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Allocating city space to multiple transportation modes: A new modeling approach consistent with the physics of transport[*]

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Allocating city space to multiple transportation modes:
A new modeling approach consistent with the physics of transport

Abstract

A macroscopic modeling approach is proposed for allocating a city's road space among competing transport modes. In this approach, a city or neighborhood street network is viewed as a reservoir with aggregated traffic. Taking the number of vehicles (accumulation) in a reservoir as input, we show how one can reliably predict system performance in terms of person and vehicle hours spent in the system and person and vehicle kilometers traveled. The approach is used here to unveil two important results: first, that restricting access to a city's congested areas can improve mobility for all travelers; and second, that dedicating street space to more sustainable modes like buses can improve accessibility for all modes, even if space is taken from cars. In this way, we show that this reservoir approach can determine the level of accessibility that can be sustained by a city of given structure, and can furnish insights into how city space should be allocated between various modes to improve accessibility for all travelers. We end the paper by discussing the value of expanding the approach so that neighborhood street networks can be modeled using systems of multiple, multimodal reservoirs.

1 Background

Cities around the world are growing and motorizing rapidly. This trend is driven by people's need for improved access to activities such as employment, shopping, education, healthcare, and social events. As more people compete for limited urban space to travel, there is an increasing need to understand how this space is used for transportation and how it can be managed to improve accessibility for everyone.

This paper presents new findings on how to allocate space to various transportation modes and implications that can be used to increase accessibility. The results are based on realistic models of congestion dynamics and can be implemented with readily available data. Ultimately, the goal is to understand what sustainable level of accessibility cities of different structures can achieve. Understanding these accessibility outcomes parametrically for all possible city structures would inform the decision making process, thereby helping cities achieve their sustainability goals.

1.1 Accessibility

Accessibility is defined here as the number of activities (jobs, shopping, leisure, etc.) that a person can reach with given budgets of time and money. Accessibility depends both on the density of opportunities as determined by the city structure and on the speed with which people can move about the city, which can be described as the mobility provided by the transportation system. Greater accessibility is achieved with denser city structure and increased mobility.

There are two complementary approaches for investigating the effect of city structure and mobility on accessibility. One approach is to look for appropriate city structures given the mobility character provided by their transportation systems. This is generally done by planners, who may study the trade-offs of transit oriented development around an existing or specifically designed transit system, for example. By exploring many city structures for given mixes of modes, the complete space of accessibility outcomes can be explored.

The dual approach is to consider the city structure and the transportation demand as given, and look to improve mobility. In general, this is the method engineers use to explore the same space of accessibility outcomes. When the city structure is given, accessibility is determined by the distances that can be traveled within given budgets of time and money. We adopt the engineering approach in this discussion, focusing on relationships between distance and time. Improvements in mobility then directly translate to improvements in accessibility, but there is no loss in generality because this relationship can be obtained for any city form.

1.2 Character of Problem

The problems of urban transportation systems are characterized by multiple modes competing for the same road space. These modes vary from city to city but may include pedestrians, non-motorized vehicles, buses, and cars. With different performance characteristics, these modes interfere with one another, and the resulting congestion restricts mobility for everyone. Effective performance of the road space requires careful allocation of the available space to the different competing modes. This allocation of space is a political process, which should be informed by the correct physics. The present paper speaks only to the physics of the problem.

To understand the physics of urban mobility, multiple modes need to be studied under uncongested and congested urban settings. Most importantly, this investigation should be done with realistic models of urban congestion to develop useful and applicable principles. Two curious findings arise from our preliminary work. First, restricting access to congested areas can improve mobility for everyone, even those who are restricted; and this is achieved with fewer vehicles on the road. Second, dedicating street space to sustainable modes such as bicycles and buses—taking space away from the automobiles—can improve accessibility for all modes including the automobiles.

2 Previous Work

Existing literature on the physics of urban mobility can be divided generally into city-scale (macroscopic) efforts described in Section 2.1 and street-scale (microscopic) works described in Section 2.2. Thus far, city-scale investigations have only considered the behavior of one mode in a time-independent environment (without a rush-hour). Until the 1970s this mode was almost always the automobile, but since then some planning studies have looked at public transport on a city scale, particularly buses on idealized road networks. Making road space allocation decisions, however, requires consideration of multiple modes. To date, such considerations have been made only at the much finer street scale and still in a time-independent (unrealistic) environment. Thus, the existing body of work leaves a gap to be filled—a physically realistic time-dependent, city-scale model including multiple modes is much needed.

2.1 Single Mode Work at the City-Scale

Researchers in England developed early steady-state models at the city scale. Smeed (1966) considered the number of vehicles that can usefully enter the central area of a city and proposed a model based on the area of the town, the fraction of that area devoted to roads, and the capacity expressed in vehicles per unit time per unit width of road. He constructed curves describing the theoretical capacity of urban street systems given different road structures—ring network, radial-arc network, and radial network. Using data from several British towns and a handful of other European cities, Smeed estimated the vehicle carrying capacity of a road network based on his proposed theory. This suggested that the maximum number of vehicles that can usefully enter a city can be roughly predicted from the area and structure of a city’s road network.

Also in England, Thomson (1967) developed a linear relationship between the average speed and total traffic flow on a street network using extensive data collected on a series of Sundays from the streets of central London. Wardrop (1968) expanded this model by taking into account the effect of road geometry and intersection control. The expanded model relates the average traffic speed in a central urban area to average traffic flow, road width, density of signal-controlled intersections, and proportion of green time.

Recognizing the need for simple macroscopic traffic models, Zahavi (1972a) investigated the relationship between the basic parameters of traffic flow, road density (length or area of road per unit area), and weighted vehicle space mean speed. From data of traffic and road networks in London and Pittsburgh, he observed that the traffic intensity is proportional to a so-called α, the ratio of road density to space mean speed. The α, which would vary from city to city or neighborhood to neighborhood, represents the interaction of flow and speed combined. By comparing the α-values across different parts of a city, Zahavi argued that the α-relationship can be used as a performance indicator (Zahavi, 1972b). Although these early works identified relationships describing traffic performance at the city scale, they were not used to study congestion dynamics. All of the aforementioned speed-flow relations are monotonically decreasing and are not able to describe congested conditions.

In the late 1970s, a "two-fluid model" (TFM) was introduced by Herman and Prigogine (1979) establishing macroscopic relationships for vehicular traffic in large cities. The authors assumed that the speed distribution is composed of two parts: one corresponding to moving vehicles and the other to vehicles that are stopped due to local conditions such as traffic control devices, congestion, or accidents. Parked cars are not included in the model since they are not components of the moving traffic. The theory relates the average speed of traffic to the fraction of moving vehicles. The TFM assumes that a city traffic network is ergodic—the fraction of stopped time of a single vehicle circulating in the network over a sufficiently long period of time is equal to the mean fraction of the stopped vehicles in the network over the same period of time. This model describes a relationship between the average total trip time per distance traveled and the stopped time per total distance traveled. The TFM was further developed and tested by Herman and Ardekani (1984) with data collected in Austin, Texas and other cities. But the TFM is an equilibrium theory that has not been extended to the dynamic case.

On the public transport side, city-scale modelers have looked at how systems should be designed. Wirasinghe, Hurdle, and Newell (1977) considered how to systematically design a bus transit system for an idealized city with centralized demand. They developed a model to minimize costs to users and operators by setting stop spacing and service headways, and then determining where feeder-buses to rail stations versus direct-buses operate most efficiently. This logistics method, as elaborated in detail in Daganzo (1992), can be applied to model many urban systems, such as sewers, waste disposal, and urban freight, at the aggregated city-scale level. However, these models have been only applied to one mode, and in the steady state.

2.2 Multimodal Work at the Street-Scale

Work has also been done to look at how multiple modes can share the road, but only on the street-scale level. Sparks and May (1971) developed a mathematical model to evaluate priority lanes for high occupancy vehicles on freeways. They looked at the effect on total passenger travel time if a lane on a specific road section were dedicated to multiple occupant vehicles. This consideration of different occupancies between vehicles is important because it recognizes that some modes are more productive than others. The importance of considering passengers rather than vehicles was further voiced by Vuchic (1981). He criticized street-scale evaluations based only on vehicle flows, because multimodal systems should not view all modes as the same.

Many researchers have looked at allocating street space between more than one mode whether it be through the dedication of a freeway lane to high occupancy vehicles or a lane for buses on a city street. One such study on a street scale by Radwan and Benevelli (1983) looked into traffic signal preemption for buses by modeling both isolated intersections and a series of intersections along an arterial. By analyzing trade-offs in costs to road users, the study considers the multimodal nature of the road system, but this is done on a limited network.

Black, Lim, and Kim (1992) also studied how space should be between private and public modes on city streets. Like earlier studies, they focused on passenger travel time, in this case considering various degrees of mixing among modes in traffic, as well as high occupancy vehicle lanes and bus-only lanes. This method has limited applicability, however, because it assumes steady state traffic flow which ignores the fluctuations and spill-over effects that typically characterize urban traffic congestion. Analyses were conducted on one arterial street at a time, so the analytical methods were also applied only on a street scale.

More recently, Currie, Sarvi, and Young (2004) argued for a full accounting of impacts including environmental impacts in planning studies of road space allocation. That analysis is based on a disaggregate micro-simulation which relies on intensive travel data inputs that are typically unreliable or unavailable, as explained in Section 3 of the present paper. While the above-cited methodology, to its credit, promotes accounting for a wide range of impacts, the analyses have yet to be conducted on a full city scale.

3 Reservoir Framework for City-Scale Modeling

City scale modeling can be performed through one of two approaches: disaggregate models that describe the city and its transport activity in great detail or aggregate models that look macroscopically at groups of vehicles and people. In theory disaggregate models are appealing because they track every movement in the city providing very precise results. In practice, however, these latter models require mountains of data that are unavailable and the approximation of these data yield inaccurate results. For example, large origin-destination tables are expensive or impossible to collect and lose meaning in the dynamic case. Furthermore, street systems subject to congestion have been shown to be chaotic (Daganzo, 1998), and this prevents accurate predictions—even with good data. Since the detailed predictions of these models cannot be tested, we shall focus on aggregate models that involve observable inputs and outputs. These latter models can be tested and verified.

Looking at traffic on a road system in an aggregate way is much like looking at a tub of water—a reservoir. Details about each individual drop are not necessary to understand the water's general behavior in the reservoir. Some characteristics of the basin and how much water is in it give us enough information to know how quickly it will drain. For traffic, some knowledge of the road network in a city or neighborhood and the accumulation of traffic on those streets is enough information to predict how quickly vehicles and people move to their destinations. A theory of urban traffic dynamics along these lines has been formulated in Daganzo (2005, 2007) and further verified in Geroliminis and Daganzo (2007).

In this framework, the size of the reservoir depends on the city structure and may also be affected by the design of the transport network and by management policies. Adding streets to the network, for example, increases the size and changes the character of the reservoir. Management policies that reserve space in the reservoir for certain modes can also change the reservoir's ability to serve people.

We are finding from experiments (Geroliminis and Daganzo, 2007) that for a given set of trips, reservoir models can reliably predict the hours and kilometers traveled by vehicles and people by mode and time of day. This is valuable information because these measures are key determinants of the sustainability of urban transport. Based on the character of the reservoir, model outputs can be correlated with indicators of interest including: accessibility level, the costs to users and service providers, and externalities such as emissions and resource consumption.

The reservoir model can be extended to encompass more than one mode. Management strategies can be implemented to partition the reservoir so that road space is deliberately allocated between competing modes. This would allow for the analysis of the performance of different modes using the same road space under different management strategies, such as mixing traffic or separating modes by special-use lanes.

The reservoir model can also be extended by treating a transportation system as an interconnected network of reservoirs, where each reservoir represents the streets in a neighborhood. In this extension, different parts of a city can be subject to different management strategies. Perhaps bus-only streets are allocated only in the central business district while other parts of the city allow vehicles to operate in mixed traffic. The effect of changes in one reservoir on the behavior of adjoining reservoirs can also be considered with this model. We next describe the basic building block of this theory: a single reservoir serving one mode.

4 Single-mode Reservoirs

As explained in Daganzo (2005, 2007), the key to describing reservoir dynamics is the relationship between the number of cars on the neighborhood street network (the reservoir accumulation) and the number of vehicles exiting the network either by driving out of the neighborhood or by reaching their destination within it—the reservoir outflow.

This relationship between accumulation and outflow is conjectured to be similar to the so-called "fundamental diagram of traffic flow," but rather than describing the behavior of traffic on a single road link, the relationship describes traffic behavior macroscopically on a street network; see Figure 1. The shape of this macroscopic fundamental diagram (MFD) should be intuitive.[1] At low accumulations the outflow is low because there are few vehicles in the reservoir, so few can exit. Likewise, at very high accumulations the outflow is low because traffic congestion prevents vehicles from moving towards their destinations. Note that there is a "sweet-spot" in between at which outflow is greatest. This is the capacity of the system, and it is at this point

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[1] The term MFD more aptly applies to the relationship between average flow in the network and the network's average traffic density. But, as shown in Daganzo (2005, 2007) and Geroliminis and Daganzo (2007), outflow is linearly related to network flow and density to accumulation. So, no harm is done by using the term to describe the relationship between outflow and accumulation here, as we do.

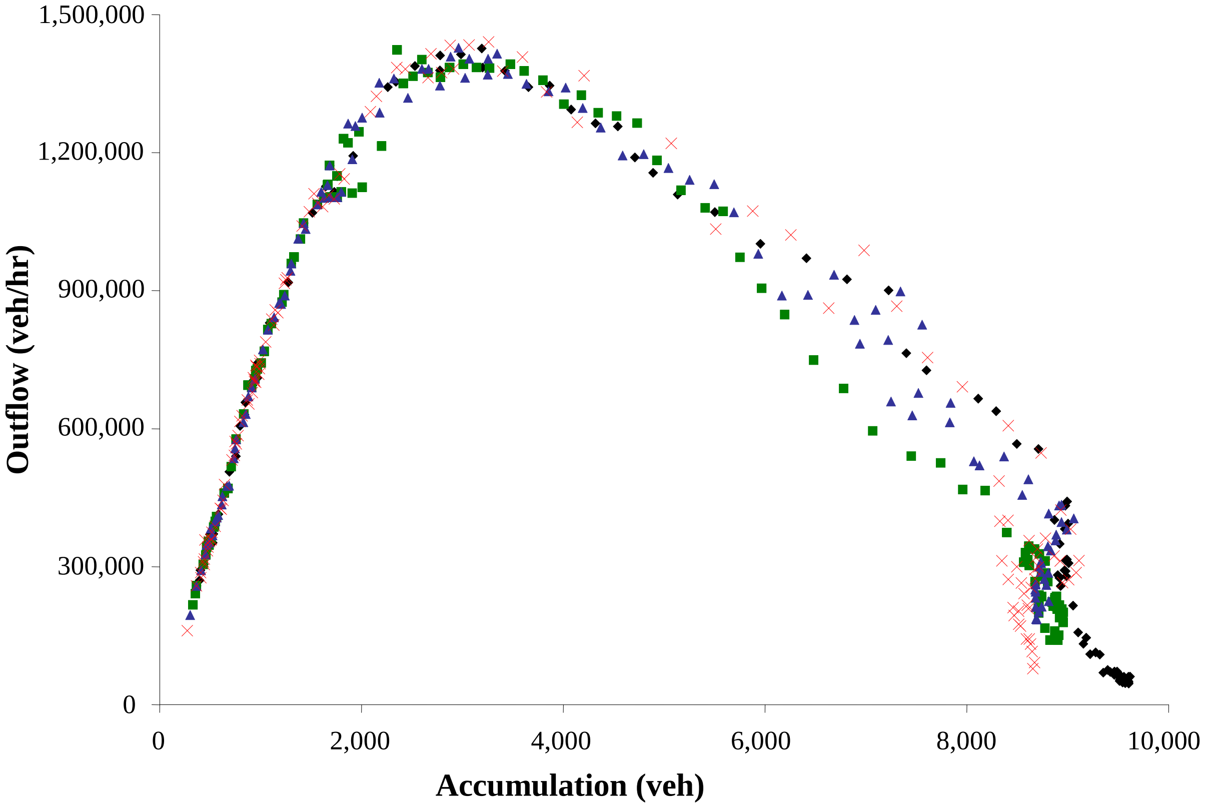

Figure 1. Outflow vs. accumulation for the San Francisco network. Different symbols correspond to simulation runs with different demand patterns.

that the network produces the greatest mobility. Greater outflow corresponds to more people reaching their destinations and thus greater accessibility.

Using a 4-hour simulation of San Francisco's central business district (see Figure 2), Geroliminis and Daganzo (2007) have shown that growing accumulation produces reservoir outflows in the predicted way. In the simulation, the reservoir is the entire network of streets shown in the figure. Estimated demand patterns were scaled up to simulate a full range of vehicle accumulations from empty streets to complete gridlock. The accumulation and outflow values that arise closely follow a curve, as shown by Figure 1. Additional simulations for different days with very different demands produce data along the same curve. This result is important because it means that if accumulation can be monitored, outflows can be predicted without knowing the origin-destination demand.

Since the system's performance is consistent under varying demand inputs, a neighborhood's MFD can be used to make reliable decisions about controlling demand. Note that the outflow in Figure 1 consistently drops toward zero after the accumulation is allowed to exceed a

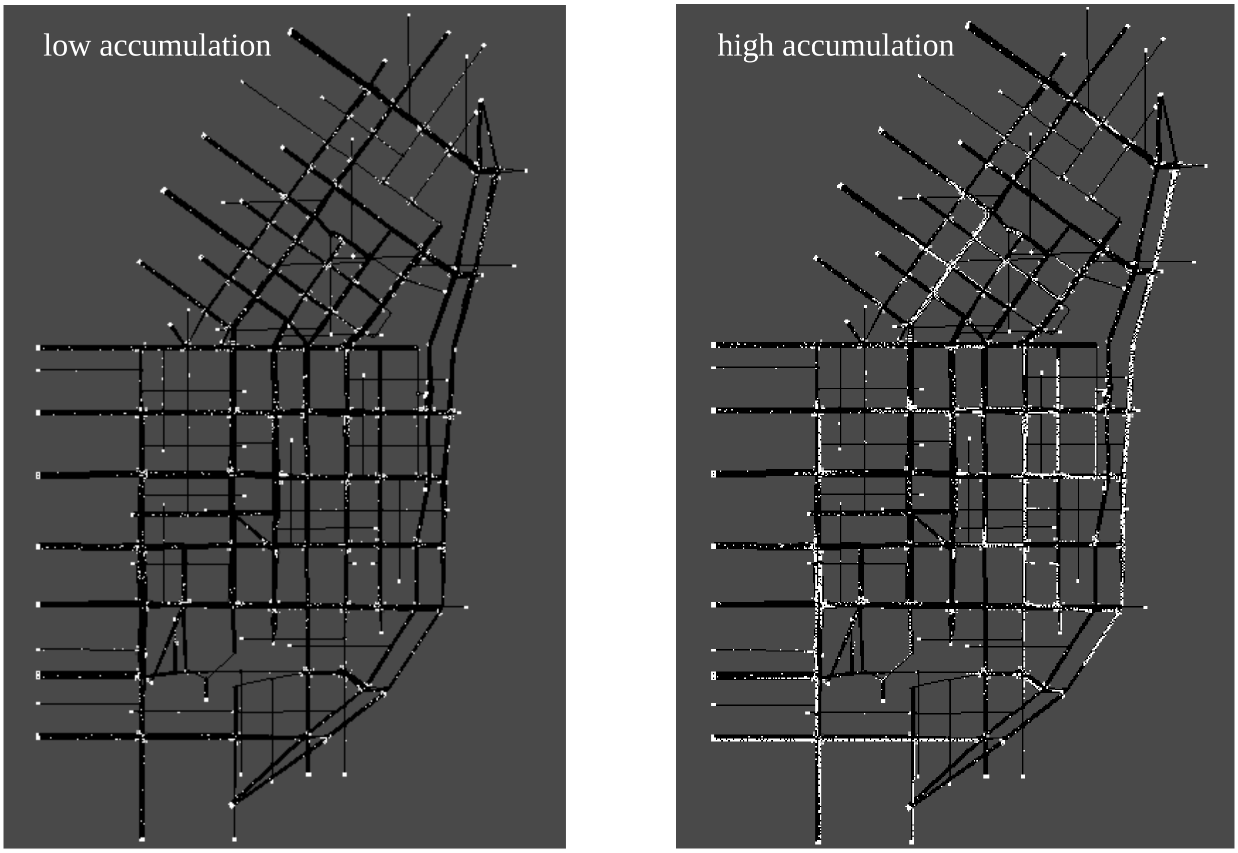

Figure 2. Views of the San Francisco network under low and high accumulations. White dots represent vehicles, and black sections show vacant road space. For our animation, see http://www.ce.berkeley.edu/~daganzo/Simulations/MFD/MFD.html.

reproducible sweet-spot. To increase outflows, we might try to discourage vehicles from entering a neighborhood that is already crowded beyond the sweet-spot; for example, by re-timing the signals or with congestion pricing.

In the first 4-hour simulation of San Francisco, the accumulation was allowed to increase beyond the sweet-spot with demand unrestricted. In a second simulation, vehicle entries into the reservoir were restricted, as described in Geroliminis and Daganzo (2007). In this second case, pre-timed traffic signals placed around the periphery of the neighborhood prevented accumulation inside from growing past the sweet-spot. The result is a higher total outflow, illustrated by the greater cumulative outflow (i.e. the total number of trips ending) versus time; see Figure 3. The plot for the original uncontrolled case shows that the rate of trips ending increases at first as the accumulation rises, and then drops about half way through the simulation as the accumulation surpasses the sweet-spot and traffic congestion prevents vehicles from reaching their destinations. In the signal-controlled case, the higher rate of trip completions is sustained by preventing some vehicles from entering the reservoir when its accumulation is at the sweet-spot. This allows more vehicles to reach their destination in the same amount of time. So,

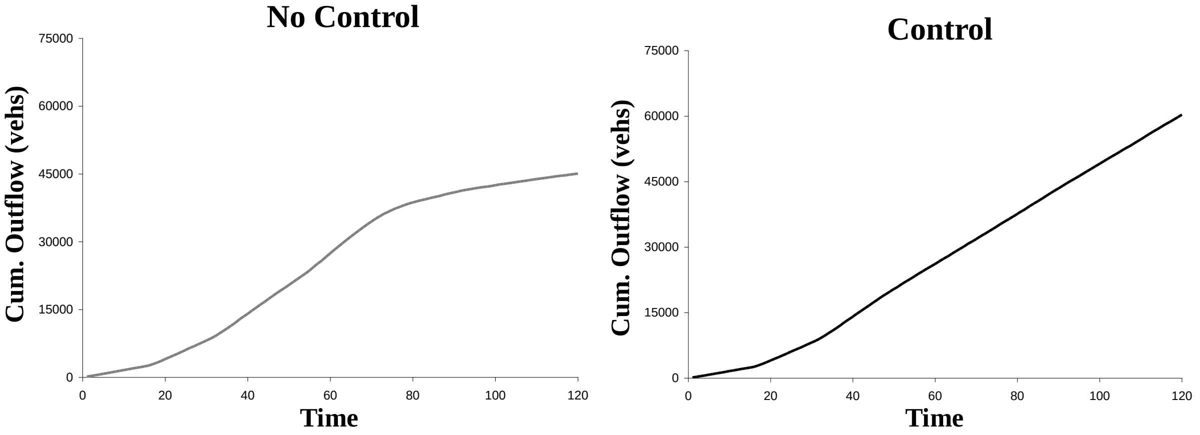

Figure 3. Cumulative outflow vs. time for uncontrolled (left) and controlled (right) systems. For our animation, see http://www.ce.berkeley.edu/~daganzo/Simulations/MFD/MFD.html.

as claimed at the outset, the restriction improves everyone's accessibility for the given demand. And quite importantly, this is done with fewer vehicles on the road.

Pre-timed signals controlled the reservoir to maintain a higher outflow, but signals work best when timed to a known demand. If the system is monitored, the control can be varied in response to real changes in accumulation, and the system could be designed to maintain maximum outflow by keeping accumulation in the sweet-spot.[2] The challenge then becomes finding ways of monitoring the system. In theory, real time accumulation could be perfectly measured everywhere in the network, but in practice this value must be estimated from selective sampling. To make monitor-based control a reality, we need to devise new ways of fusing the available data in urban networks; and new ways of interlinking traffic signals to operate them more flexibly.

With reliable estimates of real-time accumulations, one could devise a myriad of workable policies to keep accumulations in their sweet-spots so as to enhance accessibility. Modifying traffic signals, as was done in the controlled reservoir simulation, is one method of achieving this without affecting the number of trips per mode. Strategies could also be used to change the number of trips per mode by encouraging the use of more sustainable modes such as shifting trips from cars to buses. Parking or peak hour tolls are pricing strategies that can do this, but it should be recognized that the different modes may be competing for scarce resources. To avoid "lose-lose" effects, significant shifts in mode share should be accompanied by shifts in how road

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[2] As explained in Daganzo (2005, 2007), only neighborhood-wide control schemes that adapt slowly to the varying conditions should be used.

space is allocated between modes. Reservoir models can do more than design policies in neighborhoods served by single modes. The models may also offer a means for designing ultimodal policies. But further advances in understanding the physics of multimodal neighborhoods are required before this is possible. We next describe research to this end.

5 Multimodal Reservoirs

Our ultimate goal is to understand whether systems of interconnected multimodal reservoirs are an effective way of modeling cities, and the limitations of the approach. To this end, advancements have been made in understanding one component of this system—a single reservoir serving two modes. The two modes can share the same road space, such as buses and cars jointly using city streets or general purpose freeway lanes. Or, the two modes can be separated by dedicating road space for one or both modes, as illustrated in Figure 4. Sidewalks are a prime example as they separate pedestrians from other vehicles, but special-use lanes serve the same purpose. They take many forms such as bus lanes, bicycle lanes, and even high occupancy vehicle (HOV) lanes. The latter improve accessibility by giving priority to vehicles

Figure 4. Road space in a multimodal reservoir can be (a) shared by mixed traffic or (b) separated by modes. Space can be dedicated to specific modes such as special-use lanes for (c) bicycles or (d) high-occupancy vehicles. (Photographs Courtesy: (a) Wendy Tau, (b) Cláudia Almeida, (c) ITS Berkeley, (d) Valerie Reneé)

that carry the greatest number of person trips. Recent studies of HOV lanes on freeways have produced findings that are relevant to dedicated lanes for other modes, as we describe next.

As for any mode, space for HOVs should be reserved taking into account the spatiotemporal differences in demand and road geometry. With regard to space, a fixed number of lanes can be reserved everywhere in a network, or the amount of dedicated road space can be varied from place to place. With regard to time, the number of lanes reserved can be the same at all times or vary with the time of day. Variable controls, moreover, could be based on historical information or by monitoring and incorporating real-time information. These spatiotemporal decisions are important because they allow for customized and targeted control strategies, but if made incorrectly, space could be wasted.

The key issue in dedicating road space is that if an HOV lane is introduced into a system, and the lane is underutilized, the queue of traffic in the remaining general purpose lanes will lengthen to occupy more space on the freeway. However, if that HOV lane is only slightly underutilized and the individual lanes have the same capacity to carry traffic flow in both scenarios, then the queue will not lengthen significantly. In this case, the total vehicle hours of travel (including delay) are nearly the same in both scenarios. By providing an HOV lane, all of this fixed delay is transferred to low occupant vehicles. Thus, HOV lanes reduce the total number of person-hours of delay which increases accessibility. The greater the vehicle occupancy, the greater the benefit, so clearly the separation of modes is good if the dedicated lane is well utilized and if the mode given preference carries many more occupants.

There are even some situations where dedicating road space can be good even if the reserved space is severely underutilized. The lengthening of the queue may not be problematic if there is uncongested freeway upstream for the queue to grow. One example of this is a radial freeway leading into a city center. Although the HOV lane may be severely underutilized and the queue grows longer, vehicle delay will only increase if the queue blocks upstream ramps. If those ramps are not busy, the effect will be small. By allowing HOVs to bypass this queue, even underutilized HOV lanes can reduce the total person-hours of delay, and therefore increase accessibility without significantly increasing the vehicle-hours of delay.

Separating modes can be bad, however, if there is no room there is no room upstream for the growing queue. This could happen on congested ring roads where queues could fill the road space and reduce flow. Furthermore, the queues could spill over onto adjacent streets reducing flows there as well. Another bad candidate would be outbound radial roads emanating from a city center. These spillover queues can develop into gridlock negatively affecting all vehicles.

These conclusions assume that the maximum flow carried by a lane is the same whether that lane carries mixed traffic or not. A surprising result of HOV lane research is that the flow through a freeway bottleneck can actually increase when HOVs are separated from general traffic. Simulations show that bottleneck discharges after an HOV lane is activated are greater than when all vehicles travel together (Menendez and Daganzo, 2006). This higher discharge rate was observed whenever the HOV lane is not severely underutilized. The simulation further revealed that the separation of modes reduced the frequency of disruptive lane-changing maneuvers, and thus smoothed the measured flow. Therefore, the phenomenon was called the "smoothing effect."

Importantly, this phenomenon has been confirmed with real freeway data (Cassidy et. al., 2006). Cumulative vehicle counts from a vehicle bottleneck studied in this reference—see Figure 5—have been plotted on oblique coordinates, subtracting a background rate to visually emphasize changes in vehicle flow. Note how although the flow of vehicles in the HOV lane drops, the total discharge flow of all lanes combined remains constant. Thus, the favorable effect observed in simulation is also observed in reality.

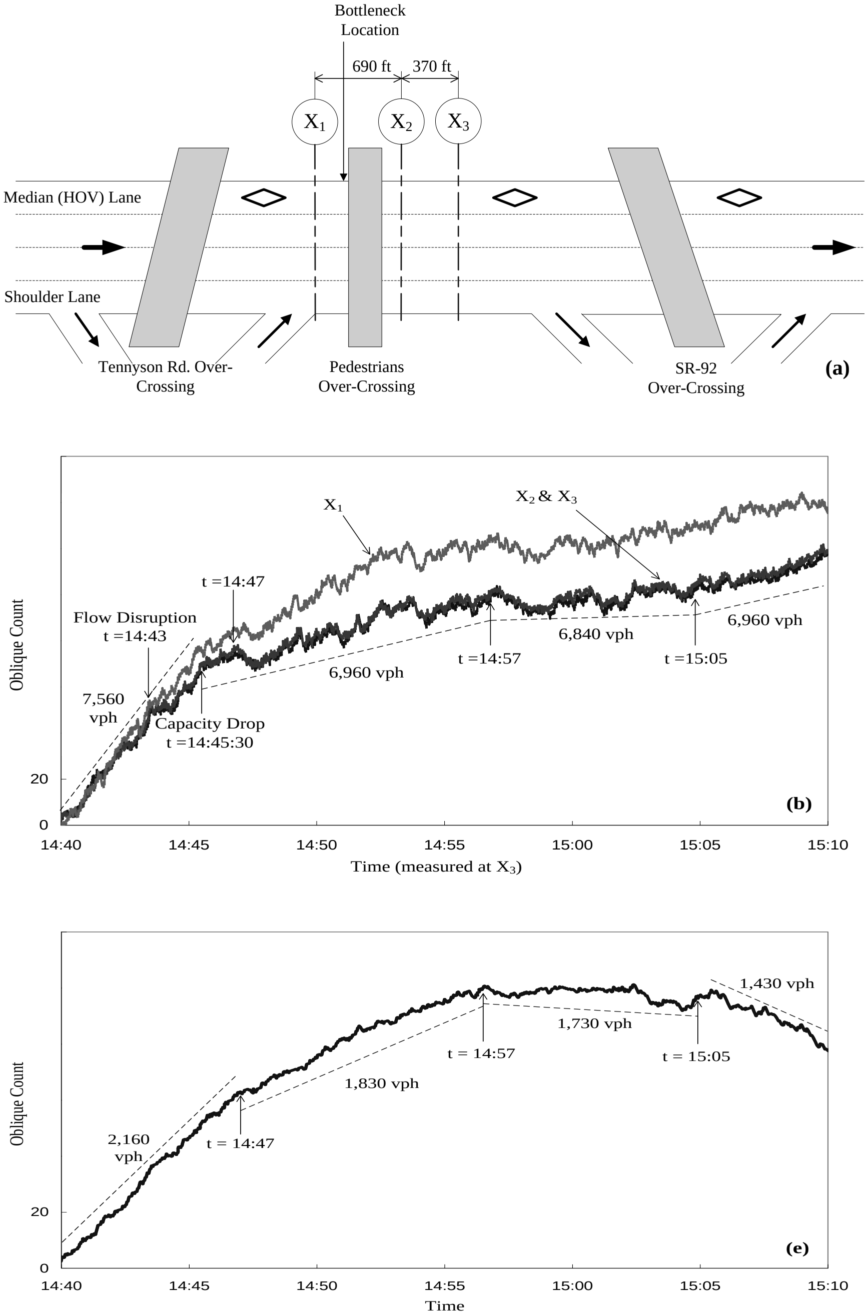

Figure 5. Oblique cumulative plots of (b) all lanes and only the HOV lane (c).

The smoothing effect occurred even though the two separated modes, high and low occupancy vehicles, are composed of vehicles with the same characteristics like size and acceleration. This suggests that the smoothing effect would be much more pronounced when separating modes that are more distinct, such as buses and cars. Separating the latter two modes would reduce disruptive vehicular interactions since cars would not be delayed by large, slow, and frequently stopping buses. Likewise, buses would not be delayed by queues of cars blocking bus stops and intersections. Clearly, there should be cases where, by separating the modes on urban streets, all modes should be better off. Since buses may carry large numbers of people, instituting priorities for buses can potentially reduce person-hours of delay considerably more than in the automobile and HOV case. Therefore, dedicating street space to sustainable modes can improve accessibility for all modes as claimed in Section 1.

Complications arise in real cities because modes can only be effectively separated if the road is sufficiently wide. When making allocation plans, there will typically be some links that are too narrow to accommodate separation schemes, such as near bottlenecks. Queues from these bottlenecks often spillover onto wider streets in the network, and on these wider links, separation of modes is possible (see Figure 6). Total person-hours of delay can then be reduced by providing a congestion bypass lane for buses on these wider streets.

Bus lanes and HOV lanes can therefore be deployed in much the same way. The more accentuated smoothing effect expected for buses means that bus lanes may even be deployed in congested ring roads or congested city centers. A nice feature of city street networks is that they are dense, and while an entire freeway cannot be devoted to HOVs, an entire street may be devoted to buses if parallel streets can carry the other modes. This is most effective if the bus lines in a city can be designed to fully utilize the dedicated space. An example of this is Oxford Street in London which is devoted to 19 bus lines, and is so fully utilized that it tends to be congested with buses. Methods to systematically analyze all these issues now seem within our grasp.

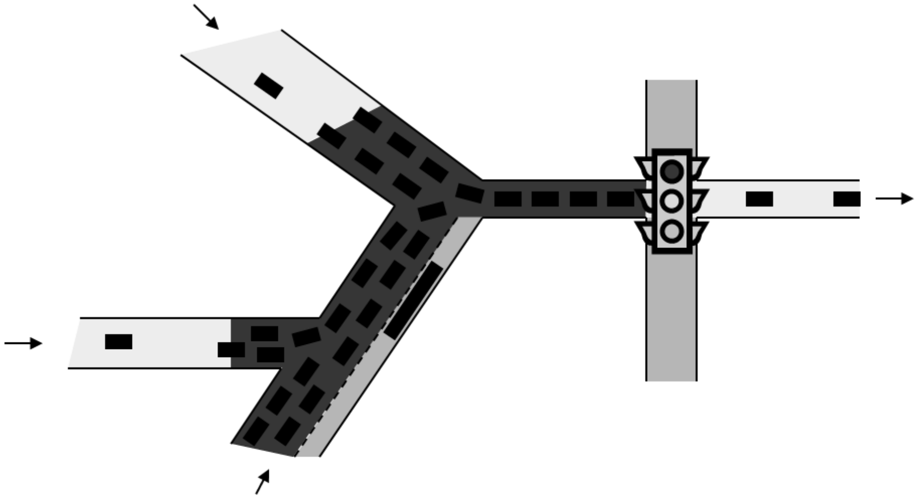

Figure 6. It may not be possible to separated modes on congested streets, but delay can still be reduced by providing congestion bypass (e.g. a bus-only lane) on wider streets.

6 Conclusions and Future Work

The ideas of Section 5 only pertain to reservoirs with two modes and have not yet been embedded in a dynamic model. Further empirical and theoretical work on the behavior of more distinct traffic modes (e.g. buses and cars) is needed. Furthermore, allocating space among modes in one reservoir is only part of the ultimate goal. Work is ongoing to understand systems of multiple single-mode reservoirs, and this is a stepping stone towards developing physically verifiable models of systems of multiple multimodal reservoirs.

These advances should help decision-makers, engineers, and planners determine how best to allocate urban space to the various modes and to design sustainable transportation systems to improve accessibility. Not only should the allocation of existing road space be understood, but so too should the consequences of devoting different total amounts of space to transportation, and the ultimate impacts of city infrastructure on accessibility.

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