Simulations of different scenarios of the use of autonomous vehicles with a multi-agent model

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SHORT SUMMARY

With technological advances and real-life trials taking place, the advent of autonomous vehicles (AVs) seems to be a matter of time. This raises many questions about the impacts that such a mode of transportation would have on mobility and its externalities. Using a multi-agent model, MATSim, this paper provides some answers to these questions by proposing three possible scenarios of use for autonomous vehicles that are simulated for the Montreal region:

- Private autonomous vehicles
- Robotaxis
- Shared robotaxis

Depending on the scenario, the introduction of AVs can engender a strong increase in travel distances due to empty driving. These additional kilometers lead to an increase in greenhouse gases, as well as an increase in congestion. Only one scenario, in which AVs are used as shared robotaxis, makes it possible to limit these effects.

Keywords: Autonomous and connected vehicles, Agent-based modeling, private autonomous vehicles, shared autonomous vehicles, Shared mobility.

1. INTRODUCTION

The advent of autonomous vehicles is becoming reality. Being able to predict their impacts is therefore a critical question (Fagnant & Kockelman, 2015). The number of studies on the impacts of this technology on the transportation system is continuously increasing. However, the impacts induced by AVs depend on implementation scenarios. These can be privately owned and used to replace conventional cars or shared as robotaxis to replace carsharing or taxis. This research proposes and compares different implementation scenarios using agent-based simulation.

The existing literature on AVs often focuses on shared autonomous modes, for example the impacts of robotaxis or the characteristics for such a service, like the size of vehicle fleet. Private use of AVs has been addressed much more sparsely, except for its impact on parking demand. A common implicit assumption seems that private use is inherently bad for the environment and not worth investigating. Here, both scenarios, i.e. private and shared, are considered and their impacts compared. Two sharing forms of AVs are considered: private use of robo-taxis and ride-sharing.

In most existing studies, the impacts of AVs are evaluated by only looking at AVs with little regard to other travel modes. In our paper simulations of the proposed scenarios are multi-modal. In the simulation, agents can chose between different travel modes depending on their characteristics (income, age, driving licence, activity plan, etc.) and the characteristics of competing travel modes. In contrast with the study of (Hörl, 2017), this research also includes a scenario with private autonomous vehicles.

2. METHODOLOGY

Simulations are performed using the open-source multi-agent software MATSim (Axhausen, Horni, & Nagel, 2016). The disaggregated agent-based approach of MATSim allows the explicit modeling of AVs. Dedicated extensions of the tool, DVPR (Maciejewski, 2016) and DRT (Bischoff, Führer, & Maciejewski, 2019), have already been developed and used to model the behavior of AVs. MATSim extension for mobility-as-a-service (MaaS) modes, relies on a centralized system that receives requests as soon as an agent wants to use a MaaS mode. The request is either accepted or rejected depending on the balance between supply and demand. If the request is accepted, a vehicle is dispatched to take serve the request. The dispatching of vehicles can be optimized using different strategies (idle, nearest vehicle, etc.).

In total three scenarios are simulated. The first scenario describes the case where AVs will be private owned and used. AVs can only be shared between household members (including children). This scenario is called private autonomous vehicle (PAV). The second and third scenarios are concerned with the shared form of AVs. The second scenario simulates robo-taxis that do not accept ride-sharing. when an agent requests a robo-taxi, the closest available vehicle is dispateched to it, if any is available. Otherwise, as soon as a vehicle becomes available it is dispatched to the closest request. This mode is called shared autonomous vehicle (SAV). In the third scenario, rides on robo-taxis can be shared. When an agent requests a robo-taxi, the vehicle with the least increase in operation time (detour and waiting times due to the new request) is derouted to serve the request. This mode is called pooled shared autonomous vehicle (PSAV).

The scenarios are simulated in the city of Montreal. The synthetic population of Montreal is adapted from (Manout & Ciari, 2021). Other than PAVs, SAVs and PSAVs, other competing travel modes are also included: public transport, walking and cycling. Conventional privately owned cars are removed and replaced by AVs. Results of the three scenarios are compared with a baseline mobility scenario from 2018.

On the supply side, households that owned a conventional vehicle in the baseline scenario have a private autonomous vehicle in scenario 1. In scenarios 2 and 3, only the highest income households (10 per cent) have a private autonomous vehicle. For the rest, they have access to SAVs in scenario 2 and PSAVs in scenario 3. The shared vehicle fleet was sized on the assumption of 10 percent of demand (1 vehicle for every 10 agents), which has been seen repeatedly in the literature as providing a good level of service (less than 15 minutes) (Boesch, Ciari, & Axhausen, 2016; Bischoff & Maciejewski, 2016a, 2016b; Fagnant & Kockelman, 2018). PSAVs offer four seats.

3. RESULTS AND DISCUSSION

Modal share

One of the questions raised by the introduction of a technology that makes travel as convenient as with a conventional car but without the burden of driving is: will autonomous vehicles replace public transport? Figure 1 shows that the modal share of the motorized modes (car and car-passenger for the baseline scenario, and PAV, SAV, and PSAV for scenarios 1, 2, and 3, respectively) is fairly stable. Active modes and public transport even gain some share, although by small margins.

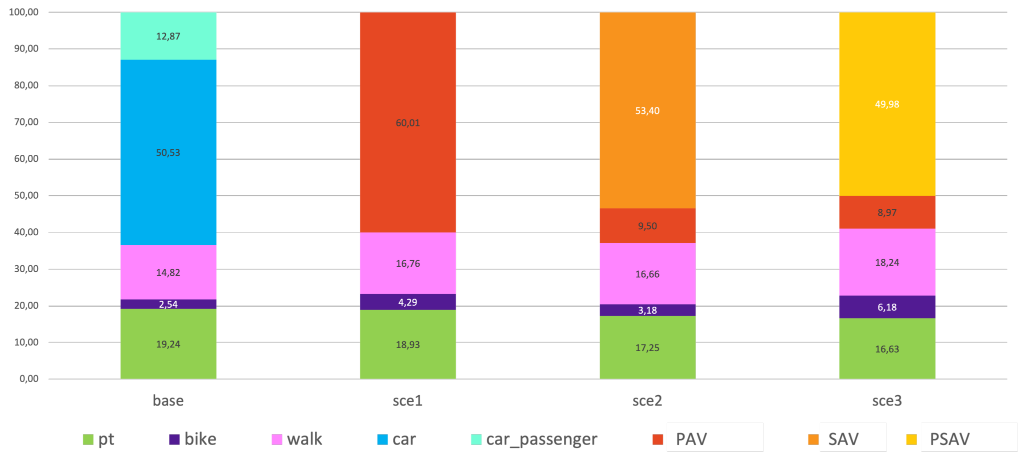


Figure 1: Modal shares of the three scenarios in comparison with the baseline scenario

It should be noted that these results are very sensitive to the cost assigned to the mode of transport, as well as to the performance of the service offered.

Travel distance

Table 1 shows the average Vehicle-Kilometers of Travel (VKT) and distance per trip and per vehicle on the road network. Scenarios 1 and 2 show a very large increase in VKT (71 % and 85 %, respectively). For scenario 1, $0{,}52 \cdot 10^6$ km or 24 % of the additional km produced compared to the baseline scenario come from the demand induced by the modal shift and $1{,}61 \cdot 10^6$ km (76%) from empty travel to serve requests. For scenario 3, the increase is less important, as ride-sharing is allowed. This is also due to the design of the dispatcher algorithm that minimizes vehicle travel distance.The share of empty kilometers is also lower for PSAVs. In terms of average distances per trip, the effect of empty trips can be observed, since the distances with passengers for autonomous modes are approximately equal to those with car in the baseline scenario. In contrast, for the PSAVs in scenario 3, the average vehicle distance is less than the passenger distance because passengers can be grouped together. The average distance per vehicle, shows also that shared vehicles are used much more.

Scenarios	Base	Sce1	Sce2			Sce3		
Modes	car	PAV	PAV+SAV	PAV	SAV	PAV+PSAV	PAV	PSAV
VKT (10^6 km)	2,98	5,11	5,12	0,97	4,55	4,14	0,87	3,27
Extra VKT (10^6 km)		2,13	2,54			1,16		
Evolution		+71 %	+85 %			+39 %		
Avg distance/veh. (km)	30,8	85,8		120,4	352,3		108,9	252,8
Avg distance /trip (km)	14,55	20,96		25,11	21,06		24	16,12
Empty share		0,31		0,35	0,31		0,34	0,21

Table 1: Comparison of the travel distance (VKT) and average distance by trip and vehicle between the three scenarios

Environmental impacts

Total energy consumption and GHG emissions of the three scenario are calculated using the Canadian vehicle sales data. Two assumptions about the fleet are considered:

A: SAVs and PSAVs are sedan

B: all autonomous cars are sedan

		hyp.A			hyp.B		
	base	sce1	sce2	sce3	sce1	sce2	sce3
Energy consumption. (10^6 MJ)	35,5	54,7	41,8	31,9	35,3	38,1	28,6
Evolution cons.		+ 54 %	+ 18 %	-10 %	0 %	+8 %	-19 %
GHG emissions (10^9 g GEG)	2,36	3,64	3,11	2,36	2,72	2,94	2,21
Evolution emis.		+54 %	+ 32 %	0 %	+15 %	+25 %	-6 %

Table 2: Energy consumption and GHG emissions

As expected by such a large increase in VKT, there is an increase in total energy consumption and GHGs emissions. The only scenario that meets the objective of reducing emissions is scenario 3. By limiting empty miles for the PSAV mode, smoothing automated driving and changing vehicle type, a decrease in energy consumption is observed. However, if instead of considering the same fleet composition as today for the private ownership scenario we consider a fleet entirely composed of medium sized cars, increase in GHG emissions declines from 54% to 15%. Overall, improvements in driving through automation do not compensate for the energy impacts of driving empty, but fleet adjustments could help limit the impact.

Congestion on the network

As the number of kilometers travelled increases, the question of congestion arises. What is the impact of automation on network congestion?

Congestion is computed for all links in the network as the ratio of vehicle throughput between 7AM and 8AM to link capacity. Map 2 represents the congestion ratio for each link. A value close to 1 (in red) means that the capacity is reached, a value close to 0 (in light yellow) means that the traffic is in a free-flow state or close to it. For a more formal comparison, the average ratio has been calculated for the whole network by weighting congestion by the length of the link. Values are very low because some links are fine feeder roads. Later indicators will be calculated by type of road.

Furthermore, according to local guidelines (Gourvil & Joubert, 2004), traffic is considered congested as soon as the ratio exceeds 0.7. The sum of the link lengths in this case was calculated. Table 3 presents these results. In terms of capacity, the current value for non-automated vehicles was left, the assumption of improved capacity, as autonomous vehicles can drive closer to each other, was not considered in this study.

All scenarios experience an increase in congestion. Congestion is greatest in scenarios 1 and 2. These are the two scenarios with the largest increase in VKT. Indeed, the fact that vehicles cannot take several passengers at the same time increases the number of vehicles on the network. But it is mainly the empty trips to pick up a new person that generate more traffic.

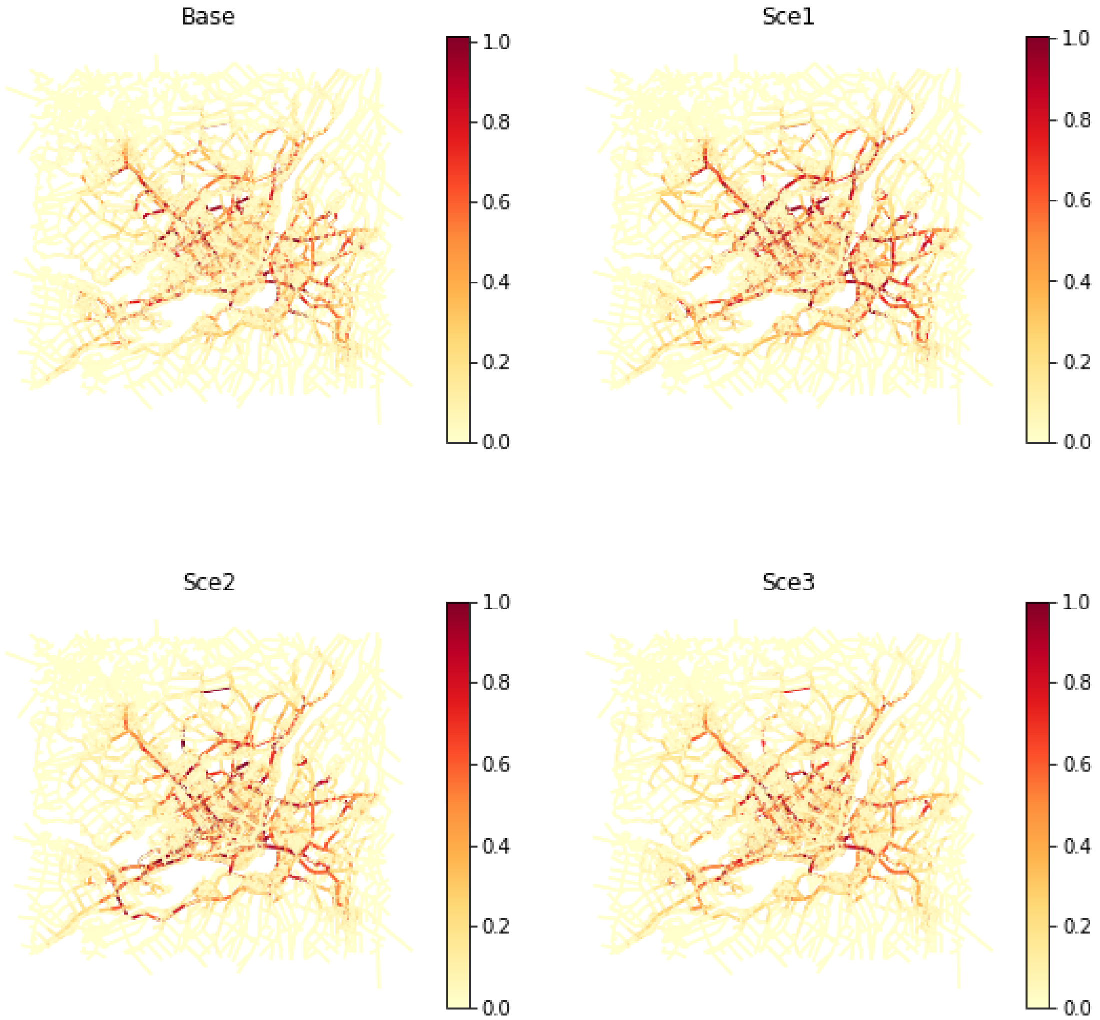


Figure 2: Congestion maps of Montreal for the different scenarios

Table 3: Congestion indicators

Scenarios	base	sce1	sce2	sce3
r_{moyen}	0,070	0,090	0,086	0,076
$km_{r>0,7}$	639	1073	1066	682

Service Performance : waiting time and utilization

The agent-based approach allows the evaluation of the performance level of AV services. From an operator's point of view, it is important to track the use of the fleet and waiting times, which are closely linked.

Figure 3 presents the waiting times throughout the day. Waiting times are very high for shared modes during the morning rush hour, exceeding 1 hour. Figures 5 and 6 show that during the morning rush hour, all vehicles are occupied driving empty to pick-up a passenger or driving with a passenger onbroad. The demand is greater than the supply and waiting times are very high. As time goes by, requests are processed and waiting times decrease even if the fleet remains fully used for the SAVs.

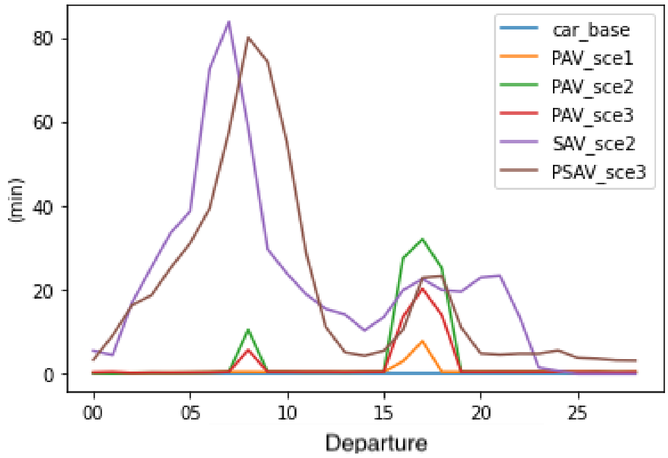


Figure 3: Median waiting times for passengers

In the evening peak, vehicles travel less to serve demand. Therefore, fewer empty trips are performed by SAVs and PSAVs and waiting times are lower than in the morning peak.

For PAVs, the number of empty trips is higher in the afternoon. We observe that the fleet remains under-utilized in the case of private ownership. 88% of the vehicles are on standby during a simulation. However, this does not prevent significant waiting times when two agents from the same household want to use a vehicle at the same time.

For shared modes, during the part of the day in which most activities take place (between 6:30 a.m. and midnight), the use of vehicles is more profitable with only 2.6% of SAVs not being used and 31% of PSAVs.

The analysis of waiting times (figure 3) and vehicle utilization (figures 5 and 6) shows that the size of the fleet is not sufficient to provide a good level of service. Waiting times exceed the 15-minute threshold in 32%, 55% and 51% of cases for PAVs in scenario 1, for SAVs in scenario 2 and PSAVs in scenario 3, respectively. The initial assumption of 1 vehicle for 10 agents is based on the literature (Boesch et al., 2016; Bischoff & Maciejewski, 2016a, 2016b; Fagnant & Kockelman, 2018). Despite using similar AV and SAV allocation algorithms are as in the case of Berlin, Europe, our conclusions are different. The result does not seem to be transferable to a North American city like Montreal. For the results presented in North America, the model used was not the same and the resolution of the network was different. Therefore, this assumption should be reviewed and the fleet size should be increased to provide a better level of service.

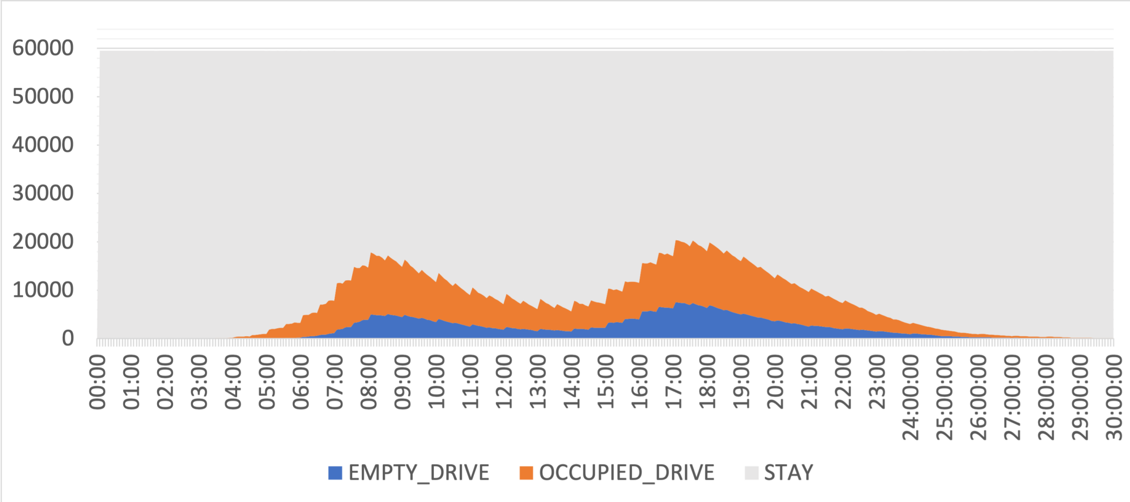


Figure 4: Distribution in time of the use of PAVs in scenario 1

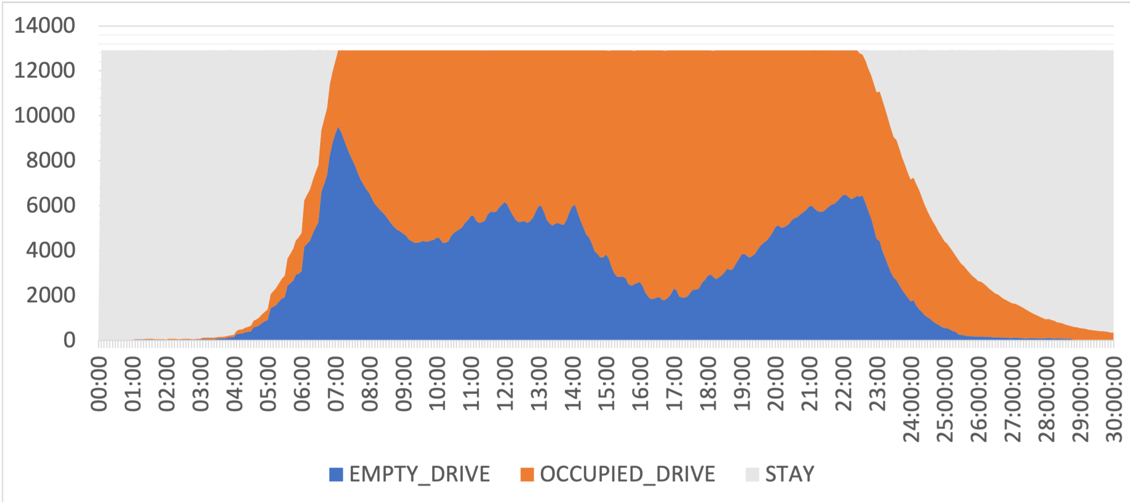


Figure 5: Distribution in time of the use of SAVs in scenario 2

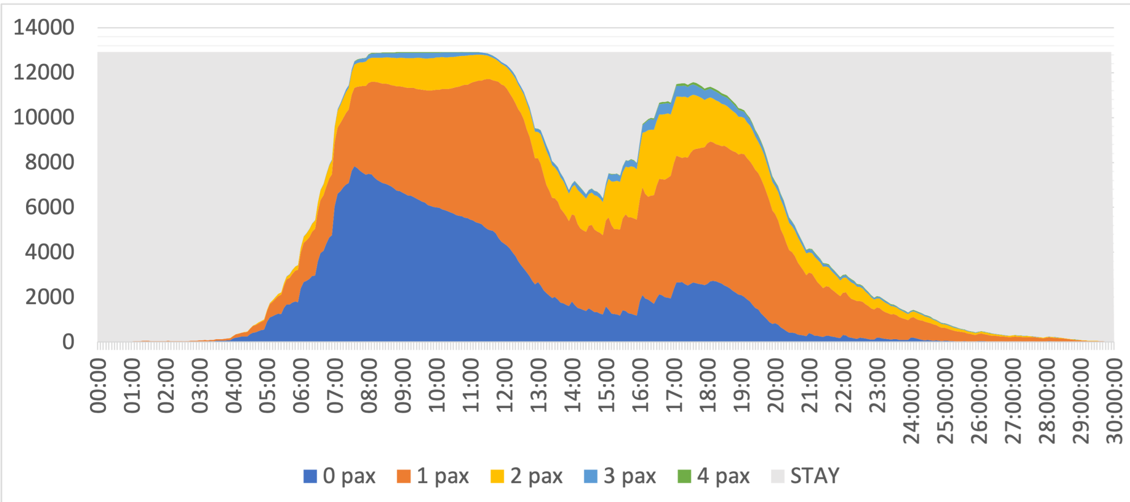
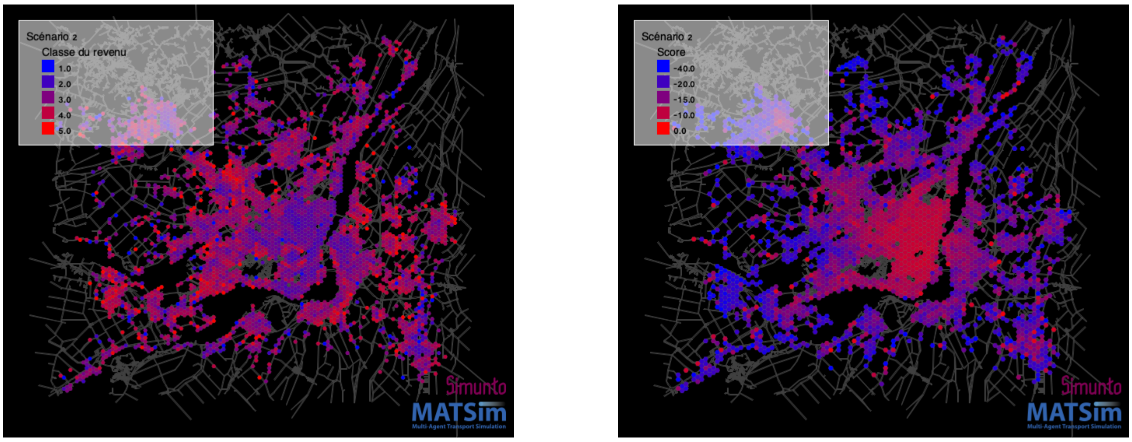


Figure 6: Distribution in time of the use of PSAVs in scenario 3



(a) Income class of the household **(b) Scoring of the agent**

Figure 7: Comparison between the scoring and the revenue

Equity analysis

Thanks to its agent-based design, MATSim gives an insight on the economic utility derived by different agent from using AV services. Surprisingly, we notice that households with a higher income have lower scores in scenarios 2 and 3 (see figure 7). This is due to the residential location of high-income households who live in low-density areas. In these areas, the level of service of AVs is not as good as in central and dense areas and waiting times are, therefore, higher.

4. CONCLUSIONS

This work allows for comparing, at different levels, three different scenarios of AVs. To the authors' knowledge, this research is among the first to compare between the impacts of private use and on-demand shared services.

Outcomes of the multi-agent model confirm previous findings and assumptions, but with some significant differences. As expected, in comparison to private use, the pooled shared service has a better environmental performance and differences are not small, but they can be reduced with appropriate policies, for example having a different fleet composition. In comparison to environmental impacts, results about the modal transfer and congestion are less alarming. In general, results suggest a more nuanced reality than the heaven or hell dichotomy (where private ownership would be "hell" and a shared use "heaven") as it has been sometimes mentioned in the public discourse.

For this work, modeling parameters have been set based on the literature. The calibration may not be adapted to the Montreal case. This can be seen in the unrealistic waiting times. This is an avenue to be explored in order to obtain more reliable results. The model used also has limitations in terms of the likelihood of using autonomous vehicles for private use. Currently, informal, intra-household carpooling is not allowed.

A significant limitation of the agent-based approach is computation times that are very long. This limits the possibility to explore other scenarios or to conduct sensitivity analysis on explored scenarios. Work is ongoing to improve the efficiency of MATSim and AV algorithms.

Finally, although the extreme scenarios presented here, almost exclusively either private or shared vehicles, are useful for analysis, more complex scenarios in which several different uses would coexist may be more realistic, and will be explored in the future.

ACKNOWLEDGMENT

The authors would like to thank Jalon, for funding the project on which this paper is based.

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