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Modeling Changes in Public Transit and Private-for-Hire Usage When Implementing a Spatial Tax

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Abstract

Private-for-Hire (PfH) transportation options, such as Uber, Lyft, and taxicabs, are consistently growing in popularity. With this expanded utilization, cities are struggling to maintain usage of their public transit systems. While PfH transportation has been heavily researched, there is a need to further study how its effects on transit usage may be minimized. In this paper, previous work in traffic modeling and analysis of transit and PfH differences are expanded to develop an agent-based decision model in order to simulate and analyze the effectiveness of implementing a location-based tax in and around the city center of Portland, Oregon. The results of this simulation show that implementing a low-cost location-based tax increases transit usage in the Portland area. These results inform city policies on the outcome of establishing one possible measure to encourage transit usage in Portland, increasing the ability of city officials to make informed decisions in regard to public transportation policies.

1. Introduction

With the growing pervasiveness of smartphones and other technology in our daily lives, our options and preferences for transportation have evolved in favor of quick, easy, and personalized choices. *Private-for-hire* (PfH) services such as Uber and Lyft have thus been gaining popularity over the past decade. Cities including Portland have seen a decrease in transit usage in just the past two years, [1] [2] causing concern about the future utilization of transit services. Further, an increase in PfH trips causes an increase in the amount of low-occupancy vehicles on the road. This can lead to increased traffic congestion, which can harm transit efficiency, which can further increase congestion; ultimately, the utilization of PfH transportation can significantly increase traffic.

This paper supplements the results of Clifton et al. [3] to analyze the effects of implementing a location-based tax in and around Portland's city center and the extent to which these effects are dependent on tax value. This is done through the development of an agent-based decision-making model to simulate one weeks worth of transportation decisions in Portland. The model simulates these travel decisions and calculates the percentage of trips conducted by transit and PfH transportation methods. These percentages are then analyzed in the context of various spatial tax values to determine if this would be an effective method in encouraging transit usage and what results would occur from different scenarios. We predict that implementing a spatial tax will increase the amount of trips taken by transit and that the model will be sensitive to this tax value; as the tax increases, transit usage will also increase at a linear rate.

2. Background and Literature Review

PfH trips are those that are taken with private vehicles-for-hire or *Transportation Network Companies* (TNCs). Vehicles-for-hire have been common modes of transportation for decades and include services such as taxicabs, limousines, rickshaws, and carriages. TNCs, however, are a more recent innovation, although they have similarly become very popular in the recent years. TNCs are app-based ride-sharing and ride-sourcing services that match local drivers with app users, [4] the most popular of which being Uber and Lyft. These companies have arisen in many areas around the world, especially in large U.S. cities such as Portland.

With this increasing use of PfH transportation methods has also come an increase in researchers studying its effects on various areas. Clewlow and Mishra, [5] for example, conducted an analysis of ride-hailing adoption and its effects on public transit, finding a six percent reduction in bus usage and a three percent reduction in light rail usage after the introduction of ride-hailing services. Other researchers, such as Hall et al., [6] however, have found that ride-sharing serves as a complement to public transit and may actually increase transit ridership. This indicates that the replacement of transit with PfH transportation may be context-dependent, which is confirmed by Gehrke et al. [7] in a study showing that the likelihood of replacing transit usage with ride-hailing is associated with individual income.

One topic that is agreed upon, however, is the effects of PfH transportation on traffic. Researchers, such as Hermawan and Regan [8] and Erhardt et al., [9] have found that PfH transportation significantly increases traffic congestion due to an increase in low-occupancy vehicles. This increase in traffic congestion can cause a decrease in transit efficiency, which can further worsen congestion, creating a cycle of delays. Whether or not PfH transportation is replacing transit, it is commonly thought to increase crowding on roads, especially in an urban context.

Agent-based and activity-based modeling have been extensively used in the context of understanding and solving transportation issues. For example, Djavadian and Chow [10] demonstrated how modeling may be used to represent two-sided transportation markets, verifying this with a simulation of the first-last mile problem. Zellner et al. [11] similarly showed how agent-based modeling can be used to improve the first-last mile problem. Models have also been used to analyze the results of hypothetical changes to public transit systems, as in the case of Lemoine et al. [12] Modeling is especially useful for transportation problems as it can be used to represent complex networks, such as a city, and invoke hypothetical changes without disrupting the existing network.

Clifton et al. [3] analyzed a complete universe of PfH trips to uncover the differences in trip duration between PfH and transit. Using observed PfH tours, transit trips for the same origin and destination pairs were generated. The differences in trip duration were then analyzed and mapped to determine how they varied in time and space. The results show that PfH trips become more beneficial as they occur farther from the city center. Based on these findings, the authors suggest that the city invoke a tax on any PfH trips occurring within two miles of Portland's central city in order to encourage passengers to take transit in places where it is competitive with PfH transportation.

This paper details the process and results of testing this recommendation by implementing an agent-based model to represent the Portland area and simulating the effects of invoking this spatial tax on PfH trips. This directly builds off of the findings in Clifton et al. and evaluates the sensitivity of transportation decisions to one such incentive.

3. Materials and Methodology

Python and the agent-based modeling package Mesa [13] were used to create a model representing the city of Portland. This model simulates one week of transit in the Portland area and returns the percentage of trips taken by transit and the percentage of trips taken by PfH. This model was run for eleven different spatial tax values to analyze how transit usage was affected by this spatial tax and to what extent. The results were then analyzed to determine how transit usage is dependent on tax value and to create scenarios for various tax implementations in the city.

3.1. Model Design

The model used in this experiment is an agent-based decision model consisting of a grid of cells, each constituting one-quarter mile, and 583,776 agents to represent the area and population of Portland. One run of the model simulates seven days of travel, in which each agent takes four trips. This trip count is based on the average number of trips taken by each household in the U.S. and the average household size, reported by the U.S. Department of Transportation. [14] Two of these trips occur during rush periods, in which wait times for both transit and PfH transportation have higher possible values. The model was tuned to replicate as closely as possible the reported values of annual transit trips [1] and annual PfH trips [15] in Portland, which show that approximately 88.89 percent of trips are taken by transit and approximately 11.11 percent of trips are taken by PfH methods. The model is designed to analyze this changing percentage of transit usage depending on the value of a tax placed on any trips within two miles of Portland's central city (Figure 1).

For each trip, every agent chooses to take either transit or PfH based on a number of factors and personal characteristics. Before choosing a transportation method, an agent is assigned equal probabilities of taking each mode, a random amount of money to spend on transportation, a random amount of time to spend traveling, and a random importance of convenience, where convenience is defined by the wait time and number of vehicle transfers required in a trip. The agents are also assigned a random destination, which may be anywhere on the grid besides their current location. An aggregate value is first calculated for each transit method. This is done by calculating the euclidean distance between the agent's origin and destination, the

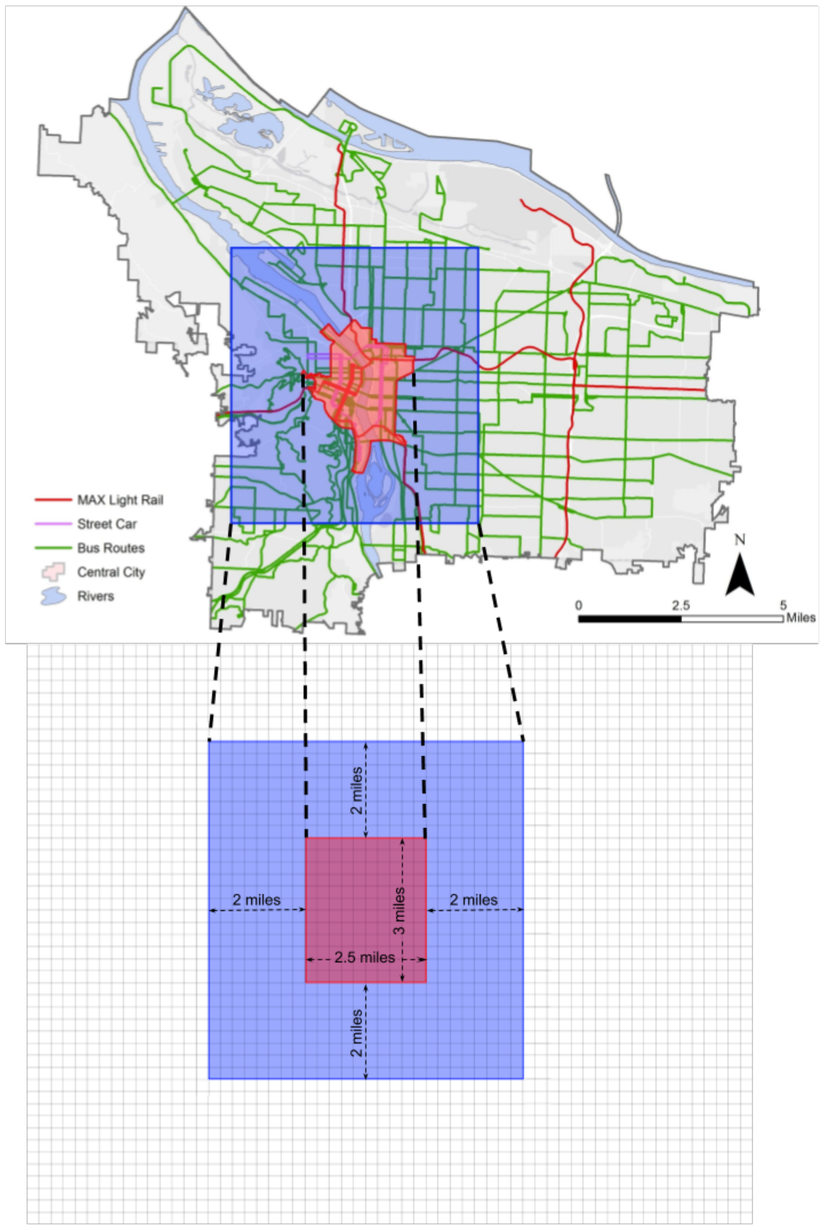

Figure 1: The simulated grid has a city center (red) and two-mile taxable zone (blue) corresponding to Portland's geography. Image Source: Clifton et al.

initial access time, the trip duration, the monetary cost, and the trip's inconvenience. The initial access time is a random integer chosen between a range of possible values. These ranges vary depending on whether or not the trip is taking place during a rush period. The aggregate value is then returned as the sum of the time and the cost for making the trip with the chosen transportation mode, which are both weighted based on the original replicated transit and PfH percentages.

The agent then decreases the probability of each mode based on the aggregate value, the percentage of their remaining time and money being used, and their conceived importance of convenience. Whichever transportation method has the highest resulting probability is chosen by the agent. The available time and money resources are reset to a random value at the start of every "day", or after four trips.

3.2. Model Validation

Several aspects of this model are aligned with real observed values in order to ensure an accurate depiction. As discussed above, the initial percentages of trips taken by transit and PfH are based on values reported by TriMet and PBOT, two transportation organizations in Portland. To achieve these values, independent weights were added to represent the importance of trip duration and trip cost. The weights that result in a ratio closest to reality show that agents consider cost much more important than time. The number of trips per simulated day is based on the average number of persons per household and the average number of trips per day for each household, resulting in the average daily number of trips per person. [14] The number of active agents is based on the Portland city population as reported in the 2010 US Census. [16] The cost for transit is based on Portland's flat hour-based fee; likewise, the cost for PfH is based on the cost formulas for Uber and Lyft pricing, with variable fees localized to Portland. Lastly, the overall duration of a PfH trip is based on the average Portland driving speed of 23 miles per hour. [17]

3.3. Tests

The completed model was run to simulate seven days of travel in Portland, in which 583,776 agents took four trips per day - two occurring during rush periods and two occurring during calmer periods. Each run of the model included a varying tax level, ranging from zero to five dollars and increasing in

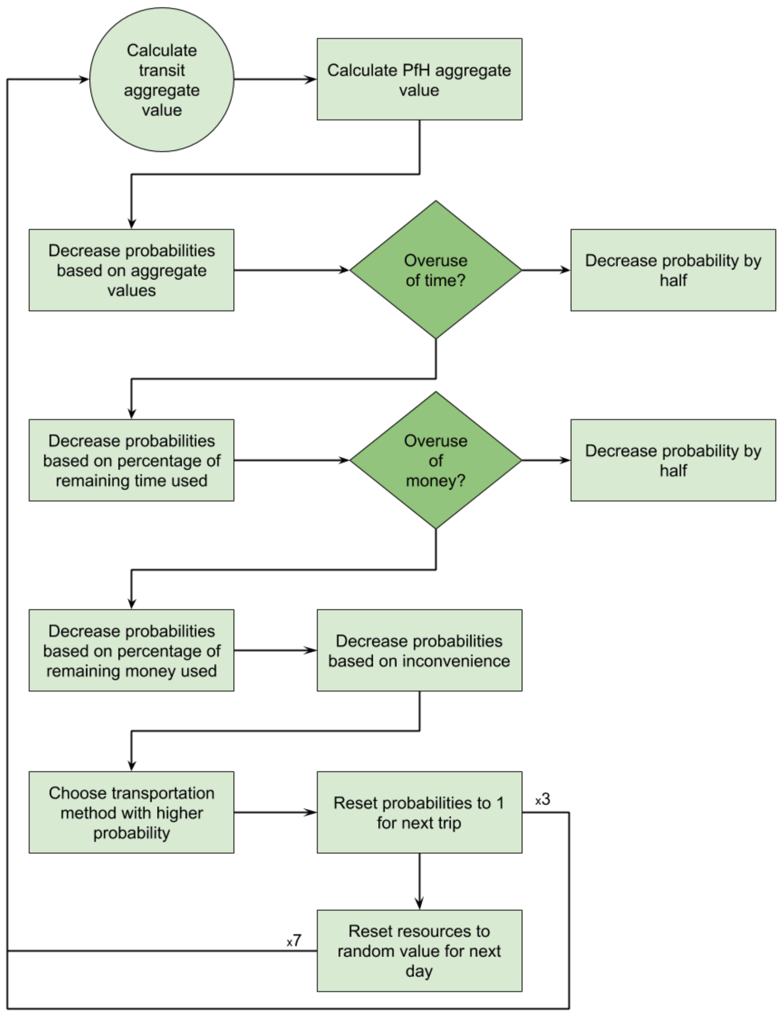

Figure 2: The agent decision-making process consists of a number of steps and decisions.

fifty cent increments. At the end of each trip, the model reported the percentage of trips taken by transit and the percentage of trips taken by PfH. These percentages were then averaged to analyze the overarching transportation decisions at varying tax levels. For each tax value, the average transit usage for each trip was collected and analyzed to show how agents' transportation decisions change throughout the day. The overall mean transit usage for each tax level was also collected, in order to analyze the overarching effects of the tax and its value on transportation decisions.

4. Results and Discussion

The results of this experiment show that implementing a spatial tax on PfH trips in Portland does have an effect on transportation decisions; agents are more likely to take transit when the tax is present. Moreover, there is a positive correlation ebtween the percentage of trips taken by transit and the tax value, indicating that the results are sensitive to the cost of the tax. Approximately 88.08 percent of trips are taken by transit when no tax is in effect, while this increases to approximately 91.15 percent when there is a \$5.00 tax. (Figure 3) However, the rate of change in transit usage is nonlinear; as tax value increases, the change in transit usage from the previous tax value becomes less severe. (Figure 4) For example, increasing from no tax to a \$0.50 tax causes a 0.39 percent increase in transit usage, while increasing from a \$4.50 tax to a \$5.00 tax only causes a 0.24 percent increase in transit usage.

To verify this decreasing rate of change, a simulation was run with a tax value of \$10.00. If the rate of change is linear, transit usage should increase by an average of 0.31 percent with each \$0.50 increase in tax, based on the mean rate of change for all conducted simulations. Therefore, a \$10.00 tax should increase transit usage by 6.2 percent, resulting in 94.28 percent of trips being taken by transit. However, the resulting transit usage with a tax of \$10.00 is 93.24 percent. This confirms that the rate of change in transit usage when increasing the spatial tax value is nonlinear.

These results validate the hypothesis that instituting a spatial tax on PfH trips will cause an increase in transit usage. However, the rate of this increase was unexpected. While it was hypothesized that transit usage would increase linearly as the tax value increases, this was not the case. As discussed above, the rate of change in transit usage decreased as the tax value increased. This

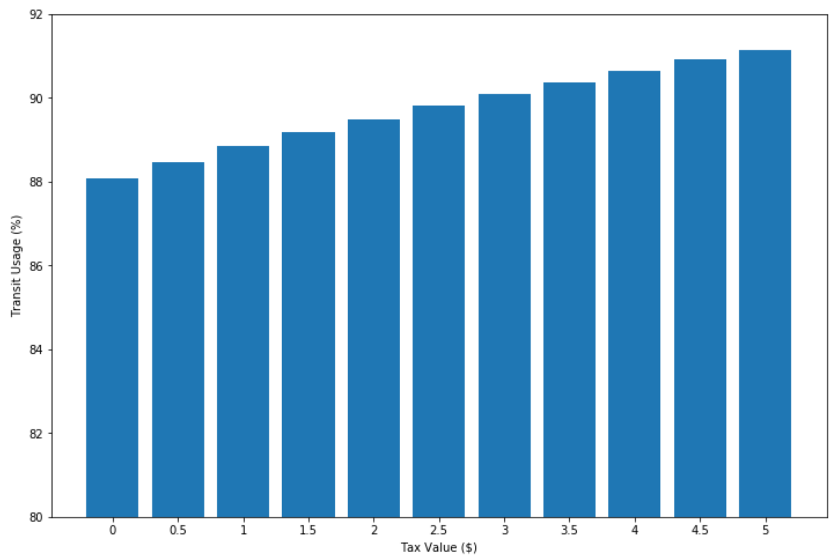

Figure 3: Transit usage increases as spatial tax increases.

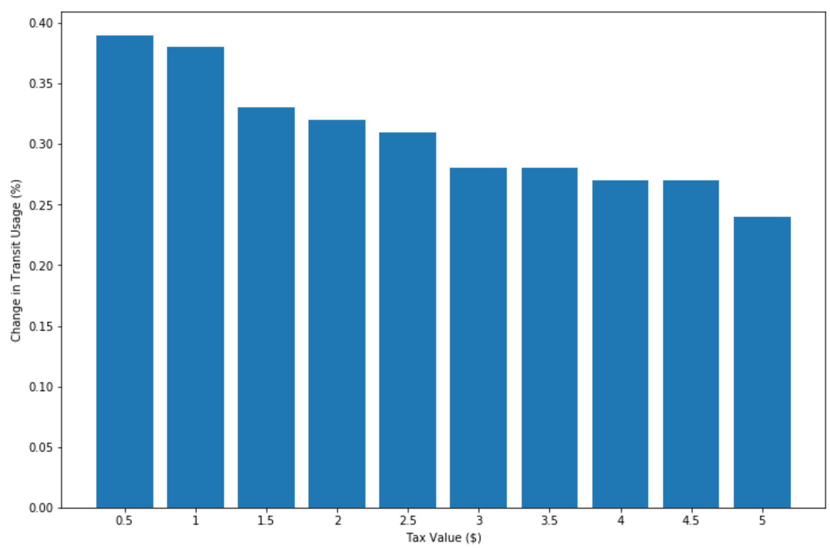

Figure 4: The rate of change in transit usage decreases as tax value increases.

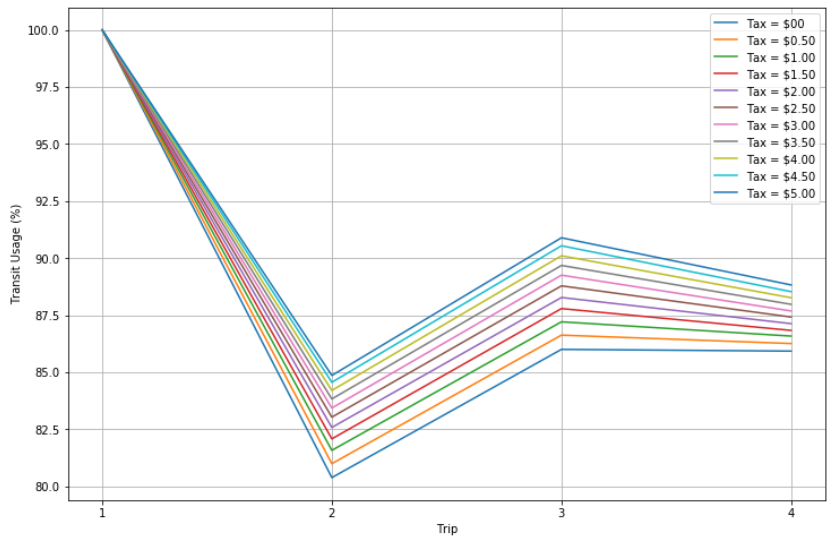

Figure 5: Transit usage oscillates throughout the day as agents' time and cost considerations change.

suggests that the mere presence of the tax may be most important to agents, rather than its actual value.

Although each tax value results in a different percentage of trips taken by transit, analyzing the average agent behavior throughout the day shows that agents follow the same decision pattern regardless of tax value. (Figure 5) One theory for this behavior is a fluctuating balance in time and money resources. All agents choose to take transit for their first trip, aligning with the weights discussed above that place higher emphasis on cost than time. On the second trip however, agents are left with more money than time; as a result, more choose to take PfH transportation, as it is generally quicker than transit. By the third trip, the agents' remaining time and money have roughly evened out. The remaining two trips follow a similar pattern as the former, in which agents have no particular lack of resources, and so choose transit as the cheaper option. On the next trip, however, some agents make up for the large amount of time spent on transit and choose instead to take PfH.

Ultimately, these simulations show that implementing a spatial tax increases transit usage. The change in transit usage from no tax to a $5.00 tax is approximately 3.07 percent. Moreover, approximately 27.63 percent of trips originally taken by PfH are converted to transit when the maximum tax value is implemented, and implementing just a fifty cent tax decreases the number of daily PfH trips by 3.5 percent of its original value. If Portland officials were to establish a public policy adding a tax of $1.50 to any PfH trip within a two-mile radius of the city center, TriMet's transit usage would increase by over one percent. Likewise, a tax of $3.00 would increase transit usage by two percent.

5. Conclusion

This paper details the development of an agent-based decision-making model to simulate transportation usage in Portland and the effects of installing a spatial tax on PfH trips. This is done in order to evaluate the effectiveness of such a policy on increasing local transit usage and combating the increase in low-occupancy vehicle trips caused by PfH transportation. The simulations of this model found that implementing a spatial tax would increase transit usage at a nonlinear rate. A $0.50 cent tax would increase transit usage by 0.39 percent, while a $5.00 tax would increase transit usage by 3.07 percent. These results shed light on how effective an implementation of this tax would be, which can be utilized in making an informed decision on the establishment of PfH-based public policies in Portland. This model also has the potential to be expanded and adapted to simulate other policies and analyze their effects on transportation decisions.

The largest limitation of this work is that the model is relatively simple. While several factors such as rush hour, random preference, and varying resources are taken into account, there are several more that could be added. These include differences between weekends and weekdays, transportation options besides transit and PfH, and a more complex daily schedule. Future work would benefit from implementing further complexity in this model in order to more accurately simulate observed nature.

As mentioned above, this model may be expanded in the future to simulate similar public policy scenarios. Future work may also verify the imbalanced resource theory as to why transit usage fluctuates throughout the day. A larger scale of simulations may also prove beneficial in better understanding how tax value affects transit usage, specifically by analyzing a larger range of tax levels over a longer period of time.

6. Acknowledgements

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