# TRANSIT APPLICATIONS OF VEHICLE-TO-VEHICLE AND VEHICLE-TO-INFRASTRUCTURE TECHNOLOGY

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**ABSTRACT**
Advances in mobile devices, wired and wireless information connectivity, and computing power make possible new forms of traffic management and control. In a near-term future where vehicles, signals, and central traffic control servers are all connected, what would be the implications for public transit? What role would transit play? In this paper, we describe some ways in which vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications can be applied to public transit, focusing on changes in transit stations and service typically controlled by public agencies. We review some novel and emerging applications of such technology that could improve transit service and operational efficiency. These include: real-time communications via display devices at transit stations and stops, anti-bunching feedback protocols, crash prevention sensors, dynamic routing in response to nonrecurring congestion, and dynamically managed lanes which enable transit priority. Each of these promises unique benefits, and offers unique implementation challenges. Taken as a whole, they give a sense of the potential of connected transit systems. We conclude by discussing the path to implementation and the questions that remain.

# INTRODUCTION

## Information Technology, Connectivity, and Transportation

Advances in mobile devices, wired and wireless information connectivity, and computing power make possible new forms of traffic management and control. Traditionally, traffic control has relied on the signal, which simply uses light to tell drivers whether they can go in a given direction. Increasingly, signal systems are connected to central servers, which coordinate signals and use embedded sensors or cameras to detect traffic conditions in real-time and optimize signals accordingly. The technology now exists to connect vehicles to the system, enabling vehicle-to-vehicle communications and vehicle-to-infrastructure communications. When vehicles are connected to a central server, much richer communication is possible. For example, central servers or signals can issue routing instructions or restrictions, which can be targeted in terms of vehicle type, time of day, or vehicle occupancy. Communications from the vehicle to the central server are also possible. With funding from the National Science Foundation, researchers at UCLA are now testing the signal transmissions technology to implement such a connected traffic control system.

In a near-term future where vehicles, signals, and a central traffic control server are all connected, what would be the implications for public transit? What role would transit play? In this paper, we describe some ways in which vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications can be applied to public transit, focusing on changes in transit stations and service typically controlled by public agencies. Such V2V and V2I applications consist of communications on an established signaling channel between mobile computing devices on transit vehicles, in transit stations, and at a central server or network of servers. The signaling channel could be Wi-Fi or Bluetooth, for example, though it is typically an established wireless protocol or dedicated short-range communications channel (1). We explore some novel applications of such technology that could improve transit service and operational efficiency. We note that connecting transit could have benefits within the broader context of urban transportation and intelligent transportation systems. Finally, we explore the path to implementation and identify some of the questions that remain.

## The Role of Transit in Urban Transportation

In order to be comprehensive, any vision of the future of urban traffic control must consider transit. Transit carries significant percentages of trips in metropolitan areas: about 11% of commutes within major cities are taken by transit (*2*), and off-peak, non-commute transit usage is on the rise (*3*). Recent decades have seen an increase in investment in transit, both overall and as a percentage of all public investment in transportation (*4*). Our discussion focuses particularly on buses, which serve the majority of transit trips as well as the majority of transit service miles (*4*).

Transit vehicles offer a unique platform to implement V2V and V2I innovations. Because they are publicly owned and operated, they have the potential to instigate a large-scale change in transportation systems. Buses typically operate on streets in mixed traffic, so their interactions with signal systems and other traffic control systems – however technologically sophisticated – resemble the interactions that private vehicles would have. Transit vehicles have broad geographic and temporal coverage, along regular routes with regular running intervals. Additionally, transit vehicles already engage in richer and more dynamic communication with transportation infrastructure than most private vehicles do: for example, buses often preempt traffic signals in order to facilitate faster average speeds on the roadway network.

As we will discuss below, vehicle and infrastructure connectivity offers an opportunity to improve transit service quality. Potential benefits to the transit rider include improved on-time performance, reliability, and station waiting experiences. Connected vehicle technology also promises transit riders many of the same benefits as it does to occupants of private vehicles, such as collision avoidance, dynamic routing to minimize travel time and respond to real-time incidents, and implementation of congestion pricing and other forms of dynamic management. Potential benefits to transit agencies include improved operating efficiency. Additionally, transit vehicles can provide a testing ground for early deployment of connected systems, especially distributed traffic and pollution sensors. Connected transit vehicles and infrastructure have the potential to spur private and public sector innovation by establishing a market for V2V and V2I technology.

## APPLICATIONS FOR CONNECTED TRANSIT VEHICLES AND INFRASTRUCTURE

The following section describes some ways connected vehicle technology can improve transit service, such as increasing operating efficiency and improving the waiting experience at stations. Some of these are more easily implemented than others, and some would require public and political acceptance. We present both short-term and long-term strategies for the integration of transit into a connected traffic management framework.

### Transit Stop Devices

Few transit agencies provide real-time information at stops. In those that do, screens typically display estimated arrival times for the next train or bus, or waiting passengers can call or text phone numbers to hear automated messages that tell them when their bus is coming. Mobile applications such as NextBus provide passengers with estimates of arrival time based on transit vehicle's real-time location and other factors. The majority of transit stops, however, are simply a pole in the ground with a sign indicating the route number.

Advances in internet connectivity allows transit agencies to connect all of their stops and stations to a central network. A completely connected network of transit stops would enable paradigm shifts in service delivery, and has the potential to change the ways boarding requests are made and service changes are communicated. A connected display screen would show a variety of real-time information, such as updated arrival times, seat availability for each route serving the stop, and service alerts. Technology for an inexpensive, hardy screen already exists; such devices could employ E-Ink display technology, like on e-readers, which has low energy requirements and can run off solar power (5).

Instead of being limited to simply displaying information, a connected device provides two-way communications through the use of touch displays or integrated buttons, as well as wireless communication with mobile devices. Such a device has the potential to improve operational efficiency by enabling boarding requests. Many bus stops are served by multiple routes, and as people queue up at a stop, operators are unable to distinguish which passengers wish to board their route. If no passengers are alighting, they end up making unnecessary stops. The boarding request button would address this issue by allowing transit users to choose their specific route out of a list of all routes that service the stop. Pressing the button sends a boarding request to the next arriving bus on the requested route, and the operator would be alerted of the need to pick up a passenger. Boarding requests would be 'fulfilled' and thus deleted from the queue when the requested route's bus arrives. If a transit stop device fails to communicate with the network, the bus would make regular stops as is current practice, without the aid of the boarding request feature.

Boarding requests would be especially valuable in the case of a single waiting passenger, or very few waiting passengers. It would also be helpful during times of congested traffic and at stops where multiple transit vehicles are scheduled closely together. It could improve fuel efficiency, transit travel times, and schedule reliability, by allowing buses to bypass unnecessary stops. Additionally, it could improve roadway capacity for all vehicles at bus stops, because unrequested buses would not have to queue up in small boarding zones and bays.

**Anti-Bunching Feedback**

Bus bunching refers to a common phenomenon in which buses that are scheduled to be evenly spaced end up traveling in together in groups. Vehicles scheduled with perfect headways will invariably become irregular (*6*). Bunching has multiple causes, including perturbations in travel times due to traffic conditions and driver incentives. For example, bunching can occur when one vehicle is slowed by congestion and additional passengers accumulate at stops. This slows boardings and leaves fewer passengers for the vehicle following the delayed vehicle. The phenomenon is most common on high volume routes with low headways.

By combining V2V and V2I communications, onboard data, and a central server, a transit agency could prevent bunching. An algorithm based on bus occupancy, boarding and alighting requests, and other information could enable the transit operator to issue vehicle-specific instructions to increase separation when vehicles on the same route have bunched together. For example, a leading bus may be given instructions to bypass all boarding requests, while the following vehicle continues to pick up passengers. By automating the coordination between one or more drivers based on specific combinations of boarding and alighting requests, a transit operator could reduce dwell times and travel times on high-volume routes.

**Crash Prevention**

According to the Federal Transit Administration (FTA), there were more than 4,000 transit crashes reported in 2009, resulting in over 200 fatalities and over 2,500 injuries (*7*). In addition to the concomitant bodily injuries and loss of life, collisions create financial burdens for transit agencies and disrupt roadway traffic.

Transit vehicles also pose dangers to pedestrians, cyclists, and occupants of private vehicles, all of whom can be involved in a crash with a transit vehicle. For example, over a third of bus-pedestrian accidents occur during turning maneuvers, with left-turns being the most common (*8*).

Existing transit vehicle sensing devices provide information to the operator, but they only offer one-way communication; bus drivers can react to the behaviors of surrounding vehicles, but the other drivers have no means of predicting the bus's movements other than through visual signals. Two-way V2V data communication and on-vehicle sensors could augment existing visual communication to reduce the risk of collisions between transit vehicles and private vehicles. For example, buses in Bristol, UK are testing devices that give operators an audible alert when bicyclists are in the vehicle's blind spot (*9*).

**Dynamic Rerouting**

About half of congestion is nonrecurring, caused by accidents, work zones, or weather (*10*). Crashes and other unexpected events reduce the effective capacity of the roadway, causing delay and a loss of transportation system reliability. Currently, there are few avenues through which people can receive information about nonrecurring congestion. This results in frustrating unexpected delays for private vehicle drivers and transit riders alike. Mobile applications such as Waze and Google Maps have begun to offer such information to drivers of passenger vehicles, but we are not aware of transit operations that are immediately responsive to nonrecurring congestion. Additionally, transit users waiting at stops have no idea what happened to their bus or train, much less where to find rerouted services or relocated stops.

Connected vehicle technology can mitigate the effects of nonrecurring congestion. V2V communications can relay delay information and suggest alternative routes to operators approaching the incident causing the delay. In the case of rerouting, operators can quickly inform riders within the affected vehicles of the new route and schedule, reducing passengers' anxiety and uncertainty. V2I communications can relay and display this information on transit stop devices at affected stops.

**Dynamically Managed Lanes**

The goal of active traffic management is to improve facility performance, which could take place along a variety of dimensions: increased throughput and capacity, decreased crashes, and decreased transit headways, or uniform traffic speeds. An interconnected traffic control system would enable new forms of active traffic management and configurations of managed lanes. Managed lanes are those for which operators apply some restriction on the vehicles that may enter. These include toll lanes, high-occupancy (HOV) lanes, high-occupancy / toll (HOT) lanes, reversible lanes, and bus-only lanes. Data collection and communications technology make it possible to change the stipulations on travel in the lane in response to real-time conditions. This may take the form of varying the price of a toll lane based on demand, allowing private vehicles in a bus lane depending on the time of day, or changing the direction of travel the lane serves.

Managed lanes and dynamic toll lanes currently exist in various forms, such as reversible lanes and other peak-hour restricted lanes, and are primarily on highway systems with intermittent access points. Existing managed lanes could be converted to dynamic lanes. While the utility of reversible and peak-hour lanes is limited to specific traffic patterns at specific hours, dynamic lanes would allow for greater flexibility and optimization of the facilities. This makes them especially useful in unexpected situations and emergencies.

One major advantage of dynamic lanes is the capability to change directionalities and restrictions in response to real-time demand. This could take many forms, three of which we illustrate below. For example, a dynamic lane might be open to all types of vehicles during off-peak hours or when demand is low.  During peak hours, in response to congested conditions, the lane could change to a high-occupancy lane only accessible to carpools and transit vehicles.  The following scenarios describe each of these operating forms in further detail, with a focus on the benefits for public transit.

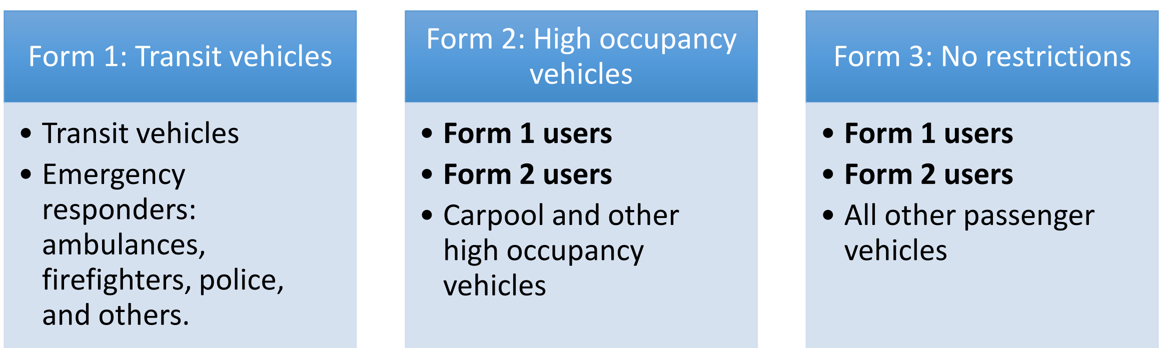


**FIGURE 1  Proposed forms of operation for dynamically managed lanes.**

*Form 1: Transit Priority Lanes (with Emergency Vehicle Access)*

Dynamic lanes can act as transit priority lanes. Existing concepts for transit priority lanes include bus-only lanes, bus rapid transit implementations, and concepts for intermittent bus lanes (IBLs). IBLs may take the form of restrictions that only come into effect during peak hours, or dynamic restrictions where the lanes are activated once the flow of general traffic is operating below a speed that inhibits bus transit speeds.  This restriction might be triggered when all traffic is moving slowly and throughput is low, or when transit vehicles with on-board Automatic Passenger Counting devices report their current occupancies to a centralized navigation server. Prioritizing transit vehicles during peak hours would encourage greater transit use and could reduce aggregate person-delay.

In this form, V2V and V2I communications technology can also facilitate the movement of emergency vehicles. Currently, emergency vehicles use lights and sirens to alert other vehicles of their presence, but drivers can be slow to shift out of the way when the road is congested, or they may find it difficult to ascertain the approach and direction of the emergency vehicle. V2V and V2I communications would allow emergency vehicles to send in advance their approach and intended route to other drivers. V2I technology can also improve existing traffic signal preemption systems, reducing travel times for the emergency vehicle. Finally, by broadcasting lane restrictions, the technology makes it possible to clear any lane connected to the managed lane network.

*Form 2: High occupancy vehicles, tolling, and transit permitted*

In addition to restricting lanes to emergency use, dynamic lanes could improve passenger throughput and travel time reliability on highway managed lanes. In many cases, toll, HOV, and HOT lanes are either underutilized or over-utilized, because tolls, times of restriction and occupancy restrictions may be unresponsive to real-time conditions. Converting such lanes to dynamic lanes could improve their performance. Connected sensors can monitor real-time levels of traffic and adjust the degree of restrictiveness in response. When demand for the lane is low, most restrictions could be lifted to allow any vehicle to use the lane. Transit buses that operate in such lanes would benefit from reduced travel times and increased travel time reliability.

Another trigger for operating in Form 2 might be high pollution levels. Smog and pollution is often local, with “hotspots” that have worse air quality than in other places, especially along freeways or heavily traveled corridors; there are also areas where there is a large population of people for whom exposure to particle emissions and other emissions pose a greater health risk, such as children or older adults. Currently, there are stationary sensors that collect environmental data, such as emissions levels, weather conditions, and traffic conditions, but traffic management is not responsive to this information. Transit vehicles could have on-board pollution sensors and report real-time data to central servers. The system could process the environmental data along with traffic levels to determine whether a low emissions cordon should be imposed in that area, corridor, or region. In this scenario, dynamic pricing could be used as a real-time pollution mitigation strategy.

These three forms are meant to be suggestive of the many ways that dynamic lanes could work, depending on the context. Like many other connected vehicle applications, dynamic lanes might be implemented with the benefits for transit in mind, but in their various forms they produce benefits for emergency access, private vehicle mobility, air quality, and other issues.

### Performance Measurements

Connected transit infrastructure could improve data collection, increasing the amount of information available for performance evaluation. While this doesn't directly influence ridership, it gives transit agencies a better understanding of their operations. Transit agencies would be better able to understand how dwell unrelated to congestion (boardings, alightings) compares with delay due to traffic congestion. This information is a step toward improving operational efficiency.

## THE TRANSITION: CONNECTING VEHICLES, INFRASTRUCTURE, AND SYSTEMS

In general, connected vehicle technologies require a minimum level of adoption in order to deliver on their promised benefits. For example, network-wide vehicle routing with a central server must require some minimum threshold percentage of connected vehicles in order to have a noticeable effect on aggregate behavior. Within this context, public transit presents an appealing opportunity to implement connected vehicle applications. Transit fleets are centrally managed and transit agencies can benefit directly by reducing operating costs per passenger mile traveled. They typically operate in congested conditions in major metropolitan areas, which provides fruitful testing grounds for what may later become private vehicle applications of V2V and V2I technology, such as pollution sensing applications and dynamic lanes. Additionally, the FTA's role in funding new vehicle purchases gives the federal government leverage in mandating or encouraging the integration of the technology.

**What the Transition Entails**

The major challenge for transit agencies is in integrating the technological capabilities into their vehicles and operations. Agencies would incur new capital and operating costs in order to install, maintain, and use the V2V and V2I technology. Transit agencies typically use a twelve-year replacement cycle for heavy duty buses and a seven-year replacement cycle for medium and light-duty vehicles. With such long cycles, system-wide deployment of on-board devices would necessarily involve retrofitting existing vehicles. Transit agencies would face the task of acquiring and installing the in-vehicle communication systems, which must be integrated with existing vehicle sensing and control systems. The transition and retrofit could happen fairly quickly, especially with federal government support and funding. Currently, several programs under MAP-21 provide funding for transit vehicle retrofits. Federal funding could also support the purchase of new factory-equipped buses.

Transit vehicles are already customized with on-board electronic equipment that monitors bus operations and passenger usage, and connected vehicle equipment would add modest costs in comparison (11). A more inexpensive alternative would be to adapt existing in-vehicle communications systems to incorporate this new technology. However, implementing dynamic lanes and installing transit stop devices would likely be much more costly.

An ongoing implementation challenge will be the fact that intelligent transportation systems are generally classified as operations and maintenance, a category that is challenging for agencies to fund (*12*).

**Government Agencies' Roles in Influencing the Transition**

It will be local transit agencies and state and local departments of transportation who will implement the connected vehicle applications described here. However, the need for interagency cooperation often makes implementation of a new idea difficult. The federal government has an important role to play in setting standards and providing funding and resources, as do regional and state governments. The FTA can set national standards for connected vehicle systems in order to successfully incorporate compatible technology into new and existing vehicles.

The government is already in the process of establishing standards and regulations for connected technology. The principal enabling technology is the Dedicated Short Range Communications (DSRC) operating in the 5.9 GHz band (*13*). While DSRC is the established channel for most intelligent transportation systems applications, further standards are needed for V2V and V2I applications. Private manufacturers will produce devices for factory and aftermarket installation in accordance with such standards. A national standard for V2V and V2I communications would also assist the FTA in creating technology standards for new vehicle acquisitions. However, we should keep in mind that the pace of government of often lags behind the speed of private sector technological innovation; we should strive for standards that ensure interoperability yet are flexible.

Another role for the federal government would be to generate and disseminate knowledge and guidance. Local transit authorities vary in terms of their abilities to evaluate and integrate new technology and to purchase and install devices. The FTA can produce guidance on system deployment, covering information on device requirements and standards, costs, and strategies for integrating the new technology and data flows into service planning. Guidance on system operations would describe how to use the technology to reduce dwell times, end-to-end trip times, and other strategies that could potentially save on operating costs while providing a higher quality service to users.

Additionally, federal, state, or regional governments could provide guidance on how to incorporate information produced and collected by connected vehicle technology into service planning and long-range planning. This may include tools to interpret traffic data on transit routes. This information could allow agencies to better understand the causes of delay and the opportunities to improve their services. Analyzing transit vehicle movements along with traffic movements can help distinguish service-oriented delay, such as the boarding and alighting of passengers, from congestion delay. For each of the novel V2V and V2I applications presented in this paper, agencies would benefit from case studies, recommended practices, and other guidance.

Finally, transit agencies and local departments of transportation will also need to provide driver education on dynamically managed lanes and new transit technology. Because the introduction of dynamic lanes and other changes represents a significant evolution in the rules of the road and traffic control devices, law enforcement bodies may wish to offer an extended educational period prior to any enforcement.

## LOOKING FORWARD

What might be the benefits of increased connectivity and data flows? Systemwide improvements for transit riders are possible, as is better optimization across the modes of travel on the roadway network. Transit deserves increased focus because of its inherent advantages for the implementation of connected vehicle and infrastructure applications. Many of the applications are new ideas that have yet to be tried. How will these work? What are the conditions for success? How will transit riders and drivers react? What is the potential for emissions reductions, service improvements, and increased facility efficiency? These are unanswered questions. Our hope is that the ideas presented in this paper motivate agencies to begin testing the unknown potential of connected transit vehicles and infrastructure.

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