THE INTERPLAY BETWEEN FLEET SIZE, LEVEL-OF-SERVICE AND EMPTY VEHICLE REPOSITIONING STRATEGIES IN LARGE-SCALE, SHARED-RIDE AUTONOMOUS TAXI MOBILITY-ON-DEMAND SCENARIOS

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ABSTRACT

The widespread adoption of autonomous vehicles could lead to a shift from individual vehicle ownership to a system of shared-ride autonomous taxis (aTaxis) operated in fleets. Explored are large-scale systems where all non-walking person-trip demand is served by aTaxis. Using New Jersey as a case study, this work looks at the implications that various empty vehicle repositioning strategies have on fleet size, empty vehicle miles, and level-of-service provided.

Results show that repositioning vehicles locally during the day can decrease the needed fleet size significantly while still providing a high level-of-service. The largest fleet, consisting of 3,232,096 aTaxis, is needed if repositioning is done once per day in the early morning to position the aTaxis to serve an exact repeat of yesterday’s typical day (of 30,125,587 individual person-trips). This incurs an empty vehicle repositioning cost that is 8.3% of the total loaded vehicle miles traveled. At the smallest theoretical fleet size of 821,646, all aTaxis available are occupied at some point during the day. Because repositioning cannot take place instantaneously, this fleet cannot provide an adequate level-of-service during peak times. For the smallest practical fleet size analyzed of 1,069,782 vehicles (10% between the largest fleet and the theoretical minimum), 96.8% of passengers are served within 5 minutes beyond the advertised level-of-service while incurring an empty repositioning cost of only 5.2% of total loaded vehicle miles. With one central fleet operator, a significantly smaller fleet of aTaxis can deliver on-demand mobility to all of New Jersey that is equivalent to, if not better than, the mobility delivered by 6,874,100 vehicles registered in New Jersey in 2014 (not all of which are operated on any given day).
INTRODUCTION

Autonomous vehicle technology has progressed significantly in recent years, with major investments from both car and technology companies. It is not too hard to envision that autonomous vehicles will soon be available to the public. The universal adoption of autonomous vehicles will bring massive changes to personal mobility in many ways. One of the key potential changes is a shift away from personal automobile ownership to a fleet service providing Mobility on Demand (MoD) in driverless autonomous taxis (aTaxis). With aTaxi fleets, the challenge arises of operating and managing vehicles — deciding the number of vehicles to purchase and moving the vehicles between trips to best utilize the fleet.

This work builds upon Kornhauser and et al. (2016) [1], which analyzes ridesharing opportunities for New Jersey and takes a preliminary look at various repositioning strategies for managing an aTaxi fleet. Fagnant and Kockelman (2016) [2] simulate a system of aTaxis or Shared Autonomous Vehicles (SAVs) in Austin, Texas with dynamic ridesharing but at a low level of market penetration to determine the optimal fleet size. The trips taken in their simulation represent 1.3% of trips taken in the region. Pavone et al. (2012) [3] perform empty vehicle repositioning, or load rebalancing, on a simulated environment with randomly generated passengers.

This paper focuses on strategies for managing large-scale fleets of aTaxis in New Jersey and their effects on fleet size and level of service provided in scenarios where all travel demand is served by aTaxis. Given a constant demand, which is representative of actual travel demand in New Jersey, an upper and lower bound for the fleet size needed to operate the system is determined. Then, using two empty vehicle repositioning strategies for moving unused vehicles, the costs of reducing the fleet size from the upper bound is analyzed in terms of empty vehicle miles traveled and level of service provided. Unlike other case studies where empty vehicle repositioning strategies have been anticipatory (Fagnant and Kockelman (2015) [4]), that is, moving vehicles based on expected demand, this paper uses reactionary local repositioning strategies, moving vehicles after demand is known.

NEW JERSEY TRAVEL DEMAND

The data set used in this analysis is a set of generated trips representing the travel demand of New Jersey’s residents on a typical weekday. These trips were generated based on the population characteristics of New Jersey by Kornhauser and et al. (2012) [5]. Taking census data, a set of individuals with characteristics reflecting those of New Jersey’s residents was synthesized. Each individual was assigned to a home and work or school location. On a typical weekday, an individual’s trips are assumed to start and end at home. Trips are assigned departure times based on probabilistic distributions of work and school schedules. Each trip is assumed to have 1 person and the complete set of trips generated contains about 30.5 million individual trips, with the average individual making 3.41 trips per day [5].

These trips were then assigned to the following modes of transport: walk, multi-modal train, car/vehicle, airplane. An “elevator-like” casual ridesharing analysis, meaning travelers were not incentivized for ridesharing, was conducted on the vehicle trips by Kornhauser and et al. (2014) [6] with the following restrictions:

- Maximum destinations of 3
- Maximum departure delay of 5 minutes from the time the first passenger arrives
- Maximum circuity, or additional distance traveled by any passenger, of 20%

This reduced the 30,125,587 individual vehicle-based person trips to 10,479,382 vehicle rideshar-
ing trips. The analyses in this paper are conducted on these ridesharing trips with the assumption that the second day’s travel demand is the same as the first day’s. Although this is an unrealistic assumption, because no two days are exactly the same, this allowed for the analysis to focus not only on the empty repositioning needing during the day, but also the requirements to position vehicles for the next day under the most simplistic circumstances.

6 System Operation

The aTaxi system operates from aTaxi stands much like elevators operate from elevator banks. These stands are located throughout New Jersey so that no trip origin or destination was more than a 5 or so minute walk. To achieve this level of service and to somewhat enhance ridesharing, aTaxi stands were located in the center of 0.5 x 0.5 mile pixels. The precise latitude and longitude coordinates of each trip origin and destination were converted to pixel numbers using the following formula:

\[
X_{\text{coord}} = \text{floor}(108.907^\circ (\text{longitude} + 75.6))
\]
\[
Y_{\text{coord}} = \text{floor}(138.2^\circ (\text{latitude} - 38.9))
\]

The pixelation of New Jersey can be seen in Figure 1a and the pixelation of Princeton, NJ can be seen in Figure 1b.

All aTaxi trips originate from and end at the aTaxi stand. Passengers will walk or bike to the stand from where ever they are in the particular pixel. Each aTaxi stand has the capacity to hold and dispatch as many vehicles as necessary. For the purposes of this analysis, it is assumed that there is one aTaxi operator for the entire state. This means that regardless of where a vehicle originated from, it can be used to fulfill a trip at its destination.

This system operates with 4 different vehicle sizes: 3 passenger, 6 passenger, 15 passenger, and 50 passenger. For simplicity, the number of shared riders on the vehicle trip strictly dictates which vehicle they are assigned to, i.e. a shared trip with 5 people is always assigned to a 6 passenger vehicle, even if there are 3, 15, or 50 passenger vehicles available. For trips with more than 50 passengers, multiple 50 passenger vehicles are always used to fulfill the trip.

20 BASELINE REPOSITIONING METHODS
21 First, an upper and lower bound for the fleet size required to operate the system and serve all demand within the advertised level of service is established.

23 Lower Bound Fleet Size
24 To establish the lower bound, assume that vehicles can be moved infinitely fast when they drop off their final passengers. As soon as this happens, it is instantly moved to an aTaxi stand that needs a vehicle for a departure and is used there. Under this assumption, the fleet size needed is the maximum number of vehicles on the road at any given point during the day. Discretizing time by minutes, the minimum fleet size is the maximum vehicles on the road at any given minute during the day. Figure 2 shows the number of vehicles on the road during any minute throughout the day, the maximum of which is the lower bound fleet size. Note that for 15 and 50 passenger vehicles, the peak is much larger than the next largest number of vehicles on the road. This means that a nontrivial number of vehicles that must be purchased to satisfy this peak demand would be unused for the rest of the day.
This lower bound establishes the smallest fleet size necessary to serve all of the demand and provides a benchmark for comparison of the various empty vehicle repositioning strategies that will be used. However, in this case, because the assumption is made that for each departure, a vehicle instantly arrives from some other location with an available vehicle, the repositioning cost, or empty miles traveled, is unknown.

**Upper Bound Fleet Size**

A “naive” repositioning strategy is used to establish the upper bound of vehicles needed. In the naive repositioning strategy, empty vehicles are moved only once per day, for example, at midnight. In this scenario, at the beginning of the day, there are enough vehicles at each aTaxi stand such that all trips are able to be served without needing to summon an aTaxi from another stand. At midnight, empty vehicles are moved so that the next day’s demand can be served without adding more vehicles or further repositioning during the day as the next day’s demand is exact the same as the current day’s. The repositioning of empty vehicles across the entire system at midnight is
(a) 3 passenger vehicles  
(b) 6 passenger vehicles  
(c) 15 passenger vehicles  
(d) 50 passenger vehicles

**FIGURE 2**: Number of vehicles on the road as a function of time. The minimum number of vehicles needed to operate the system is the maximum of each vehicle type.
referred to as Early Morning Repositioning (EMR). While repositioning, the assumption is made that the vehicles are able to move infinitely fast to their destination aTaxi stands. The vehicles are repositioned such that vehicle miles traveled are minimized.

This strategy is implemented as follows. During the day, trips departing from an aTaxi stand are satisfied by either vehicle at the pixel or one that was brought to the stand from a super source. Each arrival at a stand increases the supply at the stand and each departure decreases the supply. If there is a departure for which there is no available supply, a vehicle is brought from the super source. On day one, assume that vehicles can be brought to the pixel infinitely fast. For each subsequent day, the number of vehicles needed at each stand at the beginning of the day is known, since demand is the same, and the fleet can be positioned accordingly. The minimum fleet size needed to operate the system is the number of vehicles that needed to be brought from the super source during the day.

**Early Morning Repositioning Cost**

In repositioning the system, the goal is to minimize the total number of empty vehicle miles traveled. This problem can be solved using the classic transportation linear program. The linear program is modeled as follows:

\[
\begin{align*}
\min & \sum_{i \in \mathcal{I}} \sum_{j \in \mathcal{J}} D_{ij} T_{ij} \\
\text{subject to} & \quad T \geq 0 \\
& \quad T_{ii} = 0 \\
& \quad \sum_{i \in \mathcal{I}} T_{ij} = A_j, \quad \forall j \in \mathcal{J} \\
& \quad \sum_{j \in \mathcal{J}} T_{ij} = P_i, \quad \forall i \in \mathcal{I}
\end{align*}
\]

where:

- \(D_{ij}\) is the distance between aTaxi stand \(i\) and aTaxi stand \(j\), calculated as \(1.2 \times D_{\text{cartesian}}\).
- \(T_{ij}\) is trip matrix, or the number of vehicles moved from aTaxi stand \(i\) to aTaxi stand \(j\).
- \(\mathcal{I}\) and \(\mathcal{J}\) are the set of active aTaxi stand.
- \(P_i\) is the number of excess vehicles available at the aTaxi stand \(i\).
- \(A_j\) is the number of vehicles needed at pixel \(j\).

Even though New Jersey has been discretized into pixels, solving the linear program over all active aTaxi stands still results in an extremely large optimization problem. For the smallest case, 50 passenger vehicles, there are about \(n = 8,000\) active stands, which means there are roughly 6.5 million variables to optimize over, as \(T\) is an \(n \times n\) matrix. To condense the problem, larger pixel blocks, termed “super pixels,” are created, which are \(3 \times 3\) blocks of the standard \(0.5 \times 0.5\) mile pixels. Starting at pixel \((0,0)\), pixels are grouped into blocks of 9 pixels. The super pixel containing pixel \((0,0)\) has its center at pixel \((1,1)\). The super pixel center for any given pixel, \((x,y)\) is calculated as: \((3 \times \text{floor}(x/3) + 1, 3 \times \text{floor}(y/3) + 1)\)

The supply or demand at each super pixel is simply the sum of the supply or demand of the smaller pixels within the super pixel. Distances between super pixels are calculated from the center of each super pixel. This is able to greatly reduce the dimensionality of the linear program...
in the largest case from $n \approx 20,000$ to $n \approx 3,000$, which was able to be solved in reasonable time using an LP solver.

Though the distances that vehicles have to travel to and from the center of the super pixel are not considered, there are both cases where vehicles travel both more than in a pixel to pixel repositioning and less than in a pixel to pixel repositioning. These cases tend to average out, making super pixel to super pixel repositioning a good approximation for pixel to pixel repositioning.

### Results

**TABLE 1**: Summary of baseline metrics

<table>
<thead>
<tr>
<th></th>
<th>3 Passenger</th>
<th>6 Passenger</th>
<th>15 Passenger</th>
<th>50 Passenger</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle Trips Served</strong></td>
<td>8,659,171</td>
<td>1,526,478</td>
<td>257,149</td>
<td>36,584</td>
<td>10,479,382</td>
</tr>
<tr>
<td><strong>Lower Bound Fleet Size</strong></td>
<td>632,947</td>
<td>133,275</td>
<td>43,957</td>
<td>11,467</td>
<td>821,646</td>
</tr>
<tr>
<td><strong>Upper Bound Fleet Size</strong></td>
<td>2,425,673</td>
<td>621,132</td>
<td>154,996</td>
<td>30,295</td>
<td>3,232,096</td>
</tr>
<tr>
<td><strong>Upper Bound EMR Empty Miles</strong></td>
<td>16,039,770</td>
<td>5,515,587</td>
<td>854,912</td>
<td>204,821</td>
<td>22,615,090</td>
</tr>
</tbody>
</table>

A summary of the upper and lower bound fleet sizes for each vehicle size as well as the EMR cost, is shown in Table 1. A minimum of 821,646 total vehicles and a maximum of 3,232,096 total vehicles are needed to operate the system. The EMR cost, compared to the loaded vehicle miles traveled (VMT), is 8.3%. Although this cost is low, there is a significant difference between the upper and lower bound of vehicles. With a low empty VMT, the number of vehicles needed is going to be the significant, controllable cost-driver of operating the system. To decrease the number of vehicles needed, additional repositioning strategies are implemented.

### LOCAL REPOSITIONING

In the naive strategy, where cars are only moved empty at one point during the day, there are vehicles at aTaxi stands which are not being used for long periods during the day. To try and use vehicles more productively, local repositioning strategies is implemented, where vehicles are repositioned short distances during the day in order to increase aTaxi utilization, thus reducing fleet size. Recall that there is a departure delay of 5 minutes after the first person commands a separate aTaxi in order to wait for potential ridesharing passengers. This means that for any particular departure, if there are no vehicles available at the aTaxi stand to serve the trip, one can be attempted to be sourced from a nearby stand. If the stand is less than five minutes away, no degradation of service will result.

Two local repositioning strategies are analyzed. In the first strategy, a simple strategy, when a passenger arrives, only stands with available vehicles that can reach the departure stand before the departure time is considered. Figure 3 shows the aTaxi stands that are within 5 minutes of driving time from the departure stand, using the assumption that vehicles travel at an average speed of 30
FIGURE 3: aTaxi stands that can be reached from the departure stand within 5 minutes assuming 30 mph travel

miles per hour. The departure stand is in the center and the number in each box represents the amount of time needed to drive from that stand to the departure stand. This strategy is implemented as follows. First, a supply array is initialized with an initial distribution of vehicles. Then, each trip, ordered by departure time, is analyzed. If there is an available vehicle at the departure pixel, it is used and the supply is decreased at the departure pixel and increased at the arrival pixel of that trip. If there is not an available vehicle at the departure pixel, then vehicle supplies at nearby pixels are checked, in order of time that it takes to reach the departure pixel. If an available vehicle is found at any of these pixels, then the supply is decreased at the pixel where the vehicle was found and increased at the destination pixel. If a vehicle was not found after looking at the pixels that are within 5 minutes’ travel time of the departure pixel, then that trip is not able to be served. However, leaving trips unserved is an unrealistic strategy. An adjustment is made in the second strategy, an extended search strategy, to serve all trips. For each trip departure, the simple search algorithm is carried out. However, if there is no available vehicle that can arrive in time, then the search extends to aTaxi stands farther and farther away until an available vehicle is found. This means that the first, and possibly other passengers, will have to wait longer than 5 minutes before they depart. The arrival time of the aTaxi at the destination stand is adjusted accordingly.

APPLICATION AND RESULTS

TABLE 2: Fleet sizes analyzed. Percentages are percent between the upper and lower bound

<table>
<thead>
<tr>
<th></th>
<th>Lower</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td># of vehicles</td>
<td>821,646</td>
<td>1,069,782</td>
<td>1,292,278</td>
<td>1,602,261</td>
<td>1,738,484</td>
<td>1,960,819</td>
<td>3,232,096</td>
</tr>
</tbody>
</table>

Various fleet sizes between the lower and upper bounds are analyzed on the data set to determine the effects of each strategy on repositioning costs and level-of-service provided. Five
different fleet sizes are considered: 10%, 20%, 30%, 40%, and 50% in between the lower and upper bounds. The number of vehicles in each fleet size is shown in Table 2. An initial distribution is chosen to be proportional to the distribution of the naive strategy, rounding up to ensure integer values. This initial distribution is not the most optimal, but it is a good approximation, as choosing a random distribution would result in much higher costs [7].

**Empty Vehicle Repositioning Costs**

Both local strategies also require that the fleet be repositioned at the end of the day, similar to the naive strategy. The cost of the local repositioning strategy then, in terms of empty miles, is the empty miles traveled in the local repositioning during the day and the empty miles traveled in the EMR at midnight. This cost for each strategy and fleet size is shown in Figure 4, broken down the contributions from local repositioning and EMR.

Though empty VMT was expected to be higher with the addition of local repositioning, this was not the case. Overall, the empty vehicle repositioning cost is very low and even with local repositioning; in all cases, the total number of empty repositioning miles is less than that of the naive strategy, which was 8.3% of loaded VMT. As the fleet size increases, the EMR empty miles increase as well, since there are more vehicles that need to be repositioned. For local repositioning, as the number of vehicles decreases, the amount of local empty miles increases. This is because fewer vehicles are available, so operators need to look farther from their stand to find an available vehicle.

Local repositioning costs in all cases are a very small percentage of the total repositioning costs, ranging from .68% for a fleet size of 50% between the upper and lower bounds to 1.0% for a fleet size of 10% between the upper and lower bounds. Figure 5 shows histograms of empty miles traveled in local repositioning for the 10% fleet size case. For all vehicles, there is a long
right tail. Most vehicles are traveling short distances, with the large majority of vehicles traveling no more than 10 miles, but there are a few that have to travel very long distances. This indicates that during the day, vehicles tend to travel near areas with more departures, which means that this system should be able to provide a good level of service, as empty vehicles are easily accessible.

However, the difference between the vehicle distribution at the end of the day and the required distribution at the beginning of the day is significantly different. In Figure 6, histograms of empty miles traveled for EMR in the 10% fleet size case is shown. Though there are still right tails, it is not as long as the local repositioning tails, and distances traveled tend to be longer, which is to be expected given the larger overall EMR cost.

**Level-of-Service Provided**

In the naive strategy, all passengers are served within the advertised level of service, but at a cost of very large fleets. With smaller fleets, a high level of service is still able to be maintained. As seen in Table 3, a large majority, over 80%, of vehicle trips are able to be served within the advertised
level of service (5 minute departure delay), even when reducing the fleet size to 10% between the lower and upper bound fleet sizes. The percentage of trips served increases as the fleet size increases, since more vehicles are available. However, this means that there are vehicles that are idle during the day that could be used more efficiently.

Of the strategies analyzed, the extended search is the most realistic operating strategy. If there were no vehicles available within 5 minutes, a fleet operator would not leave the trip unserved, but continue to look for an available vehicle as to not lose customers. An evaluation of the additional wait times for passengers in the extended search strategy, shown in Table 4, shows a very high level of service for even the smallest fleet size analyzed. The percentage of passengers able to be served within the advertised level of service is considerably higher than the percentage of trips able to be served within the advertised level of service in most cases. This indicates that a large part of the trips that are not able to be served within the advertised level of service are trips in smaller vehicles with fewer passengers.

These results have significant implications for the fleet size needed to operate the system.
TABLE 3: Percentage of vehicle trips served within advertised level of service in each repositioning strategy

<table>
<thead>
<tr>
<th>Fleet Size</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>Naive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Strategy</td>
<td>82.7</td>
<td>87.7</td>
<td>91.3</td>
<td>94.1</td>
<td>96.1</td>
<td>100</td>
</tr>
<tr>
<td>Extended Search</td>
<td>86.7</td>
<td>89.6</td>
<td>92.0</td>
<td>94.1</td>
<td>95.9</td>
<td>100</td>
</tr>
</tbody>
</table>

TABLE 4: Percentage of passengers served as wait time increases beyond advertised level of service for various fleet sizes

<table>
<thead>
<tr>
<th>Fleet Size</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within advertised</td>
<td>95.4</td>
<td>96.4</td>
<td>97.2</td>
<td>97.9</td>
<td>98.6</td>
</tr>
<tr>
<td>Within advertised + 1 minute</td>
<td>95.7</td>
<td>96.3</td>
<td>97.5</td>
<td>98.2</td>
<td>98.8</td>
</tr>
<tr>
<td>Within advertised + 5 minutes</td>
<td>96.8</td>
<td>97.8</td>
<td>98.5</td>
<td>99.0</td>
<td>99.5</td>
</tr>
<tr>
<td>Within advertised + 10 minutes</td>
<td>97.8</td>
<td>98.7</td>
<td>99.2</td>
<td>99.6</td>
<td>99.8</td>
</tr>
</tbody>
</table>

More than 98% of passengers are able to be served within the advertised level of service with a fleet of 50% between the minimum and maximum fleet sizes. Even with a fleet size of 10% between the minimum and maximum fleet sizes, 95.4% of passengers can be served within the advertised level of service and nearly 98% of passengers are served within an additional 10 minute wait. Given the extremely high level of service provided with the smaller fleets, it is both unnecessary and impractical to implement the naive strategy.

One drawback of the extended search strategy, as implemented, is that although most additional wait times are short, the distribution of wait times has a heavy right tail, with wait times of over an hour in a few extreme cases.

LIMITATIONS AND FUTURE WORK

This paper serves as a starting point for many future analyses of large-scale aTaxi fleet operations. A few are highlighted. Many simplifying assumptions were made in these analyses which can be adjusted for future work. For example, the analyses in this paper only consider a single state-wide aTaxi operator for all of New Jersey. In an operational scenario more comparable to the traditional taxi systems of today, taxis would be owned and operated regionally, with restrictions on pickups outside of a taxi’s home region. This type of operation would have a nontrivial effect on empty repositioning costs, fleet size, and efficiency that need to be further explored.

As mentioned previously, the number of passengers on each trip determines the vehicle size used. However, there may be scenarios where it is more efficient to use multiple vehicles of smaller sizes or larger vehicles to serve the trip. This could also change depending on the ridesharing strategies used. In this data set, the ridesharing was implemented with inefficiencies, leading to large vehicles traveling large distances with only a few passengers [7].

Finally, these analyses can be used to determine an optimal fleet size to operate a statewide...
system, given costs of purchasing and operating vehicles, as well as penalties for passengers not
served within the advertised level of service.

3 CONCLUSION
4 This paper analyzed the effects of empty vehicle repositioning strategies on fleet size and level-
of-service provided in a large-scale, mobility-on-demand aTaxi system in New Jersey without the
need to anticipate future demand, which is no simple task to do well. The scenarios analyzed
suggest that, with local repositioning, all of the travel demand of New Jersey can be served with a
fleet of shared-ride aTaxis that is much smaller than the current fleet of vehicles operating in New
Jersey. In 2014, there were 6,874,100 registered motor vehicles in New Jersey, including public
buses [8]. The demand can be well served with an aTaxi fleet 10% between the lower and upper
bound, or 1,069,782 vehicles. With this fleet size, one aTaxi would replace more about 6 traditional
vehicles. This would have tremendous benefits in terms of decreasing environmental pollution and
vehicular congestion, as well as decreasing the need for parking structures.

While full adoption of autonomous vehicles as the primary mode of transport is still far off,
the benefits of large-scale aTaxi systems can be quantified and may eventually play a major role in
reducing the congestion and environmental issues that are faced in many metropolitan areas today.
REFERENCES


