendency) with the speed of the vehicle in front. It also accounts for the AD of the latter. The second IF detects the convenience to overtake comparing the speed of the vehicle in front with the speed of the vehicle in front in the other lane and the distances $d_i$ and $d_j$. The speed tendency (or preferred speed, hereafter used interchangeably) is the top speed that a vehicle will try to reach without exceeding it. The distance between vehicles is measured from the front of the current vehicle to the back of the vehicle ahead.

In Algorithm 2, $ac = 2 \text{ m/s}^2$ for maximum acceleration and $ac = -4 \text{ m/s}^2$ for maximum deceleration, similar to the values presented in [31]. Variable $se_{di}$ is defined in equation (1), $br_{di}$ is defined in equation (2) (an analogue formula applies to $br_{dj}$; just replace $sp$ with $sp_j$), and $ex_{di}$ is defined in equation (3). The constant $re_{di}$ is approximately the mean perception-brake response time observed.
in [32]. Constant $de_{hec}$ is in the headway mode range presented in [33], which is 1.8 to 2.2 s for densities between 20 and 80 PCU/km. If the distance between the current vehicle and the vehicle in front is less than or equal to the safe distance between the two, the current vehicle decelerates; otherwise, the algorithm applies the following rules: (1) if the headway is larger than or equal to the headway tendency plus 0.3 seconds, the current vehicle accelerates, (2) if the vehicle speed is larger than or equal to the 110% of the speed tendency, the current vehicle neither accelerates nor decelerates, (3) if the headway is less than or equal to the headway tendency minus 0.3 s, the current vehicle decelerates, and (4) if the headway is in the interval (1.8 s, 2.1 s], the current vehicle $AD = 0$. The speed is limited in case 2, and in case 4, a relaxation state is reached in which there is no need of taking $AD$ actions.

### Table 1: Segment infrastructure.

| Segment | Speed bumps | Traffic lights | Bus stops | Length (m) | Start GPS coordinate | End GPS coordinate |
|---------|-------------|----------------|-----------|------------|----------------------|-------------------|
| $S_1$   | 2           | 0              | 0         | $l_1 = 501$ | 19.284512, −99.500927 | 19.285725, −99.505498 |
| $S_2$   | 2           | 0              | 0         | $l_2 = 500$ | 19.285725, −99.505498 | 19.286330, −99.510221 |
| $S_3$   | 0           | 1              | 1         | $l_3 = 500$ | 19.286330, −99.510221 | 19.286711, −99.514964 |
| $S_4$   | 3           | 2              | 2         | $l_4 = 501$ | 19.286711, −99.514964 | 19.286477, −99.519630 |

Algorithm 1: Overtaking.

```plaintext
if ((Clause 1 AND Clause 2) OR (Clause 1 AND Clause 3))
{
    if ((Clause 4 AND Clause 5) OR (Clause 6 AND Clause 7) OR (Clause 8 AND Clause 9)) {Overtaking();}
}
```

| Clause 1 | $sp_f < sp_{lim} \times 0.8$ | the speed of the vehicle in front ($sp_f$) is less than the 80% of the speed tendency ($sp_{lim} = 60$ kn/h). |
| Clause 2 | $ac_f \leq 0$ | the acceleration or deceleration (AD) of the vehicle in front ($ac_f$) is less than or equal to zero |
| Clause 3 | $sp_f < sp \times 0.8$ | the speed of the vehicle in front is less than the 80% of the speed of the current vehicle (sp) |
| Clause 4 | $sp_f < sp_{u} \times x_1$ | the speed of the vehicle in front is less than the $x_1 = 70\%$ of the speed of the vehicle in front in the other lane ($sp_{u}$) |
| Clause 5 | $di_{u} - x_2 > di_{f}$ | the distance between the current vehicle and the vehicle in front in the other lane ($di_{u}$) minus $x_2 = 0$ is greater than the distance between the current vehicle and the vehicle in front ($di_{f}$) |
| Clause 6 | same as clause 4, with $x_1 = 80\%$ |
| Clause 7 | same as clause 5, with $x_2 = 2$ |
| Clause 8 | same as clause 4, with $x_1 = 90\%$ |
| Clause 9 | same as clause 5, with $x_2 = 4$ |

Algorithm 2: Driving.

```plaintext
if ($se_{dl} \geq di_{f}$) {$ac = -4$} else
{
    if ($he \geq de_{he} + 0.3$) {$ac = 2$}
    if ($sp \geq sp_{lim} \times 1.1$) {$ac = 0$}
    if ($he \leq de_{he} - 0.3$) {$ac = -4$}
    if (($he \leq de_{he} + 0.1$) AND ($he > de_{he} - 0.2$)) {$ac = 0$}
}
```

Notation:
- $ac$ = acceleration or deceleration of the current vehicle.
- $de_{he} = 2$ s, headway tendency.
- $br_{di}$ = braking distance of the current vehicle.
- $br_{di_{f}}$ = braking distance of the vehicle in front.
- $ex_{di}$ = extra distance.
- $he$ = headway, the time needed by the current vehicle to reach the vehicle in front.
- $p_u = 4.2$ m, car’s length.
- $re_{ti}$ = reaction time to brake.
- $se_{di}$ = safe distance between the current vehicle and the vehicle in front.
Even though Algorithm 1 cannot include 100% of the human reaction possibilities to decide when and how to overtake and Algorithm 2 cannot do the same for the AD actions when following another vehicle, these cover common intuitive behaviors. The vehicles considered in the simulations of the experiments that follow are of three types: cars (width = 1.7 m and length = 4.2 m), taxis (same geometry as cars), and buses (width = 2.5 m and length = 10.3 m).

The variable flow for a certain vehicle type varies from one simulation to another around the observed value in the avenue under study in calm hours. Thus, the traffic dynamics of each simulation could be consistent with that of other avenues with equal number of lanes and comparable flow for each vehicle type. As random processes were not included in the traffic (out of the scope), there is no need to run multiple simulations per variable configuration to achieve output convergence. The simulation time of each simulation of the three experiments is 900 s.

3.2.1. Experiment 1: Buses’ Related Variables. Simulations in experiment 1 were configured as follows: the entrance speed of all vehicles is 40 km/h, and buses’ dwell time is 30 s (the time they wait at bus stops), following the range from 8 to 35 s reported in [34]. After the dwell time, a bus in a bus bay stop tries to re-enter the circulation if possible. If not, after 10 s (by a programmed rule), a vehicle circulating in the lane adjacent to the bus stop, and behind the bus, decelerates to allow the bus to re-enter. For the curbside bus stop, the dwell time is also 30 s, during which the circulation of the vehicles behind is obstructed. Buses circulate only in the rightmost lane and therefore do not overtake. If a vehicle overtakes, it waits for 5 s to do it again in case it has to, imitating a driver who does not overtake immediately once it has; instead, it waits to understand the traffic around him before attempting to perform an overtaking maneuver once again. A car arrives per lane every 7.5 s (or per avenue each 3.75 s). The cars’ speed tendency is 60 km/h. The average travel speed (ATS) is calculated with equation (4), the travel speed of the $i_T$-th vehicle is $v_{i_T} = l_j/t_{i_T}, l_j$ is the length of the $j$-th segment, and $t_{i_T}$ is the time that the $i_T$-th vehicle needs to traverse $S_j$. Subindex $T$ indicates the vehicle type, $T$ = {car (c), bus (b), taxi (t)}. $N_T$ is the total number of vehicles of type $T$ in the simulation.

$$\text{ATS}_T = \sum_{i_T=1}^{N_T} \frac{v_{i_T}}{N_T}$$  \hspace{1cm} (4)

Segment $S_j$ is the scenario of the simulations of experiment 1. We selected four variables (factors): time interval between buses arrival ($TL_b$), buses’ speed tendency ($SL_b$), a bus stop obstructing the circulation (curbside stop, denoted as BS1), and a bus stop in a space designated to not interfere with circulation (bus bay stop, denoted as BS2). The time interval between buses per avenue takes values around 100 s (from observations each ~86 s a bus enters the avenue), and hence $TL_b$ = {50 s, 100, 150, 200}. Buses’ speed tendency ranges between 30 and 60 km/h; therefore, $SL_b$ = {30 km/h, 40, 50, 60}. The presence of factor BS1 (or BS2) is set with 1 and absence with 0, and thus $BS1 = [1, 0]$ and $BS2 = [1, 0]$.

The variables’ values of each simulation are presented in Table 2, along with the average travel speed of cars ($\text{ATS}_c$) and buses ($\text{ATS}_b$). An orthogonal experimental design was adopted, following the approach in [35]. In Table 2, columns 2 through 5 conform an orthogonal array.

The minimum number of simulations (NS) to obtain meaningful results is calculated with the following equation (see [36]):

$$\text{NS} = 1 + \sum_{i=1}^{k} \text{NF}_i (\text{NL}_i - 1).$$  \hspace{1cm} (5)

Index $i = 1, \ldots, k$ is used to enumerate cases. The $i$-th case corresponds with a number of levels and the number or factors with that many levels. $\text{NF}_i = $ number of factors and $\text{NL}_i = $ number of levels. In experiment 1, we have two factors with four levels and two factors with two levels, and hence $\text{NS} = 9$. Nevertheless, 16 simulations were performed for completeness.

3.2.2. Experiment 2: Taxis’ Related Variables. The simulation parameters from experiment 1 remain mostly the same for experiment 2, with the following differences: a bus arrives every 86 s, vehicles entrance speed is 30 km/h, and buses’ and cars’ speed tendency is fixed at 60 km/h. To perform simulations, we selected segment $S_j$ which has one bus bay stop and one traffic light (green time = 30 s, yellow = 3 s, and red = 27 s).

The objective is to determine which variables related to taxis have an impact on the average travel speed of cars.
3.2.3. Experiment 3: Cars’ and Traffic Infrastructure Related Variables. The objective is to determine the impact of (1) speed bumps, (2) the time interval between cars, and (3) cars’ preferred speed (heterogeneous and homogeneous speed cases), in the cars’ average travel speed. For our simulations, we selected segment $S_c$, which has three speed bumps and two intersections with a traffic light in one. Seven cars enter the avenue per intersection per traffic light cycle. The first traffic light, numbered in the traffic flow direction, has a green time of 42 s, yellow of 3 s, and red of 45 s. The second has a green time of 67 s, yellow of 3 s, and red of 20 s. The cars from upstream enter $S_c$ with a speed of 40 km/h and from the perpendicular streets at 15 km/h. A car decelerates to a speed of $\sim 10.8$ km/h to pass a speed bump (see [25]).

| Simulation | $T_{L_b}$ (s) | $S_{L_b}$ (km/h) | $B_{SL}$ | $B_{S2}$ | $A_{T_{S1}}$ (km/h) | $A_{T_{S2}}$ (km/h) |
|------------|---------------|------------------|---------|---------|----------------------|----------------------|
| 1          | 50            | 30               | 0       | 1       | 42.82344             | 17.73234             |
| 2          | 50            | 40               | 1       | 0       | 37.8702              | 19.87394             |
| 3          | 50            | 50               | 0       | 0       | 43.01352             | 36.49824             |
| 4          | 50            | 60               | 1       | 1       | 38.3968              | 15.36566             |
| 5          | 100           | 30               | 1       | 0       | 40.41936             | 17.90665             |
| 6          | 100           | 40               | 0       | 0       | 43.02828             | 19.8711              |
| 7          | 100           | 50               | 1       | 0       | 40.90032             | 14.75813             |
| 8          | 100           | 60               | 0       | 0       | 43.15932             | 39.47796             |
| 9          | 150           | 30               | 0       | 0       | 43.01604             | 26.59828             |
| 10         | 150           | 40               | 1       | 1       | 41.6052              | 14.26122             |
| 11         | 150           | 50               | 0       | 1       | 41.8032              | 21.44045             |
| 12         | 150           | 60               | 1       | 0       | 43.13556             | 21.44754             |
| 13         | 200           | 30               | 1       | 1       | 41.80536             | 13.33422             |
| 14         | 200           | 40               | 0       | 0       | 43.1352              | 31.6418              |
| 15         | 200           | 50               | 0       | 1       | 43.13196             | 21.31394             |
| 16         | 200           | 60               | 0       | 1       | 42.07248             | 22.67647             |

(ATS$_S$), buses (ATS$_b$), and taxis (ATS$_T$). The variables are speed tendency of taxis $S_{L_b} = [40$ km/h, 50, 60], time interval between taxi per avenue (from observations each $\sim 18$ s a taxi enters in one of the two lanes) $T_{L_b} = [9$ s, 18, 27], and the time interval between stops (i.e., when a taxi makes a stop to drop off or pick up customers and after 5 seconds, the time lapse until it decelerates to stop for the same reason) $T_{S} = [30$ s, 45, 60]. The taxi blockage time, to pick up or drop off passengers, is 5 s. This time is set relatively short as taxis stop at any lane. In the avenue under investigation, taxis have a defined route and collect and drop customers during their journey and transport as many clients as they can carry.

Table 3 shows the variables’ values in an orthogonal array (columns 2 to 4) and the measured average travel speed of each vehicle type. The array has three factors with three levels each; therefore, NS = 7. Nonetheless, we perform two more simulations for completion.

4. Results and Discussion

4.1. Experiment 1. ANOVA was conducted to determine the factors influencing a response (the average travel speed of a vehicle type). The analysis of variance results, with the data in Table 2, is presented in Table 5. In the following, considering 90% confidence intervals (unless otherwise mentioned), a factor with $P$ value $< 0.1$ influences the response, i.e., it is significant.

With ATS$_T$ as the response, factors $T_{L_b}$ and $B_{SL}$ are significant. Factor $B_{SL}$ does not influence ATS$_S$, as a bus does not interrupt the circulation when it waits in a bus bay stop. Also, as cars are able to overtakes slow buses most of the time, factor $S_{L_b}$ is not influencing the response.

If ATS$_T$ is the response, factor $S_{L_b}$ is slightly significant (with 80% confidence intervals, 0.1866 $< 0.2$), while factors $B_{SL}$ and $B_{S2}$ (curbside and bus bay stops, respectively) both impact ATS$_b$, as a bus waits during the dwell time either if it is in a bus bay or a curbside stop. $B_{SL}$ is impacting slightly more the response than $B_{SL}$, mainly because a bus spends time to re-enter in the circulation lane if it is in a bus bay stop. Factor $T_{L_b}$ is not influencing ATS$_T$, since buses (ideally) do not interfere with each other not even at the shortest time between buses’ arrival (50 s).

Simulation 8 ($ATS_T = 43.1593$ km/h) is compared with a new simulation (numbered 17, not shown in the respective table), with factors $T_{L_b} = 100$ s, $S_{L_b} = 60$ km/h, $B_{SL} = 1$, $B_{S2} = 0$, and response $ATS_T = 40.9953$ km/h. Then, $B_{SL}$ does change. The percentage ($P$) of ATS$_T$ reduction, since buses stop at the curbside stop (simulation 17), is calculated with equation (6) (which calculates a loss, or a gain, in percentage).

\[
P = \left( \frac{x_1 - x_2}{x_1} \right) \times 100\%.
\]  

(6)

ATS$_T$ drops if there is a curbside stop. To measure the loss, we compare simulations in pairs, with same $T_{L_b}$ and different $B_{SL}$ (the other influencing factor). Comparing simulation 3 vs 4, the response drops to 10.74%. From 8 vs 7, it drops to 5.23%. From 12 vs 11, it drops to 3.08%. From 15 vs 16, it drops to 2.45%. Then, the response’s loss drops as $T_{L_b}$ of the compared simulations increases.

Also, ATS$_T$ is influenced by $T_{L_b}$. We compared simulations with same $B_{SL} = 1$ and different $T_{L_b}$. By comparing simulation 7 vs 4, the response drops to 6.13%. From 10 vs 7, heterogeneous (HE) case, the speed is uniformly and randomly assigned so that 50% of the cars’ preferred speed = 60 km/h and that of the other half = 40 km/h. In the homogeneous (HO) case, the preferred speed = 50 km/h for all cars. ATS$_T$ is calculated considering the cars traveling from the start of $S_c$ excluding the cars from perpendicular streets. Table 4 shows the variables’ values and the output of each simulation. Columns 2 to 4 conform an orthogonal array, with $NS = 6$ (one factor with four levels and two factors with two levels) plus two more for completeness.
it drops to 2.15%, and from 16 vs 11, it drops to 0.64%. Again, we observe that the percentage becomes smaller as the compared $TL_b$ values become larger. Yet, when comparing simulations with same $BS1 = 0$ and different $TL_b$, we notice almost the same response: the $ATS_c$ of simulation 3 is 43.01 km/h, that of 6 is 43.02 km/h, and that of 12 and 15 is 43.13 km/h. Hence, without curbside stop, the buses’ arrival time interval in the range 50 s to 200 s has no impact in the $ATS_c$.

With $ATS_b$ being the response, ANOVA shows that both $BS1$ and $BS2$ significantly affect $ATS_b$. Comparing simulation 8 ($BS1 = 0$, $BS2 = 0$) with 4 ($BS1 = 1$, $BS2 = 1$), the response percentage loss is 61.07%. There is no evident response difference between simulation 12 ($ATS_b = 21.44$ km/h), with a bus bay stop ($BS2 = 1$), and simulation 16 ($ATS_b = 22.67$ km/h), with a curbside stop ($BS1 = 1$). Considering simulations 1, 6, 15, and 12, all with $BS1 = 0$ and $BS2 = 1$, $ATS_b$ increases from simulation 1 to 12 in 20.95%, since variable $SL_b$ also increases (from 30 to 60 km/h).

### 4.2. Experiment 2

ANOVA results (with data in Table 3) are presented in Table 6. All factors impact $ATS_c$, factor $SL_c$ affects $ATS_b$, and factor $TL_c$ affects $ATS_b$. In addition, considering 80% confidence intervals, $TL_c$ and $TS$ also have an effect in $ATS_b$, and $TS$ also has an effect in $ATS_b$.

### Table 3: Experiment 2 simulations.

| Simulation | $TL_c$ (s) | $TS$ (s) | $SL_c$ (km/h) | $ATS_b$ (km/h) | $ATS_c$ (km/h) | $ATS_b$ (km/h) |
|------------|------------|----------|---------------|----------------|----------------|----------------|
| 1          | 9          | 30       | 60            | 39.57012       | 32.09062       | 21.02119       |
| 2          | 9          | 45       | 40            | 38.457         | 32.13989       | 21.1505        |
| 3          | 9          | 60       | 50            | 38.68164       | 32.36504       | 20.95096       |
| 4          | 18         | 30       | 40            | 38.03076       | 25.79638       | 21.46608       |
| 5          | 18         | 45       | 50            | 39.71952       | 32.36252       | 21.78511       |
| 6          | 18         | 60       | 60            | 41.634         | 38.59164       | 22.78577       |
| 7          | 27         | 30       | 50            | 41.14548       | 31.67957       | 22.07477       |
| 8          | 27         | 45       | 60            | 43.40268       | 38.38464       | 22.66538       |
| 9          | 27         | 60       | 40            | 41.50512       | 28.4391        | 22.84675       |

### Table 4: Experiment 3 simulations.

| Simulation | $B$ | $TL_c$ (s) | $TS$ (s) | $SL_c$ (km/h) | $ATS_b$ (km/h) |
|------------|-----|------------|----------|---------------|----------------|
| 1          | 3   | 4          | HO       | 26.60634      |                |
| 2          | 3   | 6          | HE       | 26.80146      |                |
| 3          | 2   | 4          | HE       | 27.05976      |                |
| 4          | 2   | 6          | HO       | 30.208572     |                |
| 5          | 1   | 4          | HO       | 32.271084     |                |
| 6          | 1   | 6          | HE       | 31.658328     |                |
| 7          | 0   | 4          | HE       | 32.325696     |                |
| 8          | 0   | 6          | HO       | 37.74348      |                |

### Table 5: ANOVA results (experiment 1).

| Factor   | $P$ value ($ATS_b$) | $P$ value ($ATS_c$) |
|----------|---------------------|---------------------|
| $TL_a$   | 0.0861 < 0.1        | 0.8643 > 0.1        |
| $SL_b$   | 0.6937 > 0.1        | 0.1866 > 0.1        |
| $BS1$    | 0.0018 < 0.1        | 0.0011 < 0.1        |
| $BS2$    | 0.935 > 0.1         | 0.0009 < 0.1        |

From Table 3, simulation 4 has the lowest $ATS_b$, with $SL_c$ and $TS$ at minimum values. Simulation 8 presents the highest $ATS_b$, with $SL_c$ and $TL_c$ at maximum values. Thus, the relevance of $SL_c$ in $ATS_b$ is made evident.

The $ATS_c$ percentage gain between simulation 4 (minimum values of $SL_c$ and $TS$) and simulation 6 (maximum values of $SL_c$ and $TS$), both with $TL_c = 18$ s, is 9.47%.

We perform two more simulations: simulation 10, with $TL_c = 9$ s, $TS = 30$ s, $SL_c = 50$ km/h, resulting in $ATS_b = 36.7081$ km/h, $ATS_c = 29.915$, $ATS_b = 20.0617$; simulation 11, with $TL_c = 27$ s, $TS = 60$ s, $SL_c = 50$ km/h, resulting in $ATS_b = 42.1927$ km/h, $ATS_c = 36.4168$, $ATS_b = 22.5704$. Comparing simulation 10, with $TL_c$ and $TS$ minimum values, and simulation 11, with $TL_c$ and $TS$ maximum values, both with $SL_c = 50$ km/h, the $ATS_b$ gain is 14.94%.

To evidence the significant impact of $SL_c$ in $ATS_b$, we cluster simulations according to speed tendency in three groups (see Table 7). Notice that, by arranging data, first in subgroups of $SL_c$, then inside these subgroups by ascending $TS$, the table self-orders in $ATS_b$. Hence, $TS$ is firstly affected by $SL_c$ and secondly by $TS$.

The factor significantly influencing $ATS_b$ is $TL_c$. In Table 3, simulations 1, 2, and 3, with $TL_c = 9$ s, present close values of $ATS_b$, with the average being 21.04 km/h. For simulations 4, 5, and 6, with $TL_c = 18$ s, the response is increasing along with $TS$, with the average being 22.01 km/h. The same occurs for simulations 7, 8, and 9, with $TL_c = 27$ s and average response of 22.52 km/h. Then, $TL_c$ is firstly affecting $ATS_b$, followed by $TS$. Comparing simulation 3 ($TL_c = 9$ s) and 9 ($TL_c = 27$ s), both with $TS = 60$ s, the response gain is 9.04%.

### 4.3. Experiment 3

ANOVA results (with data in Table 4) are shown in Table 8. All factors impact $ATS_c$. 

### Table 6: ANOVA results (experiment 2).

| Factor   | $P$ value ($ATS_b$) | $P$ value ($ATS_c$) | $P$ value ($ATS_b$) |
|----------|---------------------|---------------------|---------------------|
| $TL_c$   | 0.0136 < 0.1        | 0.1992 > 0.1        | 0.0409 < 0.1        |
| $TS$     | 0.0984 < 0.1        | 0.1413 > 0.1        | 0.1767 > 0.1        |
| $SL_c$   | 0.026 < 0.1         | 0.0203 < 0.1        | 0.2384 > 0.1        |
paring simulation 2 vs 16 (B = 3) and simulation 12 (B = 2), there is a gain of 9.95%. Comparing simulation 2 vs 6 (B = 1), the gain is 18.12%. Comparing simulation 2 vs 16 (B = 0), the gain is 30.61%. Following this comparison logic, with $TL_c = 6s$ and $SL_c = HE$ (likely for real traffic), we compare simulations with a different number of bumps. Comparing simulation 2 ($TL_c = 4s$) and simulation 12 ($TL_c = 4s$) vs 6 ($TL_c = 4s$) is 9.95%. Compared with simulation 2 vs 6 ($TL_c = 4s$), the gain is 18.12%. Compared simulation 2 vs 16 ($TL_c = 4s$), the gain is 30.61%. Following this comparison logic, with $TL_c = 6s$ and $SL_c = HE$, we obtained gains of 6.84%, 19.0%, and 27.67%. With $TL_c = 6s$ and $SL_c = HO$, gains are 8.88%, 19.97%, and 36.04%. With $TL_c = 4s$ and $SL_c = HO$, gains are 9.23%, 21.29%, and 41.58%. Averaging the gain results with 3 speed bumps vs 2, the gain is 8.72%. The average gain of 3 speed bumps vs 1 is 19.59%, and increases to 33.97% for the average gain of 3 speed bumps vs. no speed bumps. It is clear that regardless of the values of $TL_c$ and $SL_c$, speed bumps harm the response.

The response in homogeneous traffic without speed bumps is approximately the same regarding $TL_c$. ATSc = 37.6718 km/h for simulation 15 ($TL_c = 4s$) and ATSc = 37.74348 km/h for simulation 8 ($TL_c = 6s$). Following this idea, we calculate the response gain comparing simulation 5 vs 14 (1 speed bumps each), simulation 11 vs 4 (2 speed bumps each), and simulation 1 vs 10 (3 speed bumps each). The average percentage gain of the four cases is 2.88%.

In heterogeneous traffic without speed bumps, there is a notorious response difference between a simulation with $TL_c = 4s$ and one with $TL_c = 6s$, corresponding to simulation 7 (ATSc = 32.3256 km/h) and simulation 16 (ATSc = 35.0068 km/h), respectively. Following the idea, we compare simulation 13 vs 6 (1 speed bumps each), simulation 3 vs 12 (2 speed bumps each), and simulation 9 vs 2 (3 speed bumps each), to calculate the response gain. The average percentage gain of the four cases is 7.04%. Then, in heterogeneous traffic, the response changes because $TL_c$ is more evident.

| Simulation | Factor values | ATSc (km/h) |
|------------|---------------|-------------|
| 4          | $TL_c = 18, TS = 30, SL_c = 40$ | 25.7963     |
| 2          | $TL_c = 9, TS = 45, SL_c = 40$ | 26.1398     |
| 9          | $TL_c = 27, TS = 60, SL_c = 40$ | 28.4391     |
| 7          | $TL_c = 27, TS = 30, SL_c = 50$ | 31.6795     |
| 5          | $TL_c = 18, TS = 45, SL_c = 50$ | 32.3625     |
| 3          | $TL_c = 9, TS = 60, SL_c = 50$ | 32.365      |
| 1          | $TL_c = 9, TS = 30, SL_c = 60$ | 32.0906     |
| 8          | $TL_c = 27, TS = 45, SL_c = 60$ | 38.3846     |
| 6          | $TL_c = 18, TS = 60, SL_c = 60$ | 38.5916     |

Table 7: Sorting TS in clusters of $SL_c$.

Table 8: ANOVA results (experiment 3).

| Factor | $B$ | $TL_c$ | $SL_c$ | $P$ value (ATSc) |
|--------|-----|-------|-------|-----------------|
| $B$    | 0.026 < 0.1 |
| $TL_c$| 0.0767 < 0.1 |
| $SL_c$| 0.0644 < 0.1 |

To compare simulations with different number of speed bumps and other factors at equal values, additional simulations were performed (see Table 9).

By reducing $B$, ATSc increases. With $TL_c = 6s$ and $SL_c = HE$ (likely for real traffic), we compare simulations with a different number of bumps. Comparing simulation 2 ($TL_c = 3$) and simulation 12 ($TL_c = 2$), there is a gain of 9.95%. Comparing simulation 2 vs 6 ($TL_c = 1$), the gain is 18.12%. Comparing simulation 2 vs 16 ($TL_c = 0$), the gain is 30.61%. Following this comparison logic, with $TL_c = 6s$ and $SL_c = HE$, we obtained gains of 6.84%, 19.0%, and 27.67%. With $TL_c = 6s$ and $SL_c = HO$, gains are 8.88%, 19.97%, and 36.04%. With $TL_c = 4s$ and $SL_c = HO$, gains are 9.23%, 21.29%, and 41.58%. Averaging the gain results with 3 speed bumps vs 2, the gain is 8.72%. The average gain of 3 speed bumps vs 1 is 19.59%, and increases to 33.97% for the average gain of 3 speed bumps vs. no speed bumps. It is clear that regardless of the values of $TL_c$ and $SL_c$, speed bumps harm the response.

The response in homogeneous traffic without speed bumps is approximately the same regarding $TL_c$. ATSc = 37.6718 km/h for simulation 15 ($TL_c = 4s$) and ATSc = 37.74348 km/h for simulation 8 ($TL_c = 6s$). Following this idea, we calculate the response gain comparing simulation 5 vs 14 (1 speed bumps each), simulation 11 vs 4 (2 speed bumps each), and simulation 1 vs 10 (3 speed bumps each). The average percentage gain of the four cases is 2.88%.

In heterogeneous traffic without speed bumps, there is a notorious response difference between a simulation with $TL_c = 4s$ and one with $TL_c = 6s$, corresponding to simulation 7 (ATSc = 32.3256 km/h) and simulation 16 (ATSc = 35.0068 km/h), respectively. Following the idea, we compare simulation 13 vs 6 (1 speed bumps each), simulation 3 vs 12 (2 speed bumps each), and simulation 9 vs 2 (3 speed bumps each), to calculate the response gain. The average percentage gain of the four cases is 7.04%. Then, in heterogeneous traffic, the response changes because $TL_c$ is more evident.

The average speed tendency in heterogeneous traffic ($SL_c = HE$) is 50 km/h (50% of the cars’ speed tendency = 40 km/h and 50% is 60 km/h), and the average speed tendency in homogeneous traffic ($SL_c = HO$) is also 50 km/h (100% of the cars’ speed tendency = 50 km/h). Even though that in both traffic configurations (HE and HO) the average speed tendency is the same, the average travel speed is different. There is an ATSc percentage gain of a simulation with $SL_c = HO$ over one with $SL_c = HE$, both with $TL_c = 6s$ and same $B$. Simulation 10 vs 2 (with 3 speed bumps each) presents a gain of 3.51%. Simulation 4 vs 12 (with 2 speed bumps each) presents a gain of 2.51%. Simulation 14 vs 6 (with 1 speed bumps each) presents a gain of 5.13%. Simulation 8 vs 16 (with 0 speed bumps each) presents a gain of 7.81%. The average gain of the four cases is 4.74%. Also, there is an ATSc percentage gain of a simulation with $SL_c = HO$ over one with $SL_c = HE$, both with $TL_c = 6s$ and equal $B$. Simulation 1 vs 9 (with 3 speed bumps each) presents a gain of 5.08%. Simulation 11 vs 3 (with 2 speed bumps each) presents a gain of 7.43%. Simulation 5 vs 13 (with 1 speed bumps each) presents a gain of 7.1%. Simulation 15 vs 7 (with 0 speed bumps each) presents a gain of 16.53%. The average gain of the four cases is 9.04%. The advantage of homogeneous over heterogeneous traffic is evident.

4.4. Research Questions. The answers to our investigative questions are as follows:

1. It was found that a curbside stop and the time interval between buses’ arrival (in that order of relevance) modify the cars’ average travel speed. Buses’ average travel speed is affected by bus bay and curbside stops.

2. The time lapse between taxis’ arrival, speed tendency, and frequency to make a stop impact (in the order presented before) the cars’ average travel speed. Taxis’ average travel speed is influenced mainly by taxis’ speed tendency. Taxis’ arrival frequency influences buses’ average travel speed.

3. It was found that the three factors: speed bumps, speed tendency configuration, and time interval between cars arrival, significantly affect (in the order presented) the cars’ average travel speed.
5. Conclusions

The $\text{ATS}_b$ percentage loss (due to the curbside bus stop) of the compared simulations with same $\text{TL}_b$ and different $\text{BS}1$ ranges from 2.45% to 10.74%. Then, from a traffic design perspective, it is preferable to avoid curbside stops, so that buses do not make stops in a way that obstructs circulation. Instead, bus bay stops are suitable, since $\text{BS}2$ has no significant effect on $\text{ATS}_b$. From the simulations compared with same $\text{BS}1 = 1$ and different $\text{TL}_b$ (as this variable affects $\text{ATS}_b$), the $\text{ATS}_b$ percentage loss is in the range 0.64% to 6.13%. Therefore, $\text{TL}_b$ could be adjusted based on a supply and demand basis.

The $\text{ATS}_b$ percentage gain, if a bus travels at the minimum preferred speed (30 km/h) compared with the maximum (60 km/h), is 20.95%. Thus, the connection between buses’ preferred speed and $\text{ATS}_b$ is evident.

As $\text{TS}$ influences $\text{ATS}_c$, it could be beneficial that taxis had designated spots (similar to bus bay stops for buses, or even sharing these) to not obstruct the circulation when these pick up or drop off customers. In this way, a taxi is not motivated to travel at low speed (since $\text{SL}_c$ is influencing $\text{ATS}_c$ and $\text{ATS}_b$) trying to find customers along the way. As $\text{TL}_c$ impacts $\text{ATS}_c$ and $\text{ATS}_b$, if the number of taxis circulating do not match the number of customers (as it is likely in the avenue under study), it is recommended to find the $\text{TL}_c$ values (considering time and day) that balance supply and demand.

In experiment 3, we found that $B$ affects $\text{ATS}_c$, regardless of $\text{TL}_c$ and $\text{SL}_c$. By gradually removing speed bumps, we noticed improvements in the response. For the avenue studied and other similar avenues, we suggest that if a speed bump is not in a space that actually benefits pedestrians, it should be removed. With $B = 0$ and $\text{SL}_c = \text{HO}$, there was no response improvement when extending $\text{TL}_c$. With $B \neq 0$, for both homogeneous and heterogeneous cases, $\text{ATS}_c$ improves as cars arrive less frequently. As $\text{TL}_c$ influences $\text{ATS}_c$ and as $\text{TL}_c$ is connected with the number of cars in circulation which in turn increases year after year, persons with transportation needs could be motivated, through better public transport services and adequate infrastructure, to use other means of transportation rather than private vehicles, such as public transport or bicycles (this poses the problem of a dedicated bicycle lane). As $\text{SL}_c$ impacts $\text{ATS}_c$ and as homogeneous speeds were proven convenient than heterogeneous, it is important to have suitable traffic infrastructure, and Consequently, people’s quality of life could be improved. Even more importantly, traffic mitigation has the added benefit of decreasing greenhouse emissions of vehicles.

Data Availability

The simulation data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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