Operator and user perspectives on fleet mix, parking strategy and drop-off bay size for autonomous transit on demand

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OPERATOR AND USER PERSPECTIVES ON FLEET MIX, PARKING STRATEGY AND DROP-OFF BAY SIZE FOR AUTONOMOUS TRANSIT ON DEMAND

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ABSTRACT

Autonomous vehicles (AVs), but in particular shared autonomous transit on demand (ATOD), promises many efficiencies in future transport provision, and may lead to concomitant changes in urban form. Considering the effects of car-oriented planning on the livability, efficiency and sustainability of 20th century cities, there is growing interest in how we may anticipate the changes that this disruption will bring about. Parking is one of the several vehicle behaviors which may be reformed by the upcoming era of AVs. In the paper, four different parking strategies as well as bay constraints are implemented to assess the influence of possible parking regulations on ATOD. Four parking strategies are explored, including demand-based roaming, parking on the street, parking in depots and mixed parking between parking on the street and in depots. We tested bay sizes of 10, 15, 20, 25, and 30m, for a mix of 3 vehicle sizes: 4-, 10 and 20-seaters. Combinations of different parking strategies and different bay sizes were evaluated from the perspective of travel time, walk distance, vehicle occupancy and vehicle kilometers traveled. Results show that strategies produce radically different utilizations of vehicles to provide the same minimum service level for a particular study area in Singapore. We conclude that urban designers and policy-makers need to consider these as important parameters when designing or retrofitting neighborhoods if they want to maximize potential benefits from this new transportation mode.

Keywords: agent-based modeling, MATSim, parking strategy, bay size, fleet mix, autonomous vehicles, transit-on-demand, mobility-on-demand
INTRODUCTION

The era of the autonomous vehicle (AV) is imminent. Instead of AVs replacing privately owned vehicles on a one-to-one basis, many are arguing that this new mode lends itself to shared use. The ultimate vision is that of a paradigm shift from mobility ownership to mobility-as-a-service: a flexible, affordable, in-time and efficient alternative to private vehicles and taxi services.

Several studies have been conducted on the emerging potential of AVs, suggesting that widespread inception may lead to:

• Enhanced road safety and reduced accident rates (1);
• Increased street capacity through fixed spacing and platooning (2);
• Increased intersection capacity with interactive intersection signal control (1);
• Reduced private vehicle fleet size, since one shared AV can replace several private vehicles (3);
• Release of parking-occupied urban space (4).

Particularly the last two points suggest that the greatest societal advantages may be gained when mobility is offered as an on-demand service, be it as pooled rides or analogous to existing taxi services. In this context, and from the point of view of the policymaker, the introduction of AVs into the urban transport context may reform the existing public transport management system.

Autonomous transit-on-demand (ATOD) is a possible new public transit mode where AVs are essentially autonomous buses. It is conceived as a stop-to-stop bus service with dynamic routing among dedicated stops, which can combine the advantages of both taxi and bus (5). It could increase passenger convenience and save travel time, however, researchers have concerns about its efficiency and vehicle occupancy.

Ride-sharing companies (essentially, companies offering a platform for informal taxi services), such as Uber, have been offering dynamic ride-sharing services for a number of years, but the number of passengers sharing rides cannot be compared to those using ordinary transit services. However, dynamic ride-sharing with autonomous vehicles can be very different from that with human drivers. For the policymaker, firstly, taxis (formal and informal) are difficult to deploy and manage for the sake of lower generalized cost or higher social benefits. For example, taxi drivers always roam and compete for more passengers, which may cause lower vehicle occupancy. Secondly, taxi companies also have their own preferences and agendas; for instance, Uber launched a so-called ‘Grey ball’ system which reject requests from a specific area or person, or excludes some groups of people from the system (6).

In comparison, the proposed ATOD service can be deployed and managed for the system optimum (assuming it is under centralized control, e.g. a transport authority or transit operator). ATOD could offer more flexible and on-demand service than buses, while being more precisely controlled and coordinated than taxis. A centrally controlled ATOD system can have a dynamically mixed fleet of vehicle sizes deployed depending on demand, in order to maximize ridership. Operating flexibly as a stop-to-stop, door-to-door or first/last mile rail connection, the flexibility of precise, centralized control could radically transform transit into a mode of choice, rather than necessity.

This paper focuses on the implementation and the evaluation of different parking strategies and drop-off bay sizes for a mix of autonomous vehicle sizes, operating as a centrally controlled ATOD system. The ATOD dispatcher attempts to provide a reasonable service level; i.e. after ordering a service, you shouldn’t wait too long, nor should passengers experience a long detour. We discuss and compare user experience and operation cost resulting from four different centralized
parking strategies, namely demand-based roaming (i.e., no parking, ever), parking on the street, parking in depots and mixed parking between parking on the street and in depots. These strategies are investigated for a number of bus bay sizes that enable different combinations of vehicle sizes to perform dwell operations simultaneously, and thus creating queues of waiting vehicles to build up on the road. From Table 1, user experience includes total travel time, average passenger waiting time, average in-vehicle time, average access/egress walking distance, average vehicle occupancy; operational cost including fixed cost, which is measured by transit stop bay construction, depot construction and fleet size, and finally variable cost, which is mainly energy consumption and measured by vehicle kilometers traveled.

**TABLE 1: Overview of Indicators**

<table>
<thead>
<tr>
<th>Perspectives</th>
<th>Measurements</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>User experience</td>
<td>Time</td>
<td>Avg. travel time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg. wait time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Avg. in-vehicle time</td>
</tr>
<tr>
<td>Comfort</td>
<td></td>
<td>Avg. walk distance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vehicle occupancy</td>
</tr>
<tr>
<td>Operation cost</td>
<td>Fixed cost</td>
<td>Fleet size</td>
</tr>
<tr>
<td></td>
<td>Bay size</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Depot size</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy consumption</td>
<td>Vehicle kilometers traveled (VKT)</td>
</tr>
</tbody>
</table>

The paper aims to extend the existing capabilities of the demand responsive transit (DRT) extension (7) of MATSim (8), a well known agent-based mobility simulation platform, to simulate ATOD as a potential future transport mode with specific parking rules. The result can help policymakers manage and regulate ATOD with an appropriate parking strategy in the near future.

**LITERATURE REVIEW**

This paper can be framed as the result of a recent series of efforts to effectively model shared AV systems using agent-based simulation, specifically MATSim. Boesch et al. (9) simulates the influence of varying demand on the required fleet size of AV taxis in Zurich. Fagnant and Kockelman (10) simulates the advances of shared autonomous vehicles in Austin. Maciejewski and Bischoff (11) found that shared autonomous vehicles may alleviate congestion in Berlin.

Parking is also a widely-debated issue in transport and urban planning. Although urban transport mainly focuses on the mobility of people and freight, according to Shoup (12), vehicles spend 95 percent of the time in the parking lot and only 5 percent of their time moving. Furthermore, a single vehicle can occupy more than one parking space, usually one is reserved at work, one is at home and a share of one in a commercial area (13). With increasing ownership of private vehicles and increasing demand, urban areas are simply running out of parking space. A number of researchers argue that AVs may reduce the need for parking space because:

- It saves parking land even at small market penetration level due to the reduction of vehicle ownership and the improvement in the vehicle occupancy (4), if offered as a service;
- It is possible to relocate parking space away from the trip origin and destination, and even outside the downtown area (1, 14);
AVs can be controlled precisely to create efficient and compact parking systems, with vehicles near-optimally stacked within millimeters from each other (15). In addition, some researchers also applied different transport models to simulate AV parking. Zhang et al. (16) tested the influence of fleet size, ride-sharing and roaming on parking demand using an agent-based model. Zakharenko (17) predicted the formation of a dedicated "parking belt" outside the commuting area using an analytical model. Using agent-based modeling, Martinez and Viegas (18) found that AVs can free up urban space by eliminating off-street parking. Lam et al. (19) simulated the integration of AV parking with a vehicle-to-grid service. It is not clear that these investigations consider the trade-offs between acceptable service levels and operational cost. We argue that the introduction of AVs, especially as a shared service, will not only reshape the future of mobility, but AV-specific infrastructure design guidelines and operating regulations will impact the quality and efficiency of automated service. In this paper, therefore, we try to show how these considerations trade off against each other, from the perspective of both transit user and operator.

**METHODOLOGY**

Simulations are executed using the Multi-agent Transport Simulation (MATSim), with implementation and modification of the Demand Responsive Transit (DRT) extension (7). MATSim is an activity-based, extensible, open-source multi-agent simulation framework implemented in Java (8). To emulate user equilibrium, the same day is simulated several times while agents optimize their own travel experience in a process of co-evolution.

The MATSim DRT extension can simulate autonomous transit with dynamic routing and ride-sharing. In the DRT extension, AVs are dynamically routed in response to passenger requests. A central dispatcher assigns passengers to vehicles, adding modifications to a vehicle’s task schedule. As shown in the white part of Fig. 1, when a new request is received, the new request will be converted to drive and stop tasks in the schedule, followed by a stay task. The drive task includes drive-to-pick-up and drive-to-drop-off, the stop task is either pick-up or drop-off, to be executed when the vehicle is idle. By default, the vehicle will remain where it is when idle. The dispatcher in the DRT extension attempts to maintain a realistic level of service by allowing reasonable detours, defined by a maximum waiting time constraint for new passengers and maximum in-vehicle travel time detour factor for passengers to be dropped off. As long as the maximum waiting time and in-vehicle time of one passenger is violated, the request will be rejected by the vehicle. This rule only applies for request dispatching and sometimes passengers wait longer than the maximum waiting time due to unpredictable traffic situations, such as traffic congestion or long queues of vehicles waiting at the stops.

As shown in the red part of Fig. 1, four different parking strategies as well as the transit stop bay infrastructure were implemented in the DRT extension of MATSim. The four parking strategies consist of demand-based roaming, parking on the street, parking in depots and a custom strategy of parking on the street or in depots at different times of the day (mixed parking strategy). In the rest of the paper, the abbreviations of roam or roaming, road, depot and mix are used to refer to each strategy accordingly. The above-mentioned parking strategies are implemented when the vehicle starts to execute a stay task and the vehicle departs when the stay task is finished, triggered by incoming pickup requests.

The bay infrastructure size constraint restricts the number of dwelling vehicles in each transit stop and required modification of the stop task. When there is sufficient bay space, a vehicle
is allowed to dwell immediately, otherwise, a queue task will be added until the currently dwelling vehicle has left the bay. Vehicles queuing up reduce the flow capacity of the corresponding link. All four parking strategies with varying bay sizes will be compared in the same simulation framework with the same input demand, road network, transit schedule and stop infrastructure. Besides these extensions to the MATSim DRT module, a new router developed specifically for ATOD is also employed, which employs information feedback to passengers, enabling the choice to walk longer for a better stop in terms of total travel time instead of always going to the closest stop.

A notable limitation of this study is that we do not consider the further complication of where vehicles need to recharge or refuel, nor where and when they need to perform maintenance activities such as cleaning and servicing.

**Demand-Based Roaming Strategy**

Demand-based roaming is similar to the roaming of taxis, which always roam and tend to drive to anticipated high demand areas when idle. The strategy works by recording demand from previous iterations at a zonal level, where the study area is divided into several zones according to a predefined cell size. In each iteration of the MATSim mobility simulation, the number of departures in each zone will be counted every 30 minutes and saved as a demand estimate for the next iteration. During the simulation, once a vehicle is idle, it will choose an adjacent destination zone through weighted sampling of anticipated demand. Within the destination zone, the vehicle performs a random walk and repeats the above process until it is assigned a passenger. To simplify and characterize each strategy, vehicles in this strategy will never stop, even if the expected demand of all zones is zero, in which case vehicles will randomly choose a zone to roam.

This (non-)parking strategy is the most prevalent for taxis and ride-sharing services in reality. Although in reality, no car really roams for 24 hours because drivers need a break, it is still an important strategy to consider for AVs, as it represents a corner solution to possible deployments. The strategy increases the probability for drivers to be matched with passengers as well as...
dynamically relocating vehicles depending on demand; while at the same time, it increases empty
mileage. In the project, the simulation aims at finding out whether the other centralized parking
strategies can replace the conventional roaming strategy with comparable service and less empty
traveling.

Parking On The Street
Parking on the street is similar to the existing parking strategy of private vehicles in many cities.
Vehicles park in the nearest available road space to the trip destination. In the strategy, the parking
lot is the street and AV buses will wait on the street for the next request once empty. Parking on
the street will block one lane and the capacity of the street will be reduced accordingly once it
is occupied for parking by at least one vehicle. Later, if all parking vehicles leave the link, the
number of lanes and the capacity of the link will recover. Some streets are not allowed for parking,
such as one-lane streets, and streets with transit stops. The number of parking spaces along the
street depends on the length of the street and the size of the vehicle, thus offering more spaces for
smaller vehicles. If the current link is not allowed for parking, the vehicle will randomly choose
one link among all next links to cruise for parking till it reaches an available space.

Parking on the street saves space of parking depots, but may cause congestion, which is
why it is discouraged in many urban areas. However, as the shared autonomous vehicle fleet is
significantly smaller than that of a private vehicle fleet, and we assume that only these transit
vehicles are allowed to use parking on the street, we expect that it will not produce a significant
reduction in capacity relative to the fleet size.

Parking In Depots
Parking in depots means that the vehicle always drives back to a depot once it is empty but can
still accept a new request either on the way or in the depot. There are several depots in the system,
onece the nearest depot is full, the vehicle has to drive to the second nearest depot and so on. After
choosing the nearest available depot, the parking place in the depot will be reserved for the vehicle,
and once the vehicle accepts a new request, the reserved parking place will be released.

This strategy is similar to existing public transit parking strategies, which relocates vehicles
away from the dense downtown area with high parking cost and limited supply. Depots can be
located in peripheral areas and the strategy can totally free up dense urban space from parking. Its
disadvantage is extra empty travel time and distance from depots to the origin of the traveler and
from the destination of the traveler to the depots, as well as the cost of purpose-built parking space.

Mixed Parking Strategy
The mixed parking strategy can switch between both parking on the street and in depots depending
on the time of day. It can be adjusted to minimize the impact on traffic flow by street parking and
the space required for depots. AVs will stay on the street for overnight parking (20:00 - 07:00) but
will switch to the depot strategy during the daytime (07:00 - 20:00). At 7:00 in the morning, all idle
vehicles will move to the nearest available residential parking lot; while at 20:00 in the evening,
all idle vehicles will move to the nearest available street. From 20:00 to 07:00, the traffic is not as
heavy as in the daytime, so AVs can park on the street to save parking space; while from 07:00-
20:00, when traffic on the street is heavy, but most private vehicles in the parking lot in residential
areas are gone for work, AVs may employ the parking lot in the residential area as depots.

It should be noted that parking on the street and in depots strategy in the mixed strategy
is slightly different from the two strategies in previous sections. Only small-size AV buses are allowed to park on the street in the mixed strategy while in parking on the street strategy, all vehicles are allowed to park. Furthermore, small-sized AV buses can park in small depots in residential areas, while with the parking in depots strategy, all vehicles have to go to the peripheral depot. Big AV buses can only park in the peripheral depot throughout the day in the mixed parking strategy.

The mixed parking strategy tries to take advantage of both road and depot strategies with dynamic traffic management. It is expected that the strategy has less operational cost than the depot strategy but will produce better user experience than the road strategy, as less congestion may result.

**BAY SIZE RESTRICTION**

The design of the stop bay is not considered in the current default MATSim transit implementation, but it will be very important for AV buses. In the default MATSim there is only one attribute, isBlockLane, which denotes whether a bus stop blocks a lane of traffic or has a bay of infinite capacity. In reality, bus bays indeed have a limited capacity, leading to bus bunching when that capacity is exceeded. In Singapore, bus bays usually can accommodate 1-3 buses (20).

Bay size will definitely influence traffic flow. Consider the example shown in Fig. 2: the dwelling time of the first vehicle is 10s and the second vehicle is 15s. If there is no bay, one lane of the road will be blocked for 10s + 15s = 25s; while if there is a bay big enough for the first vehicle, the lane will be blocked for only 10s; while if there is a bay enough for both vehicles, the lane will not be blocked. Considering that pick-up or drop-off points are widely distributed in the urban area, the design of bus bays should be considered for urban traffic management.
network and AV bus services are quite frequent, the influence of bay size design on traffic flow of
the whole network cannot be negligible. Once the bay length cannot satisfy all dwelling vehicles,
queuing vehicles will block one lane of the road. Different bay sizes enables different combination
of dwelling vehicles.

In the simulation, a bay manager is implemented to manage both AV bus and public transit. A bay in the simulation consists of a transit stop, bay length and information of the queuing vehicles. Whenever an AV bus arrives at the facility, it will register at the corresponding transit stop and check whether there is still space to dwell. If the bay is full, the vehicle will queue and a network change event will be processed to change the capacity and the number of lanes of the link. As long as there is no vehicle queuing, the capacity and the number of lanes of the link will recover immediately. Vehicles will follow a "first come, first served" rule, and jumping the queue is not allowed.

SCENARIO

For this study, we produced a scenario for a future development in Singapore, titled Waterfront Tanjong Pagar. The Waterfront Tanjong Pagar project represents a Future Cities laboratory (FCL) synergy project including eight FCL research modules led by Dietmar Leyk. The planned Tanjong Pagar network (Fig. 3) consists of 1728 links, 578 nodes, 330 pick-up/drop-off points and 1 MRT line with 5 stops. Most links in the network are one lane per direction, the expressway is two lanes per direction and the tunnel is three lanes per direction. AV buses are only allowed to park, pick up or drop off on the one-lane-per-direction streets (two lanes in total), as the expressway and tunnel are only design for high-speed traffic. Usually, when a two-lane-two-direction street is occupied for parking or dwelling, the traffic of the street will not be totally blocked, and other vehicles can still overtake the vehicle by another lane. Therefore, whenever there are parking or dwelling vehicles, the capacity and the number of lanes are reduced by half. The dispatcher allows a maximum waiting time of 10 minutes since accepted and maximum in-vehicle travel time following Eq. (1)

$$\text{MaximumInVehicleTravelTime} = \alpha * \text{estimatedTravelTime} + \beta$$

where $\alpha$ is 1.5 and $\beta$ is 10 minutes.

FIGURE 3: Planned network of new urban development area, Tanjong Pagar.

In the scenario, only MRT and ATOD are available public transit choices. Besides these, the
scenario also contains car, walking and normal taxi modes in proportions representing a realistic Singapore traffic demand. The estimated total number of trips per day in Tanjong Pagar is 262,144, 49.88% of which are public transit, 39.17% private vehicle, 3.92% taxi and 7.04% walking. No mode shift is allowed between public transport, car and normal taxis, but after each iteration public transport travelers can change their route to use only AV buses, only MRT or a combination of the two. Effectively then, the ATOD system is simulated either as an individual transport mode or as a first/last-mile solution to the existing MRT system. MRT is not subject to any bay limitation, and 10m-, 15m-, 20m-, 25m- and 30m-bays were tested for autonomous buses. The fleet consists of 4-seater, 10-seater and 20-seater AV buses, with vehicle lengths (including the small spacing between vehicles) of 5m, 6.5m and 9m respectively.

Having a mix of vehicles and bay size constraint means that only certain combinations of vehicles are allowed to simultaneously occupy a bay of a given size. Having larger bays may mean less road congestion, less dwell time and wait time, at the cost of increased infrastructure spending and lost space. For bay size 10, 15, 20, 25, 30m, it is 5, 11, 25, 59 and 138 combinations of vehicles respectively.

In order to capture effects of overnight trips, the simulation runs from 00:00 to 28:00. The vehicle mix is the same for all scenarios, 150 4-seater vehicles, 100 10-seater vehicles, and 50 20-seater vehicles. The fleet size was determined after a number of tests simulations, which revealed this vehicle mix to be adequate to serve the demand, but it does not necessarily mean that this vehicle mix is optimal. We do not spend time on justifying costs, as we feel that sensitivity analysis of relative costs for future scenarios and transport modes should be the default approach to test for robustness, and any specific relative cost allocation is likely to be wrong. That said, time constraints have prevented us from doing such a sensitivity analysis at this stage.

RESULT ANALYSIS

Summary

In Table 2, the average generalized cost\(^1\) of traveling, mode share and average ridership during the whole day are presented for each parking strategy and bay size. Cost values are produced by an econometric function depending on simulated travel time and travel distances. For all strategies, there is a gap in utility between bay size 15m and 20m, the improvement is around 0.4-0.5. Among the four strategies, roaming has the highest utility, or in other words, better transport performance from the user’s perspective, followed by road, mix and depot. Only the mode share between public transit modes is analyzed, and the mode share of all strategies is similar, except that MRT is somehow more preferred in the roaming strategy. The average ridership of the roaming strategy is lower than the other three strategies. It is not clear whether the low cost of the roaming strategy is from better AV bus experience or from a higher MRT share, which is faster.

Travel Time

As the dispatcher enforces restrictions on maximum waiting time and maximum travel time detour factor for accepting new requests, the average total travel time, waiting time and in-vehicle time should be similar across the different strategies. However, the result still shows significant variation as a function of the different strategies and bay size. Generally speaking, total travel time, waiting time and in-vehicle travel time all decrease with increasing bay size with some fluctuation as shown

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\(^1\)Generalized cost is presented here as a dimensionless utility value, and thus only useful to compare results.
TABLE 2: Overall Result

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Bay size</th>
<th>Average generalized cost</th>
<th>Mode share</th>
<th>Average ridership</th>
<th>VKT [kkm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>AV bus</td>
<td>MRT</td>
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<td>Roam</td>
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<td>Depot</td>
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</tr>
</tbody>
</table>

1. in Fig. 4. Beyond a bay size of 20m, total travel time tends to be stable. The only exception is average in-vehicle time for the road strategy, which decreases first, but increases with longer bays.
2. The average total travel time is around 12 minutes, average waiting time is around 5 minutes and the average in-vehicle time is around 6 minutes for all strategies, as was to be expected for the dispatcher constraints.
3. Furthermore, the roaming strategy performs better for the indicators of total travel time and total wait time, matching prior expectation. Roaming vehicles always go to zones with higher demand, which can explain the reduced average waiting time. It is surprising that the average in-vehicle time of the road and the roam strategy is much less than the other two strategies, because both roam and road strategy should cause more congestion and lead to longer in-vehicle travel time. A possible explanation for the roam strategy, which also has less wait time, is less detouring and lower average vehicle occupancy. The average vehicle occupancy analysis in Table 2 supports this explanation. However, the short in-vehicle time and long wait time of the road strategy is hard to explain. Further analysis needs to be done to explore the reasonable explanation.

**Walk Distance**

Average access and egress walk distance represents the willingness of passengers to go further for a better service. The graph of transit walk distance (Fig. 5) does not offer too much information, as the range of the variation is within 2m. It shows that neither parking strategy nor bay size
FIGURE 4: Total travel time (wait time + in-vehicle travel time), wait time and in-vehicle travel time of different bay size and strategies.

FIGURE 5: Average access and egress walk distance of the four different strategies.

has a significant influence on access or egress walk distance. This means that, for this scenario at least, passengers do not change their decision about which stop they use for accessing better service. This might be because we have stops on every block as this neighborhood is supposed to be transit-oriented; a more sparsely distributed stop network might produce a different result. The average egress walk is slightly longer than the average access walk time, and 200m-250m is a very
pleasant walking distance for the majority of commuters.

**Ridership**

As mentioned above, and shown in Fig. 6, the average ridership of the roaming strategy is much lower than the other three strategies, which can explain the shorter travel time and longer occupied VKT in Fig. 10a. To further analyze the ridership of different vehicle types, it is interesting that the ridership is rarely influenced by the bay size for all types of vehicles, the only exception is probably the occupancy of 20-seater vehicles for the road strategy of bay size 10.

![FIGURE 6: Ridership of the four different strategies (The number above each bar chart shows the average occupancy of the scenario).](image)

The result may simply be due to the fact that passenger demand builds up at stops, because only two four seaters (if they happen to arrive together at the stop), or one vehicle at a time can enter the stop. This means that, if a 20 seater is queuing up to dwell at a stop, it is capable of absorbing much of this built-up demand within the constraints set by the dispatcher. However, for this to work, there need to be idle 20-seaters nearby, which is what the road strategy is designed to do.

If this explanation turns to be true, it represents an interesting approach to consolidate demand and then capitalize on it with appropriate distribution of supply, all the while saving on fleet and infrastructure cost. However, much more in-depth study and sensitivity analysis with higher demand is needed to support the explanation, as well as possible user experience impacts.
Our so-called corner solution, the roaming strategy, favors significantly higher occupancy for small 4-seater vehicles, as well as lower for 10-seater vehicles and dramatically lower for 20-seater vehicles compared to the other strategies. As a lot of vehicles compete for passengers, it is not easy to fill a larger vehicle. Among the rest three strategies, the average occupancy of the road strategy for 20-seater vehicles is higher than the other two strategies, but lower for 10-seater vehicles. These occupancy levels hint at changes to the fleet mix appropriate to the parking strategy, that may be investigated through simulation-based optimization, as an extension to Wang et al. (5).

9 Delay By Queuing

Fig. 7 shows the average delay of the 5 stops with the longest delay time of each strategy. The longest average delay for all delayed vehicles can almost reach 20s for the roaming strategy, 16s for the depot strategy, 10s for the road strategy and 6s for the mix strategy. The long delay of the roaming strategy seems to be linked to the unusual result of smaller vehicles enjoying highest occupancy; therefore, larger vehicles may be queuing up behind a string of smaller vehicles, each taking up dwell time overhead. This result hints at the inappropriateness of the roaming strategy, considering that it is to some extent, the default strategy of existing taxi services. However, further study and sensitivity analysis against varying demand levels needs to be investigated to test the universality of this conclusion.

**FIGURE 7:** Average delay of each stop of the four different strategies.
FIGURE 8: Six stops with longest delay according to the above delay analysis.

FIGURE 9: Average delay of each stop of the four different strategies.
It is interesting that the 5 most congested stops are more or less the same for all strategies. These stops are depicted in the Fig. 8, which shows their locations at three locations on both sides of the road. The most congested two locations (stop 0, 90, 2000000 and 2000090) are at the two ends of the MRT station, which matches expectations.

Furthermore, a sharp transition between bay size 15m and 20m can be observed for all strategies. The result can more or less guide the design of pick-up or drop-off bays, which should be 10m for all stops except bays near MRT, which should be 20m. Further sensitivity analysis of higher demand need to be done to prove how robust this design principle might prove to be.

Fig. 9 shows the average delay time of each vehicle type. In roaming strategy, the difference among the three vehicle types is very clear, 10-seater vehicles get the longest delay, followed by 4-seater and 20-seater vehicles. It is surprising that 20 seater vehicles enjoy the smallest delay compared to the other vehicle types. Furthermore, for the roaming strategy, there is actually an increase in average delay when the bay size is increased. This result runs counter to expectation, and while the effect is not that pronounced in absolute terms, it might be sensitive to demand increase and warrants further investigation.

In the road strategy, the average delay of the three vehicle types is equally low and insignificant in absolute terms. In the depot strategy, the curve is similar to the roam strategy, but the average delay is lower for all vehicle types. In the mix strategy, large 20-seater vehicles are more stuck in the queue contrary to what is observed in the other strategies. It is interesting to observe the different types of queuing vehicles for each strategy, and more detailed analysis should be done in the future for a better exploration.

**Vehicle Kilometers Traveled (VKT)**

It is not very surprising that the total VKT and empty VKT is incredibly high for the roaming strategy, as vehicles never stop for the whole day while in other strategies all vehicles stay in the parking lot during off-peak hours. However, from Fig. 10a, it is quite interesting to observe that the total occupied distance of the roaming strategy, which is defined by the VKT with passengers, is also significantly higher than the other three strategies. This is simply due to the fact that, as could be observed in the occupancy plots, smaller vehicles are favored by the roaming strategy and there are many more of them than there are larger vehicles. Consequently, the roaming strategy results
in a lot of small vehicles driving around all the time with a small number of passengers, and so the
system looks very busy, while it is actually relatively inefficient from an operator’s point of view.

In Fig. 10b, in order to be able to distinguish differences in results between the remaining
strategies, the roaming strategy is hidden from the graph, which is 50-80 times higher than the
other three strategies. The graph confirms the assumption that vehicles travel empty longer to go
to and from the depot, the road strategy has the least travel empty distance, and the mix strategy is
in the middle.

CONCLUSION AND OUTLOOK

The above shown result confirms the successful implementation and it was surprising to find that
the four parking strategies of the ATOD system with bay size restrictions, can have such a radical
influence on the efficiency of a given mix of vehicle sizes, in order to provide the same minimum
level of service in a given area. The result also shows the possibility of the introduction of ATOD
system with high vehicle occupancy, especially for big vehicles, if an appropriate, if counterintu-
itive, strategy is chosen; namely to let these large vehicles park on the road and wait for demand to
be consolidated at relatively small stops that can only accommodate one vehicle at a time.

From the perspective of users, roaming is the best parking strategy, which has less in-
vehicle travel time and less wait time. However, from the perspective of operators, the cost of the
around 10-20s improvement of total travel time per trip is incredibly high, which is 50-80 times
higher empty kilometers traveled. Under these circumstances, the tiny difference in travel time is
quite tolerable for a 12-minute trip. For fixed cost, results from the bay size design constraint is
similar among all strategies, and the basic rule should be that 10m is big enough for the normal
pick-up or drop-off point, and 20m is for the bay around MRT. However, sensitivity of the result
against increased demand should be investigated, to ensure the strategy is robust.

Considering both user experience and operational cost, road, depot and mix strategies look
similar in terms of ridership, generalized cost, travel time and total vehicle kilometers traveled.
Considering our initial expectations, the road strategy does not have the expected increase in travel
time caused by the reduction of network capacity, probably because of the rather small fleet size.
The VKT of the depot strategy is only 1000km longer than the road strategy, which is less than
3km per vehicle per day for an area with dimensions of 3 km north to south and 4 km east to west.
Our initial concern about long travel distances for the depot appears to be unfounded for the small
Tanjong Pagar scenario.

From the perspective of urban quality and livability, people may benefit more from the
depot strategy, as it can remove car parking in the urban area and liberate people from the vehicles
taking up urban space. Given that the disadvantage of the depot strategy does not decrease the
user experience significantly, it is possible for policymakers and urban planners to arrange public
parking lots at appropriate locations in the area, away from human activity.

For future work, first, it is important to investigate the transition observed between bay
sizes of 15m and 20m, which we currently suspect to be due to the increase in the number of com-
binations of vehicles that might be accommodated given their assumed sizes for this study. It might
be possible that there is a functional form that can serve as a design guideline for bays to serve any
combination of vehicle sizes. Second, considering how sensitive ridership results were to various
strategies, it would be interesting to investigate a simultaneous simulation-based optimization of
vehicle fleet mix and bay sizes by location. Third, the result applies for a small new development
area, and the influence of the parking strategies on a larger-scale and more complicated area still
need to be explored if we are to come up with robust design guidelines.

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If you are interested in the implementation of the project, please find the code in https://github.com/strawrange/NewParking.

AUTHOR CONTRIBUTION STATEMENT
The authors confirm contribution to the paper as follows: study conception and design: Biyu Wang, Dr. Sergio Ordonez, Dr. Pieter Fourie; functionalities implementation in MATSim: Biyu Wang, Dr. Sergio Ordonez; data collection: Dr. Sergio Ordonez, Dr. Pieter Fourie; analysis and interpretation of results: Biyu Wang; draft manuscript preparation: Biyu Wang; paper review and modification: Dr. Sergio Ordonez, Dr. Pieter Fourie. All authors reviewed the results and approved the final version of the manuscript.
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