

Mesoscopic modeling framework for public transport traffic

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Abstract

We present a general framework for incorporating the passenger-centric viewpoint in a mesoscopic traffic flow model. We modify the Open Traffic Models (OTM) platform to take into account stops along links. In contrast to agent-based models that focus on interactions and mechanisms at a small scale, our mesoscopic queuing model framework scales well to urban-scale applications. Starting with a scenario that demonstrates the Braess paradox for a 100% car system, we show how prioritized public transportation on the link that causes the Braess paradox leads to a satisfactory solution.

Keywords: Computer modeling and simulation, Transportation

1 Introduction

Studying bus-car traffic dynamics using microscopic models [1] that simulate each vehicle as an agent with individual parameters leads to key behavioral insights. Yet microscopic modeling is resource-intensive and not easily scaled to larger transportation networks. For larger networks, macroscopic or mesoscopic modeling may be employed. But in modeling the system either as flows (macroscopic) or queues (mesoscopic), we gain scale at the expense of individual resolution. In this work, we discuss a simulation framework for a mesoscopic model of public transport traffic using the Open Traffic Models (OTM) platform [2], an open-source implementation of traffic models.

For newly-opened road spaces in Metro Manila, the spectre of induced demand [3] exists. Because a new road means more space and thus faster travel time, there would be a faster-travel incentive to own a private vehicle. With more vehicles, we get back to the original or possibly worse state of congestion. In addition to induced demand, we suspect that the recently-opened BGC-Ortigas link [4] might also demonstrate the Braess' paradox [5] — a seemingly counter-intuitive situation where adding a new road results in worse travel times for the same set of vehicles.

Here we create a synthetic network that demonstrates Braess' paradox for the case when all the vehicles are cars. We then incorporate public transport vehicles (with bus stops) and check how prioritization of public buses [3] would affect the Braess paradox situation. Finally, we discuss the effects on vehicle and commuter travel times as public transport ridership is increased.

2 Model

Network

We implement a road network with two paths from the start and end points (Fig. 1). One path passes through node *A*, while the second path passes through node *B*. There are three types of roads. Type 1 are low-speed links (start–*B* and *A*–end), while type 2 are high-speed links. These links have a single lane of length L . Road type 1 has $v_{\max} = 100$ km/h, while type 2 has $v_{\max} = 50$ km/h, and both links have

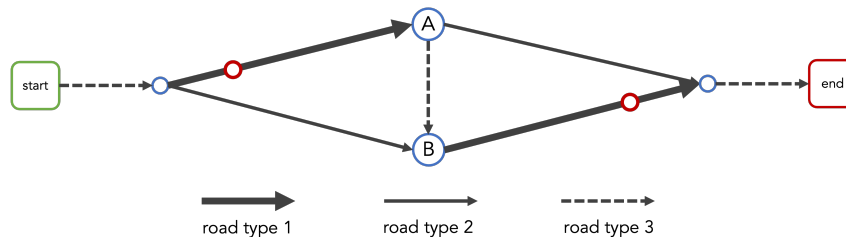


Figure 1: Diagram of the road network used. Three road types were used. Type 1 and 2 are the high and low-speed links, respectively. Type 3 was used for sources and sinks (these had length $L/10$ and $v_{\max} = 500$ km/h so that they contribute very little to travel times). The red nodes are locations of bus stops.

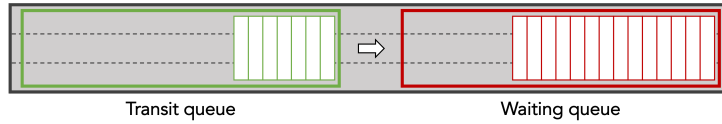


Figure 2: Transit and waiting queues for a single link in OTM. Queues are shared across multiple lanes.

capacity of $f_{\max} = 2000$ veh/hr. A third type of road was used that had length $L/10$, $f_{\max} = 10000$ veh/hr and $v_{\max} = 500$ km/h for the source/sink and $A-B$ links such that they contribute very little to travel times and do not cause bottlenecks.

Bus stops are placed on the high speed links at a relative position $0.3L$ from the start and end nodes. To illustrate the Braess' paradox, an additional road type 3 link from A to B is added to the network. This additional path provides another option for vehicles.

Mesoscopic model

Each link in the network uses a mesoscopic model in our simulations. Open Traffic Models implements a mesoscopic model similar to the one used in [6]. In a mesoscopic model, a link contains two queues: a transit and a waiting queue (Fig. 2). The transit queue delays each vehicle that enters the link by the free-flow travel time given by $t = l/v_{\max}$ for the link. The vehicle then leaves the transit queue and moves into the waiting queue, which is a first-in-first-out (FIFO) process served by a Poisson process with rate $r = f_{\max} n_{\text{lanes}}$, where f_{\max} is the maximum flow or capacity of the link.

Vehicles may exit the waiting queue of their current link if the succeeding link in their path does not have a full queue. This implementation allows for queue spillbacks to the upstream links, which is useful in modeling congestion in arterial road networks.

Bus Stop model

We developed a custom plugin for use with OTM to implement a bus-stop model to facilitate interactions between passengers and buses. We use the commodity model of OTM to distinguish between car and bus vehicle types, each with its demand flows. Buses can pick up passengers up to some capacity C . Passengers can spawn at bus stops and will travel from the left-most to the right-most bus stop. When a bus approaches a stop with a waiting passenger that wishes to board that bus, the bus will stop at the link for a duration τ to pick up passengers. However, because a mesoscopic model does not allow for vehicle-level control i.e. you cannot issue a stop command for a specified bus, we implement stops to disallow all queue transfers for the stopped link. Our current implementation does not yet support stopping flows by commodity.

Experiments

We conducted experiments varying four parameters: the base demand D , the fraction of commuters using buses f_{commute} , the fraction of cars s using link $A-B$, and the fractional supply of buses b . The car demand is given by $D_{\text{car}} = (1 - f_{\text{commute}})D$, while the bus demand is given by $D_{\text{bus}} = b(f_{\text{commute}}D/C)$. For cars, $d = sD_{\text{car}}$ is the demand that traversed path 3, while $d = \frac{1}{2}(1 - s)D_{\text{car}}$ traversed path 1 and 2. Buses traversed path 3 and pass through the two bus stops along its route.

We used $D = 1800$ trips/hr, $f_{\text{commute}} \in [0, 0.6]$, $s \in [0, 1]$, and $b = 1$ for our simulations. Bus and passenger arrivals are modeled using a Poisson process. Each set of parameters were run for 50 realizations. We measured the average travel times for the three different paths by summing the average travel times of each individual link along a path. We also measured the total trip times of passengers, from the time they spawn to the time they reach the second stop.

3 Results and Discussion

Braess' paradox presents the notion that adding a new link to a road network results in an increase in the travel time of vehicles on that network. The traffic network in Fig. 1 is used as the classic example to demonstrate Braess' paradox. Classic demonstrations of Braess' paradox have well defined cost functions for the different road types: e.g. $t = d/100$ for type 1, $t = 45$ for type 2, and $t = 0$ for type 3 roads. In such an example, Nash equilibrium occurs when the network demand is split evenly between paths 1 (start- A -end) and 2 (start- B -end); any user choosing to transfer to the other path will experience longer travel times. With the addition of a link $A-B$, the Nash equilibrium shifts to all vehicles using the new path 3 (start- $A-B$ -end). However, this new equilibrium will have longer travel times than if link $A-B$

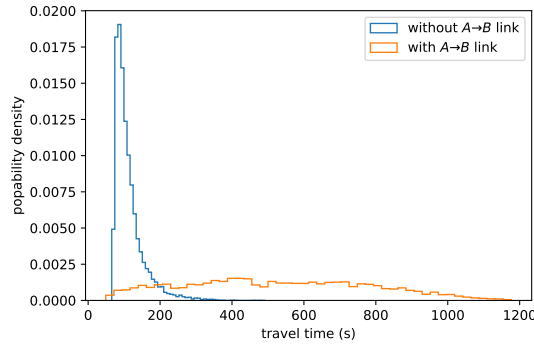


Figure 3: We demonstrate Braess’ paradox on the road network using a demand that is less than the capacity of individual links.

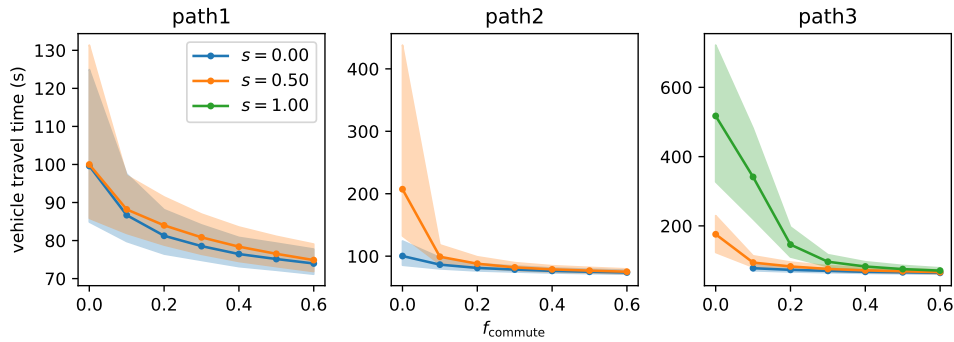


Figure 4: Vehicle travel times on the three paths. Bands are taken from the 1st and 3rd quartiles. When all cars are allowed to pass on path 3 ($s = 1$), longer travel times are observed. However, we also see that increasing the fraction of bus commuters can drastically reduce vehicle travel times in the network.

was absent — Braess’ paradox.

It is, however, difficult to model a network with the same travel times as the classic Braess network; travel times have a non-linear relationship with the road state (flow and density). Additional non-linearities can occur in the form of congestion and queue-spillback, which are situations unaccounted for by the classic Braess formulation. We tried to model this by designing road type 3 to have five times the capacity of the high-capacity links (effectively requiring a small but finite travel time to traverse). Travel times on path 3 are an optimistic estimate since we added link $A-B$ to the network such that it does not contribute much to travel times because of an unrealistic speed — travel times will be longer in reality.

We illustrate this in our simulations by setting $f_{\text{commute}} = 0$, and $s = 0$ for cars to use paths 1 and 2 only, while we use $s = 1$ for all cars to use path 3. Travel time distributions of the two scenarios show that when all cars use path 3, we replicate Braess’ paradox (Fig. 3). When demands are sufficiently low, the free-flow travel time for paths 1 and 2 is 57.6 seconds, while for path 3, it is 39.96 seconds. Despite path 3 having a shorter free-flow travel time, the shift in demand created by the “shortcut link” $A-B$ results in travel times slower than when the “shortcut” did not exist at all.

Vehicle travel times along the three paths change with the fraction of commuters using buses f_{commute} (Fig. 4). When no cars can use path 3 ($s = 0$), paths 1 and 2 have similar vehicle travel times. However, when half of the cars can traverse path 3 ($s = 0.5$), we observe path 2 having longer travel times than path 1. This is because path 2 shares the last link with path 3, which is already congested. Finally, when all cars and buses share path 3, we see the longest travel times. Note that longer travel times also coincide with larger uncertainties in travel times.

Shifting at least 20% of commuters to use buses reduces travel times (~ 30 to $\sim 70\%$). Our simulations use $C = 10$, which is like a UV express in the context of Metro Manila. Real buses would have $C \approx 60$, while jeepneys would have $C \approx 20$. With higher passenger capacity vehicles, large decreases in travel times can occur even at lower f_{commute} values. These simulations demonstrate how much more efficient our modes of mobility are if public transportation has a wider adoption.

Finally, we also accounted for the commuter’s point-of-view by measuring passenger trip travel times (Fig. 5). Passenger travel times can be broken down into two parts: waiting times at stations when

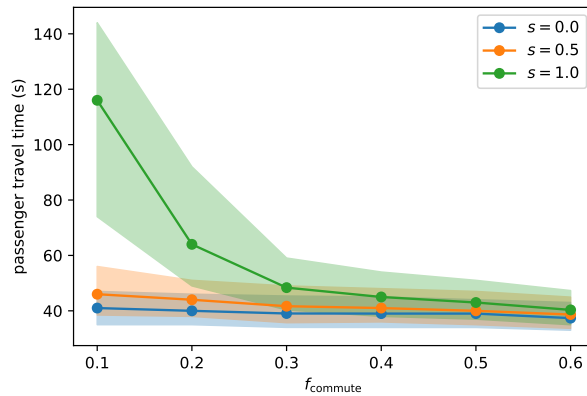


Figure 5: Passenger travel times are also correlated with vehicle travel times along path 3. We see that as more commuters shift to buses, travel times drastically decrease even when path 3 is shared with cars ($s = 1$). Bands are taken from the 1st and 3rd quartiles.

starting their trips or during transfers and the actual route traversal time. In this work, we only consider a trip that can be done in one bus ride and that the supply of buses perfectly matches the expected commuter demand. Because the route traversal times depend on the vehicle traversal times, we also see large decreases in passenger travel times when more commuters use public transportation.

4 Conclusions

Using a mesoscopic simulation framework for public transportation, our work demonstrates the advantages of shifting transport from individual cars to public ridership. The high passenger occupancies of public transportation reduce the number of vehicles on the road while still moving the same volume of commuters. Thus, increasing public transport ridership also has the effect of reducing vehicle and passenger travel times. However, encouraging commuters to use public transport remains an open challenge. Personal modes of transport remain attractive — sometimes necessary — because of several factors: route coverage, travel time reliability, commuting comfort, and convenience. These issues must be addressed alongside efforts to promote public transport use to address the worsening traffic congestion in cities like Metro Manila.

Extending our model to multiple lanes (as in real roads) presents some challenges. OTM can only stop flow at the lane-group (a collection of lanes) level; for a multi-lane simulation, cars must have a lane group that is not shared with buses so that vehicle flow on the link is only partially stopped for the lane-group containing buses. This would require prior tagging of road partitions that constrain bus flows, much like how bus lanes are where buses can load and unload (and impede traffic flow).

Acknowledgments

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