When Automation Is Not Enough: Combining Technology and Policy to Reduce Traffic Congestion in Florianopolis

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When automation is not enough: combining technology and policy to reduce traffic congestion in Florianópolis

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Abstract

The following paper analyzes the operation of autonomous vehicles (AVs) in a private and shared scenario as well the influence of adding a toll in the main bridge that connects a residential area to the city center, representing a case study of the city of Florianópolis in Brazil. We develop a mathematical model whereby the aim is to minimize the overall generalized costs and evaluate its effect on the congestion problem. The main aim of this paper is to estimate some of the impacts that can come up from the deployment of AVs in this urban area where costs of operation, parking and toll are considered and minimized. Several penetration rates of AVs with different shares of private-owned and shared vehicles are analyzed together with the influence of a toll that affects the trips distribution and congestion depicted by the level of service. The main conclusion is that effects on congestion, that can be depicted through the level of service, will only be noticeable when a toll is added and AVs represent a vast majority of the vehicle fleet and some of them are not-private owned, i.e., are shared systems. A level of service A will likely be obtained once there is a penetration rate of 50% and 80% of these AVs are shared. When AVs are 80% of the vehicle fleet, 50% of these shall be used for shared purposes. These results can only be obtained if a toll is added to the bridge, that will increase the travel costs and likely force passengers to change their travel behavior.

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Keywords: Autonomous vehicles; Policy; Urban regions; Land-use; Mobility; Florianópolis; Brazil.

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1. Introduction

According to the PLAMUS (2015), the metropolitan region of Florianópolis in Brazil faces a serious problem of urban mobility, fostered by the dependence on residents' use of the car, coupled with an overload of the capacity of the highway system. The metropolitan area of Florianópolis is essentially divided into two zones that are connected by two bridges Pedro Ivo Campos and Colombo Salles, each one has a single flow direction. Figure 1 depicts the area: residential zones at left, city center (downtown) at right. Nowadays, these two bridges experience congestion all over the day (Corrêa, 2019).

Figure 1 – Area of Florianópolis, (extracted from GoogleMaps).

The emergence of autonomous vehicles (AVs) and their operation will certainly have an impact in this reality, whether positive and negative, and this effect is still uncertain to predict. This paper aims to understand how AVs

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should be deployed in this urban area so that the overall congestion in this main city access is minimized. Several different penetration rates of AVs with different shares of private-owned and car-sharing vehicles are analyzed together with the influence of a toll that affects the trips and parking, but also congestion through the level of service.

2. Methodology

The methodological approach used to solve this problem was optimization through linear mathematical programming model that was implemented by FICO Xpress IVE (Corrêa, 2019). The objective function aims to minimize the overall operating costs at a system level, involving the parking, toll and vehicle operation costs. The model considers the possibility of parking in the downtown area of Florianópolis or in the trip origin. Besides, the model admits that vehicles might leave the passengers at the destination and return to the origin side, different park restrictions and costs are included. In order to study different shares of private-owned and shared vehicles, this model also considers occupancy rates and is in the function of passengers rather than vehicles, assuring that all passengers conduct their trips.

The assumptions of the following model are:

- The number of persons travelling by car is constant;
- Persons that travel in other modes of transport (e.g., bus, bikes, etc.) are not considered;
- Three modes of transport are studied: AVs, SAV (Shared AVs) and CVs (Conventional vehicles);
- AVs and SAVs penetration rates are inputs. CVs flow depends on these two variables and its occupancy rates.
- When convenient in terms of minimization of costs, parking in the residential area may happen – which incurs in an extra variable: the AVR (Autonomous Vehicle that Return).
- Occupancy rates in private-owned AVs and CVs are constant, but the occupancy rate in SAVs varies in function of toll costs;
- Toll cost is an input, but it varies according to the occupancy rate of the vehicles – if the vehicle is full, toll is null.
- AVs own level of automation 4 and 5., with a higher traffic efficiency than CVs;
- Each arc is one-way direction.

Sets:

I	$(1, \ldots, i, \ldots, I)$ set of notes, where I is the number of nodes. In the following case study, there are two nodes: the residential and the metropolis area;
R	$\{\ldots, (i,j), \ldots\}$ $i, j \in I, i \neq j$, set of arcs.
T	$\{1, 2, 3\}$ set of travel behaviour, where 1 represents stays in the city centre less than 2 hours; 2 represents stays from 2 to 6 hours; 3 represents stays over 6 hours.

Data and Parameters:

TOP_{park}	Operation cost of parked AVs and SAVs
TOP_{parkCV}	Operation cost of parked CVs
TOP_{AVR}	Operation cost of AVRs
F_{PEOPLE}	Number of persons travelling per hour
TTP_{CV}	Cost of travel time of conventional vehicles, expressed in dollars
TTP_{AV}	Cost of travel time of private-owned AVs, expressed in dollars
TP	Toll price for AVR
TP_{PARK}	Toll price for AVs and CVs that will park
TP_{SAV}	Toll price for SAVs
PPP	Private Parking Price
PARK_{P}	Cost of parking in public space, expressed in dollars per hour
ρ^{AV}	AVs penetration rate, expressed in percentage;
ρ^{SAV}	shared AVs penetration rate, expressed in percentage;
MSF	Traffic flow expressed in vehicles per hour, assuming a level of service C;

EVVH	Initial total flow (current), expressed in vehicles per hour
PC	Vehicles rate
TX_{OC_I}	Vehicle occupation rate (%)
$TX_{OC_{Max}}$	Maximum vehicle occupation rate
PP	Rate of vehicles that will return from the city centre over 6 hours
PWP	Rate of vehicles that stay in the city centre at least 2 hours
PWV	Rate of vehicles with free private parking in the city centre
HS	Number of hours that vehicles stay in the city centre
AVPF	Cost of private parking, expressed in dollars per hour
OP_AV	Cost of operation of AVs, expressed in dollars per kilometre
OP_CV	Cost of operation of CVs, expressed in dollars per kilometre
DAB	Length of the viaduct, expressed in kilometres
t_{ij}^{min}	minimum travel time in the crossing viaduct.
t_{ij}^{max}	maximum travel time in the crossing viaduct. (i,j), $\forall\ i, j\ \in I$.
D	Total demand expressed in vehicles per hour.
OVF	Other vehicles flow: trucks, buses, etc.
α^{AVs}	AVs traffic efficiency / passenger equivalent unit, defined between]0,1].
α^{OVF}	OVFs traffic efficiency / passenger equivalent unit, defined between]1,∞].
C_{ij}	Road capacity in each arc $(i, j) \in R$, expressed in vehicles per hour.
PES	Toll price for each empty seat;
Cost_AVP_6_i	Cost of parked private-owned AV - 6 hours
Cost_CVP_6_i	Cost of parked CV - 6 hours
Cost_AVP_2_i	Cost of parked private-owned AV - 2 hours
Cost_CVP_2_i	Cost of parked CV - 2 hours
PES_min	Minimum toll price for each empty seat
PES_max	Maximum toll price for each empty seat
TX_{OC_F}	Final occupation rate
TTP_sav	SAV Travel Time Price
tt_inicial	Initial Travel Time

Decision variables:

$f_{ij\ t}^{AV}$	discrete variable that corresponds to the AV flow in each arc $(i, j) \in \boldsymbol{R}$, per stay $t \in \boldsymbol{T}$.
f_{ij}^{CV}	discrete variable that corresponds to the CV flow in each arc $(i, j) \in \boldsymbol{R}$, per stay $t \in \boldsymbol{T}$.
f_{ij}^{AVR}	discrete variable that corresponds to the AV flow that return in each arc $(i, j) \in \boldsymbol{R}$, per stay $t \in \boldsymbol{T}$.
P_i	Sum of all parking spaces.
Pf_i^{CV}	Number of CV parking spaces.
Pf_i^{AV}	Number of AV parking spaces.
Pf_i^{AVR}	Number of AVR parking spaces.

This analysis aims to minimize costs, expressed in monetary units, as the objective function (1) details.

$$\text{Minimize(Costs)}= \sum_{(i,j)\in \mathbf{R}} Cost_{ij}^{AV} + \sum_{(i,j)\in \mathbf{R}} Cost_{ij}^{CV} + \sum_{(i,j)\in \mathbf{R}} Cost_{ij}^{AVR} \tag{1}$$

The first component of the objective function expresses the AVs cost detailed in (2); the second, the CVs cost detailed in (3); and the third, the costs of shared-AVs detailed in (4).

$$Cost_{ij}^{AV} = \left(TOP_{park} \sum_{j \in I} f_{ij\ t}^{AV}\right) + \left(F_{PEOPLE} * TTP_{AV} \sum_{j \in I} t_{ij}\right) + \left(TP_{PARK} \sum_{j \in I} f_{ij\ 1}^{AV}\right) + \left(TP_{SAV} \sum_{j \in I} f_{ij\ 2}^{AV}\right) + \left(\sum_{j \in I} Pf_{i\ 1}^{AV} * \mathrm{PARK_P} + \sum_{j \in I} Pf_{i\ 2}^{AV} * PPP + \sum_{j \in I} Pf_{i\ 3}^{AV} * 0\right) \quad (2)$$

$$\sum_{j \in I} Cost_{ij}^{CV} = \left(TOP_{parkCV} * \sum_{j \in I} f_{ij}^{CV}\right) + \left(F_{PEOPLE} * TTP_{CV} * \sum_{j \in I} t_{ij}\right) + \left(TP_{PARK} * \sum_{j \in I} f_{ij}^{CV}\right) + \left(\sum_{j \in I} Pf_{i1}^{CV} * \mathrm{PARK_P} + \sum_{j \in I} Pf_{i2}^{CV} * PPP + \sum_{j \in I} Pf_{i3}^{AV} * 0\right) \quad (3)$$

$$\sum_{j \in I} Cost_{ij}^{AVR} = \left(TOP_{AVR} * \sum_{j \in I} f_{ij}^{AVR}\right) + \left(TP \quad * \sum_{j \in I} f_{ij}^{AVR}\right) + \left(\sum_{j \in I} Pf_{i3}^{AVR} * 0\right) \quad (4)$$

The objective function is subject to the constraints expressed between (5) - (21).

Constraints (5) and (6) define the number of private-owned AVs (f_{ij1}^{AV}) and shared-AVs (f_{ij2}^{AV}). Expressions (7) defines the number of CVs (f_{ij}^{CV}), in function of the occupancy in shared-vehicles and the number of persons (F_{PEOPLE}) that is constant. Constraints (8), (9) and (10) define the conventional flow at each stay $t \in \boldsymbol{T}$, according to PLAMUS (2015). Constraints (11)-(13) limit parking of AVs. Constraints (14) limit the maximum number of AVRs (f_{ij}^{AVR}), based on the number of AVs circulating. Constraints (15) assure a minimum number of AVs, based on the number of AVs circulating and SAVs. Constraints (16) assure that AVRs start their trips. Constraints (17), (18) and (19) distribute the overall parking. Constraints (20) computes the total flow in each arc $(i, j) \in R$, where an efficiency coefficient is added for the AVs. Constraint (21) computes the travel time in each arc $(i, j) \in R$.

$$\sum_{j \in I} f_{ij\ 1}^{AV} = D * \rho^{AV} \quad (5)$$

$$\sum_{j \in I} f_{ij\ 2}^{AV} = \sum_{j \in I} f_{ij1}^{AV} * \rho^{SAV} \quad (6)$$

$$\sum_{j \in I} f_{ij}^{CV} = (F_{PEOPLE} - \left(\sum_{j \in I} \left(f_{ij\ 1}^{AV} - f_{ij\ 2}^{AV}\right) * TX_{OC_I} + \sum_{j \in I} f_{ij\ 2}^{AV} * TX_{OC_F}\right))/TX_{OC_I} \quad (7)$$

$$\sum_{j \in I} Pf_{i\ 1}^{CV} \geq \sum_{j \in I} f_{ij}^{CV} * PWP \quad (8)$$

$$\sum_{j \in I} Pf_{i\ 2}^{CV} \geq \sum_{j \in I} f_{ij}^{CV} * (PP - PWV) \quad (9)$$

$$\sum_{j \in I} Pf_{i\ 3}^{CV} \geq \sum_{j \in I} f_{ij}^{CV} * PWV \quad (10)$$

$$\sum_{j \in I} Pf_{i\ 1}^{AV} \leq (\sum_{j \in I} f_{ij\ 1}^{AV} - \sum_{j \in I} f_{ij\ 2}^{AV}) * PWP \quad (11)$$

$$\sum_{j \in I} Pf_{i\ 2}^{AV} \leq (\sum_{j \in I} f_{ij\ 1}^{AV} - \sum_{j \in I} f_{ij\ 2}^{AV}) * (PP - PWV) \quad (12)$$

$$\sum_{j \in I} Pf_{i\ 3}^{AV} \leq (\sum_{j \in I} f_{ij\ 1}^{AV} - \sum_{j \in I} f_{ij\ 2}^{AV}) * PWV \quad (13)$$

$$\sum_{j \in I} f_{ij}^{AVR} \leq \sum_{j \in I} f_{ij\ 1}^{AV} \quad (14)$$

$$\sum_{j\in I} f_{ij}^{AVR} \geq \sum_{j\in I} f_{ij\ 1}^{AV} - (\sum_{j\in I} Pf_{i\ 1}^{AV} + \sum_{j\in I} Pf_{i\ 2}^{AV} + \sum_{j\in I} Pf_{i\ 3}^{AV}) \tag{15}$$

$$\sum_{j\in I} Pf_{i\ 3}^{AVR} \geq \sum_{j\in I} f_{ij}^{AVR} \tag{16}$$

$$\sum_{j\in I} P_{i\ 1} \geq \sum_{j\in I} Pf_{i\ 1}^{CV} + \sum_{j\in I} Pf_{i\ 1}^{AV} \tag{17}$$

$$\sum_{j\in I} P_{i\ 2} \geq \sum_{j\in I} Pf_{i\ 2}^{CV} + \sum_{j\in I} Pf_{i\ 2}^{AV} \tag{18}$$

$$\sum_{j\in I} P_{i\ 3} \geq \sum_{j\in I} Pf_{i\ 3}^{CV} + \sum_{j\in I} Pf_{i\ 3}^{AV} + \sum_{j\in I} Pf_{i\ 3}^{AVR} \tag{19}$$

$$f_{ij}^{Total} = (\mathrm{OVF} * \alpha^{OVF}) + \left(\sum_{j\in I} f_{ij1}^{AV} * \alpha^{AVs}\right) + \sum_{j\in I} f_{ij}^{CV} + (\sum_{j\in I} f_{ij1}^{AVR} * \alpha^{AVs}) \tag{20}$$

$$t_{ij} = t_{ij}^{min} + f_{ij}^{Total} * \frac{t_{ij}^{max} - t_{ij}^{min}}{C_{ij}} \tag{21}$$

Parking constraints and toll costs are further explained in (Corrêa, 2019). P1 considers all public parking spaces that must be paid and not surpass 2 hours. P2 considers all private parking that is paid and up to 6 hours. P3 considers all private parking that is free and guaranteed apriori. Figure 2 depicts the summary of this calculation. An important aspect of this model is that is recognizes a different parking behavior among AVs and CVs. Constraints (17) assure that CVs will have priority to park, as they do not have an option to park elsewhere. Accordingly, constraints (18) admit that AVs may return to the other side of the bridge where there is free parking spaces.

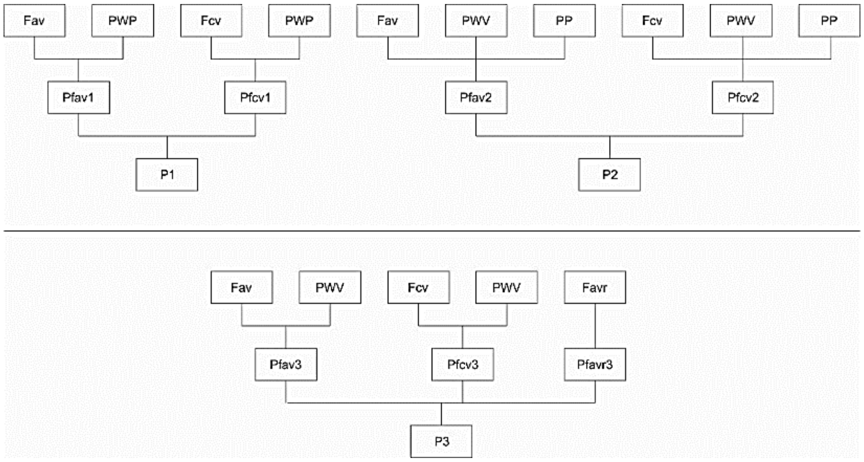

Figure 2 – Parking calculation scheme (Corrêa, 2019).

Toll costs calculation in function of PES is schematized in Figure 3. PES is the price for each empty seat and, in this experiment, corresponds to the average between the maximum and minimum value. The minimum value is calculated up to four two-way trips in one operational day. The maximum value is calculated between the cost of operation of an empty vehicle with 6 hours parking cost. The value of PES used in the following case-study was $1.50 per empty seat. This way, the toll is used as a tool to optimize and maximize the efficiency of this commuting problem. The model tries to maximize the occupancy of the vehicles in order to minimize the total costs of the system.

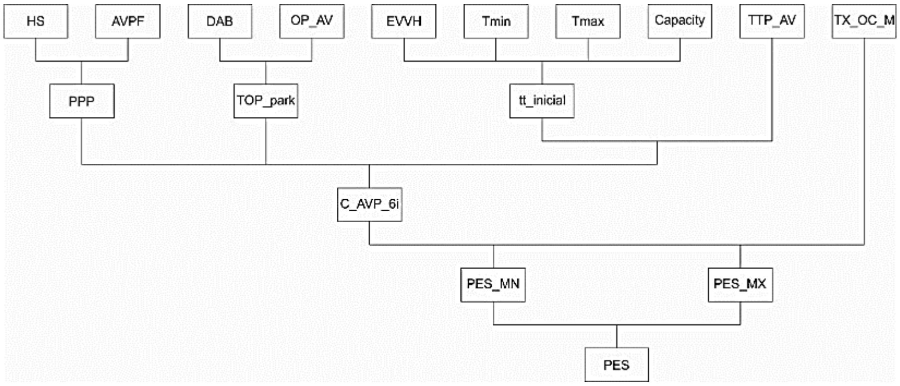

Figure 3 – Toll cost calculation scheme (Corrêa, 2019).

3. Setting up the case study: the viaduct of Florianópolis

The case study is composed of 2 nodes and 2 arcs unidirectional, representing the two bridges serving the Florianópolis metropolitan area. Two scenarios are considered: with and without AVs, with different AV penetration rates and shares of private-owned and shared vehicles

A field survey was conducted to determine how many people are transported per hour, which showed an average occupancy rate of 1.53 people per vehicle (Corrêa, 2019). The number of vehicles currently travelling was quantified by PLAMUS (2015) methodology.

The current parking dynamics, which is currently practiced in the region under study, was determined from IPUF (2016); PLAMUS (2015); PMF (2016). Thus, it revealed three parking behaviors: approximately 20% of vehicles are able to use a paid public parkin, for a maximum of 2 hours; 32% stay a short time at destination with free private parking at destination; and 48% of vehicles need to stay a short time at the destination in paid parking.

The travel time function considered in this experiment is linear for simplification purposes. The minimum travel time at each link is calculated at free-flow speed, and the maximum travel time at each link when capacity is reached considers around 10% of the free-flow speed (Conceição, Correia, & Tavares, 2017). The AVs efficiency factor that details the road capacity benefit was in accordance with Calvert, Van den Broek, & Van Noort (2011). The operating costs were in accordance with Bösch, Becker, Becker, and Axhausen (2018).

4. Results

In the first experiment, the model was run by minimizing the costs of all vehicles, where only 20% of the vehicles were autonomous. For that 20 % of AVs, we evaluated the effect of car-sharing systems with a rate of 20%, 50% and 80%. The effect of the toll added for traffic circulation was also evaluated. The results are shown in Figure 4. In this scenario, congestion is only slightly mitigated, though at a level of service D.

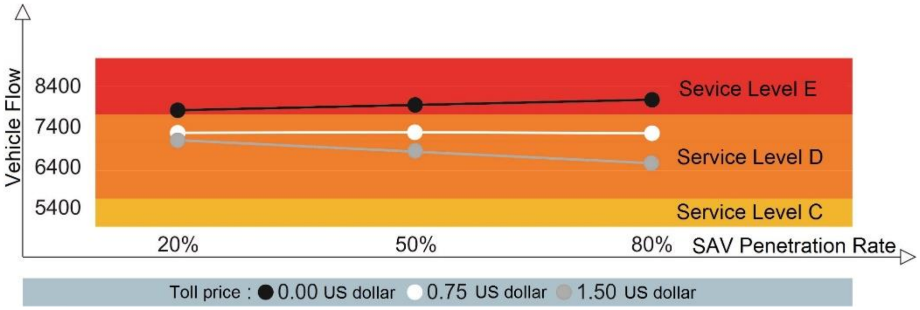

Figure 4 – Results of the model for an AV penetration rate of 20%.

In the second experiment, the model was run with an AV penetration rate of 50%, and a car-sharing rate of 20%, 50% and 80% applied to AVs. The results are shown in Figure 5. The effect of a toll revealed positive results for a penetration rate of 50% where 80% of the vehicles are shared.

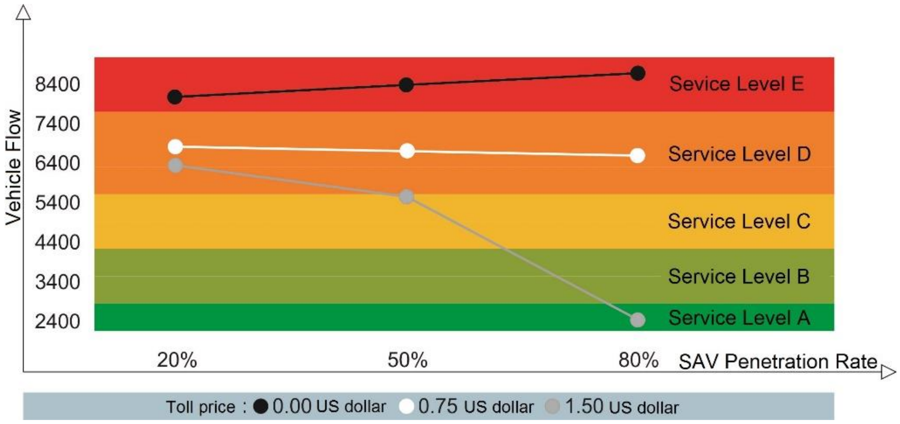

Figure 5 – Results of the model of an AV penetration rate of 50%

In the third experiment, the model was run with an AV penetration rate of 80%, with a car-sharing rate of 20%, 50% and 80% was applied to AVs. The results are shown in Figure 6. At this stage, congestion is already mitigated when 80% of the vehicles are automated and 50% of them are shared. Regardless of the scenario, a toll is needed to influence the behavior of the passengers and force them into using other modes of transports than private.

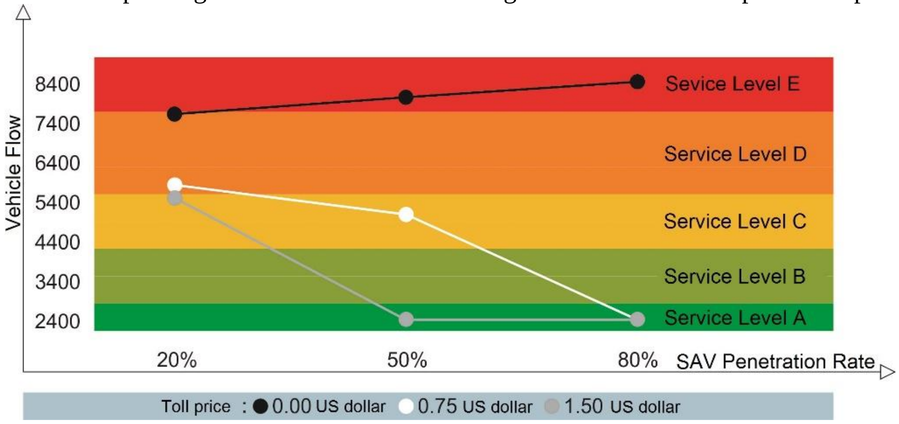

Figure 6 – Results of the model for an AV penetration rate of 80%

From the results observed in Figure 6, compared to Figure 4 and Figure 5, it is noticeable that if there is an increase in the penetration rate of private and shared autonomous vehicles, there is an increase in the volume of vehicles that return and park outside the city center in order to reduce their costs. In Figure 4 and Figure 5, the toll has an influence on reducing the total volume of vehicles per hour.

5. Conclusions

The main conclusion from this case study is that the impact of AVs in the urban environment totally depends on the intervention of public policies – this paper studied the effect of a toll considering both private and shared AVs. In scenarios where there is an urban toll associated with parking management, the operation of AVs may contribute to a decrease in urban congestion, as well as a decrease in the demand for parking spaces.

The main inference about congestion - depicted through the level of service – is that a reduction will only be noticeable when a toll is added and AVs represent a vast majority of the vehicle fleet and some of them are not-private owned, i.e., are shared systems. A level of service A will likely be obtained once there is a penetration rate of 50% and 80% of these AVs are shared. When AVs are 80% of the vehicle fleet, 50% of these shall be used for shared purposes. These results can only be obtained if a toll is added to the bridge, that will increase the travel costs and likely force passengers to change their travel behavior. The proposed methodology can be applied as a preliminary study to other case studies, such as: the city of São Luís, in Maranhão state in Brazil; and the connection between Niterói and Rio de Janeiro in Brazil.

Therefore, the deployment of automated vehicles and its implications might foster several opportunities for the requalification of the urban regions, which today is degraded, focused on land use currently assigned for vehicular transportation. However, if there is no concern regarding policies for the control and regulation of autonomous vehicles, a significant increase in trips might happen, worsening congestion.

In fact, such promising AVs technology might intensify the dependence on the use of vehicles, already happening in most Brazilian cities. AVs have the potential to create an efficient and low-cost urban mobility system that, if worked strategically, could contribute to urban spatial balance, freeing up space for pedestrians and cyclists.

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