Transit Research Roadmap

Prepared for Caltrans
by UC Berkeley PATH and Advanced Mobility Group (AMG)

July 2022

Introduction

The purpose of this report is to give an overview of the technologies that are currently in the focus of attention from industry experts, investors, researchers and government. It is structured as follows. The rest of this section reviews transportation priorities on the National and California levels. Then, the report describes emerging technologies related to public transportation and their application. After that, the report summarizes the results of the survey about their focus and priorities conducted by the authors among the cities and transit agencies of the San Francisco Bay Area and presents the conclusion..

National Priorities

As evidence of climate change continues to grow, the United States government has increased its focus on reducing environmental impact, especially with respect to the surface transportation system. The current administration has also emphasized the need to act urgently to ensure the country's infrastructure is resilient to severe-weather events caused by climate change. This has led to greater policy focus and increased federal spending in areas such as electrification, multi-modal transportation, active transportation (walking and biking), emerging technologies, and rebuilding infrastructure. Expanding the nation's workforce, maintaining safety, and social equity are other major priorities for the current administration.

As shown on their website,[1] the United States Department of Transportation (USDOT) is focusing on three major priorities:

- Safety: keeping traveling Americans safe.
- Innovation: engaging with emerging technologies.
- Infrastructure: maintaining the nation's infrastructure.

The first of these priorities has long been a goal of USDOT and its importance is becoming even clearer with new emerging threats such as COVID-19. The second

[1] USDOT. https://www.transportation.gov/priorities

priority, innovation, is also the focus of this white paper. USDOT views innovation as a catalyst to creating high-paying jobs and building a modern, sustainable transportation system. The final priority is seen as a prerequisite to ensuring our country's infrastructure is resilient to climate change. Infrastructure spending is also recognized as a stimulant to the nation's economy.

California State Priorities

California has long been a leader when it comes to protecting the environment, and the environment has become an even greater priority for the state as evidence of climate change continues to mount. On September 20, 2019, Governor Newsom issued Executive Order N-19-19, which proposes a bold climate agenda directing every agency of state government to redouble their efforts to reduce greenhouse gas (GHG) emissions and mitigate the impacts of climate change. Specifically, he directed the California State Transportation Agency (CalSTA) to:

- Align the state's climate goals with transportation spending where feasible;
- Reduce VMT by strategically directing discretionary transportation investment in support of housing production near available jobs and in accordance with the state's smart growth principles;
- Reduce congestion through innovative strategies designed to encourage people to shift from cars to other modes of transportation;
- Fund transportation options that contribute to the overall health of Californians and reduce GHG emissions, such as transit, walking, and biking;
- Mitigate increases in transportation costs for lower-income Californians.

On September 23, 2020, Governor Newsom went a step further by issuing Executive Order N-79-20. This order states that by 2035, all new cars and passenger trucks sold in California must be zero-emission vehicles. Because transportation currently accounts for more than 50 percent of California's GHG emissions, this order aggressively moves the state further away from its reliance on climate change–causing fossil fuels while creating jobs and spurring economic growth.

Caltrans' priorities as an organization closely align with the state's priorities of protecting the environment and ensuring transportation equity. These priorities are demonstrated in two major plans that were recently released: Caltrans Strategic Plan and California Transportation Plan (CTP) 2050.

Caltrans Strategic Plan

In early 2021, Caltrans released the Caltrans 2020-2024 Strategic Plan. The mission, vision, and goals that are in the plan closely align with California's transportation priorities of protecting the environment and ensuring equity for its citizens.

The Caltrans mission is to “provide a safe and reliable transportation network that serves all people and respects the environment.”

Caltrans’ vision is “a brighter future for all through a world-class transportation network.”

Caltrans has established the following six goals as an organization:

- Safety first
- Cultivate excellence
- Enhance and connect the multimodal transportation network
- Strengthen stewardship and drive efficiency
- Lead climate action
- Advance equity and livability in all communities

Emerging Technologies and Applications

Encouraging Modal Shift

Presently, many initiatives directed at mode shift propose some punishing pricing schemes or removal of parking at presumed destinations to force people to choose public transit over their car. However, this approach is unfair: it punishes the disadvantaged, allows the wealthy to continue current practices and discourages transit agencies from becoming competitive. We believe that an approach promoting competition between travel modes is more promising.

Programs informing and incentivizing people to explore transportation modes other than their own cars, need reliable and up to date information about alternatives. Travelers should be able to see the benefit of these alternatives in terms of travel time (getting to destination faster), cost (cheaper), health (sometimes cycling could be considered a safe and healthy workout in a beautiful weather), or convenience (can sleep, read, listen to or watch something during the commute). For that, we need:

1. Data about alternative modes in a standard format, such as General Transit Feed Format (GTFS) specifying public transit schedules. There can be GTFS-RT (real-time) or GTFS-Flex (on-demand routes) data available. There could be information about occupancy of parking lots at park-and-ride facilities, and so forth.
2. Secure data management system that keeps the information up to date, validates new data and maintains usage statistics.
3. Open Application Programming Interface (API) for making these data available to trip planner providers.

4. Mobile apps that make it interesting to compare the alternatives. Gamification can be a powerful tool to incentivise people to change their means of transportation.

Transit Performance Assessment

Improving public transit starts with assessment of its performance. Presently, most transit agencies consistently report their schedules through GTFS. That, plus vehicle location data provided via GTFS-RT, allow to answer the following questions:

1. On the area, agency and regional level, what percentage of vehicles is on time?
2. What percentage of vehicles provides regular location updates?
3. How many vehicles are off course at a given time?
4. Is there a regular service within, e.g. a quarter of given parcels X, Y, Z? Or, what service is there within a quarter of a mile from parcels X, Y, Z? And, what is the service frequency?
5. How regular is the service near given communities? What is the frequency of service in these areas? Specifically,
    a. What is the service reliability?
    b. What are the frequencies derived both from schedule and real time, and what is the deviation between the two?
    c. Does this service provide direct connectivity to the most popular destinations, or are transfers required?
    d. What is the reliability of timed transfers between communities of concern and popular destinations?
6. How many buses are within a given distance of a specified area and what are their locations at current time? This may be useful for emergency response and evacuation.

Combining automatic vehicle location (AVL) and automatic passenger count (APC) data produces ridership on individual route segments. With the ridership data, the following additional questions can be answered:

7. What is the transit ridership on given routes and between specified origins and destinations?
8. Are buses on given routes too crowded to safely accept passengers?
9. What is the passenger-miles traveled (PMT) on given routes or within given areas?
10. What is the bus utilization over different time periods?
11. What is the cost of transit route operation relative to trips and PMT?
12. What is the PMT in given areas? What are the most/least utilized routes starting/ending in these areas?

13. What is the correlation of PMT and VMT on neighboring freeways? This can help estimate the modal split.

There is a need for a Transit Performance Dashboard, where these questions could be explored for multiple transit agencies. Presently existing transit dashboards include:

- MBTA On-Track – Massachusetts Bay Transportation Authority's dashboard for reliability, ridership, financials and customer satisfaction;[2]
- Texas Transit Performance Dashboard – covers 27 urban and rural transit districts;[3]
- CapMetro Dashboard – Capital Metro, an Austin Public Transit dashboard for reliability, safety, ridership, financials and customer satisfaction;[4]
- NYMTA Performance Metrics – New York Metropolitan Transportation Authority publishes metrics of public transit performance;[5]
- SFMTA - COVID – San Francisco Municipal Transportation Agency's data sheet about transit ridership and revenue during COVID-19;[6]
- TriMet Dashboard – Tri-County Metropolitan Transportation District of Oregon dashboard for efficiency, safety, ridership and budget.[7]

Out of these, only the Texas Transit Performance Dashboard covers multiple agencies.

Traditionally, ridership has been the main performance metric for transit agencies. Money is at stake in addition to pride: ridership partly determines the amount of federal funding allocated to each system. The national transit industry scrutinizes passenger numbers too, celebrating a national uptick and bemoaning a downturn.

But the coronavirus pandemic has shown that ridership is an imperfect measure of transit's importance. With offices shuttered and agencies themselves advising passengers to avoid all but essential trips, passenger counts collapsed by as much as 90% on rail service in San Francisco. Ridership on buses has slumped as well. And these numbers are not coming back quickly to pre-COVID levels, as work-from-home habits forged during the pandemic stand to leave lasting marks on commuting patterns in major cities.

Few people would argue that transit systems' societal value has fallen as steeply as their ridership. On the contrary, the pandemic has reminded us that cities cease to

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[2] MASSDOT.gov. https://www.mbtabackontrack.com
[3] Texas Transit Performance Dashboard. https://www.texastransitdashboard.com
[4] Capital Metro Dashboard. https://www.capmetro.org/dashboard
[5] New York Metropolitan Transportation Authority Metrics. https://new.mta.info/transparency/metrics
[6] San Francisco Municipal Transportation Agency's data sheet. https://www.sfmta.com/covid-19-dashboard
[7] Tri-County Metropolitan Transportation District of Oregon dashboard. https://trimet.org/about/dashboard

function if public transportation is unavailable. You might be able to drive to a hospital or grocery store, but that won't do you much good if transit-reliant workers can't get there to staff it.

There exists a better measure of transit success - **reachability**. The basic method of calculating reachability is intuitive: Pick a particular neighborhood, and then determine the time it would take for a person living there to use transit to reach jobs dispersed throughout the region (people take many other kinds of trips, but commute data is most readily available). Transit planners can then aggregate the data to calculate an overall regional measure of access, or they can create one for a subset of the population (say, minorities or low-income residents). Agencies are then able to use these calculations when designing a systemwide service map or when making a narrower decision, like choosing whether to open a new route or add frequency to an existing one. An agency can continue to monitor the accessibility of its service, defined as the share of jobs reachable for a given population within a given trip time, such as 60 minutes door-to-door.

It is important to note that this reachability analysis can only be performed on a system (regional) level - not per individual agency.

Mobility Technologies

Mobility as a Service (MaaS)

The concept of Mobility as a Service (MaaS) has forever revolutionized the transportation industry. It is also changing the role of the transit providers in the mobility space - their responsibility has expanded to incorporate new and innovative approaches, integrating multiple modes of transportation and introducing new technology tools to keep communities moving. Additionally, MaaS changes the way riders and agencies interact, allowing for passengers to select among ride-sharing, bike-sharing, public transit services, and private transit services to fully customize their travel preferences and choose the solution that fits their needs through an integrated network. Transit agencies share the responsibility to facilitate that evolution.

The American Public Transportation Association (APTA)[8] recently undertook a study mission looking into MaaS systems in Europe to gather data and evaluate the readiness of American transit systems to fully embrace MaaS.[9] The study emphasized the importance of a solid, sustainable public transit system as the backbone of the MaaS concept. According to the study, a clear vision for enhancing mobility, a high quality,

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[8] American Public Transportation Association. https://www.apta.com

[9] APTA Report. Being Mobility-as-a-Service (MaaS) Ready. June 2019. https://www.apta.com/wp-content/uploads/MaaS_European_Study_Mission-Final-Report_10-2019.pdf

well-integrated public transportation system and mobility partners/contractors who share the agency's mission, are all vital components of effective MaaS initiatives.

The study also identified that regulatory policy and lack of governmental support, not technology, is the key challenge when it comes to MaaS. It is clear that technology is outpacing policy developments with many options currently available for real-time mobility apps that integrate a community's transportation options.

One of the changes expected in the near future includes the regionality of mobility. As cities grow and begin to overlap, the traditional boundaries of public transportation are blurred. One can imagine a future where a city or metroplex releases a Request for Proposals for turnkey mobility solutions for all modes, looking for a partner to handle all aspects of mobility. Clients will look for the best overall solution for their community's complete transportation needs - covering fixed route, paratransit, university and private shuttle, on-demand, school bus, contact center, rail, fare payment, maintenance services and more. Additionally, clients will look for a provider who can aggregate all services together on one platform, through one payment channel, to create seamless journeys powered by artificial intelligence and data, while also providing additional revenue streams.

Mobility on Demand (MoD)

Mobility on Demand (MoD) is one of the more popular approaches to modal shift, improving system flexibility, efficiency and convenience. On-demand options, which take many forms, are successfully incorporated into both fixed route and paratransit services, sometimes including the services of Transportation Network Companies (TNCs) and other third-party providers. Some of our first on-demand transit operations included late night services at colleges and universities, designed to ensure students have a safe ride home after traditional transportation services end for the evening. On-demand services have also been successful as a first-mile last-mile solution to increase ridership in fixed route operations and have also shown to improve passenger satisfaction and efficiency at paratransit operations, facilitating the ability to take same-day trip requests. More recently, on-demand services have expanded again with service for passengers needing wheelchairs or other mobility devices.

One specific type of on-demand transportation - microtransit - has proven to better connect various communities and/or zones to increase the use of public transit. Information technology is a vital component of microtransit operations, and there is no shortage of passenger apps available for this purpose. Through these apps, or via a designated phone number, passengers can request trips. Passengers and dispatchers can see the real-time location of their vehicle, making commutes and trip planning much easier and convenient on the part of the passenger.

Micro-Mobility

An important component of MaaS that transit agencies must embrace moving forward are micro-mobility solutions, including non-traditional technology modes such as scooters and bike sharing. These micro-mobility services can operate as first-mile, last-mile solutions for public transit systems and, to be successful, must reflect the mobility preferences of the community. For example, successful micro-mobility services could include bike sharing in a downtown environment where biking is popular, or incorporation of transportation in open-air golf carts to fixed route pick up points in a beach community.

According to the Mobility as a Service Alliance,[10] a public-private partnership dedicated to creating the foundation for a common approach to MaaS, micro-mobility solutions can help fill in the gaps in public transportation for commuters, making public transit a more attractive option for many. These solutions can also have tangible benefits for transit agencies, including reducing parking congestion and improving ridership on fixed route systems.

In many cities, commuters are able to rent bikes, scooters and other micro-mobility vehicles on a convenient app. In some cases, customers can use their mobile phones to locate a vehicle, unlock it, and pay their fee. This level of convenience is designed to appeal to today's commuter and offers services available on-demand, at any time the passenger is ready.

As agencies look to provide more complete mobility management services to the public, the future will likely mean more subcontracts with micro-mobility providers like scooter and bike sharing companies, taking accountability for their performance and adherence with applicable regulations.

Multi-Modal Connectivity and Dynamic Transit

Transit agencies in suburban regions in California and in the United States face enormous challenges for delivering cost effective transit operations, due to the fact that traveling populations are distributed in large geographic areas. Operators typically assign a limited number of buses on the maximum number of routes possible in order to offer wide geographic coverage. As a result, the headway of each bus route is long and many passengers need transfers among such routes in order to reach their destinations. Consequently, travel using transit takes much longer than the driving alternative. The longer travel time significantly discourages choices to take transit. Rural and suburban transit agencies need tools to be able to innovate transit operations.

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[10] Mobility as a Service Alliance.eu. https://maas-alliance.eu

The conventional transit system was established upon the framework of fixed routes, fixed schedules and almost fixed ticket prices. To improve the transport service in order to attract travelers from private driving, transit systems are substantially required to be flexible and dynamic. The concept of Dynamic Transit Operation can be interpreted as flexible operations, multi-mode linkages, traveler-centric, and demand-responsive.

Integrated Dynamic Transit Operation (IDTO) applications are expected to demonstrate great potentials of improving transit service. The IDTO algorithms and user apps are developed to allow holding at bus stops to meet with connecting passengers (Connection Protection or T-CONNECT), to facilitate first-mile and last-mile shared riders (Dynamic Rideshare or D-RIDE), to provide more accurate and reliable ETA/ETDs in real-time for entire-trip (RT-ETAD), to offer incentives for encouraging frequent and accumulative ridership (T-REWARD). Therefore, IDTO can offer significant reduction of travel time and connectivity improvement for a greater number of travelers, change travel demand which in turn helps congestion relief, run a more cost-effective operation, and create positive changes in inter-organizational cooperation. The implementation of IDTO may potentially change the way in which transit services are operated in suburban American cities.

Research efforts also aim to significantly improve the reliability of intramodal and intermodal connections through the integration with MaaS and MoD platforms and first/last mile mobility solutions. The function of Dynamic Connection has been designed as an add-on function to any trip planning/navigation application (such as HaCon, Google Transit, etc.) as long as the trip requires a real-time connection between successive segments.

Passenger Rail

There are three main benefits of rail transportation:

- **Mass transportation**. Rail is the only transportation mode capable of moving a massive number of people reliably at high speed. This unique capability, which is essential to alleviating a big surge in demand over a short period, makes rail a critical component of MaaS.
- **Energy efficiency**. Rail is three times more efficient compared to cars when it comes to per-capita resource consumption. It helps reduce road congestion and greenhouse emissions by taking vehicles off the road. The industry has made strides to adopt more efficient engines, cleaner fuels and electrification to further reduce the carbon footprint. By choosing cutting edge technologies such as regenerative braking, which helps to capture power from braking, the industry continues to drive higher efficiencies.

- **Economic growth**. Studies show that rail systems generate two to four dollars equivalent economic growth per every dollar invested. The construction and extension of rail systems stimulate the local economy and provide a source of working-class jobs. People can work, study, and seek entertainment in large urban areas while living in more affordable houses outside the city, knowing that they can rely on rail transportation day in and day out.

Economic and cultural factors drive the development of rail networks in each region. For instance, population density determines the type of service and the scale required, and policy often influences the direction and pace of innovation. By studying the characteristics of a country one can understand why rail systems between countries may not be comparable in volume, modes or passenger experience. Aging infrastructure and a capital-intensive operation are top challenges in the rail industry, but particularly in the U.S. a significant car culture, traditional funding practices and a lack of customer focus have been critical reasons why our passenger rail system lags compared to other systems worldwide.

Paying for the Ride

COVID-19 triggered transit agencies all over the world to adopt contactless payment technologies. For example, The Greater Dayton Regional Transit Authority (RTA)[11] and app-developer Transit[12] cooperated to allow riders purchase reusable smartcards to tap and ride without needing to buy a ticket, or select a fare before traveling. The payment platform is being rolled out in partnership with Masabi[13], a provider of mobile ticketing technology for public transport.[14]

Apps from Transit and the regional transit EZfare consortium[15] serve 13 transit agencies across Ohio, Michigan and Kentucky, allowing riders to purchase tickets through their phone and access real-time trip planning. Other cities like New York, Washington D.C., Chicago and Los Angeles have also rolled out tap-to-pay functionality for their transit systems to provide quicker, easier, and safer payment methods for riders and commuters.[16]

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[11] The Greater Dayton Regional Transit Authority.org. https://www.i-riderta.org
[12] Transotapp.com. https://transitapp.com
[13]Masabi.com. https://www.masabi.com
[14] Greater Dayton Regional Transit Authority, Masabi and Transit app Launch Account-Based Ticketing for Tapp Pay on Mobile. Press Release, Feb. 2021. https://www.i-riderta.org/news/greater-dayton-regional-transit-authority-masabi-and-transit-app-launch-account-based-ticketing-for-tapp-pay-on-mobile
[15] EZfare consortium. https://www.ezfare.us
[16] Transit payment systems revamped for post-COVID commuters. PaymentsDive. Apr. 2021. https://www.paymentsdive.com/news/transit-payment-systems-coronavirus-pandemic/598827

In Moscow, Russia, the contactless initiatives went further. In October 2021, Moscow subway system launched a Face Pay system - when a rider's credit card is charged as a result of facial recognition upon their entering the subway.[17]

Safety

Safety management in California cities generally follows the **Vision Zero (VZ)**[18] paradigm implemented via **Complete Streets** program. VZ is a strategy to eliminate all traffic fatalities and severe injuries, while increasing safe, healthy, equitable mobility for all. VZ recognizes that people will sometimes make mistakes, so the road system and related policies should be designed to ensure those inevitable mistakes do not result in severe injuries or fatalities. This means that system designers and policymakers are expected to improve the roadway environment, policies (such as speed management), and other related systems to lessen the severity of crashes. First implemented in Sweden in the 1990s, Vision Zero became popular across Europe, and now it's gaining momentum in major American cities. Presently, 13 California cities committed to VZ goals - Alameda, Berkeley, Fremont, Los Angeles, La Mesa, Monterey, Sacramento, San Diego, San Francisco, San Jose, San Luis Obispo, Santa Barbara and Watsonville.

VZ approach implies road diet - it reduces vehicular speed and throughput, but we do not know how and where congestion problems are shifted from streets where VZ is implemented. Moreover, sometimes VZ results are directly opposite of what was promised.[19] Thus, there is a strong need for a well-defined and understandable criteria of VZ proposal evaluation and before/after assessment. Not just streets and intersections with VZ modifications, but the **whole surrounding street network** must be analyzed in terms of changing traffic patterns, risks and throughput capacity.

Next, we talk about some technologies that could be employed to improve safety. These include risk analysis tools, connected vehicles and infrastructure that can signal about possible danger, driver monitoring and data sharing about work zones.

Depth Analysis

In the previous section about safety assessment, we talked about analysis at scale involving hundreds of roads and intersections - the so-called breadth analysis. Contrary to that, depth analysis zooms into a particular location - a junction or a road segment - and studies its road geometry, admissible maneuvers, observed traffic modes and their

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[17] The Guardian. Privacy fears as Moscow metro rolls out facial recognition pay system. Oct. 2021. https://www.theguardian.com/world/2021/oct/15/privacy-fears-moscow-metro-rolls-out-facial-recognition-pay-system

[18] Vision Zero Network: https://visionzeronetwork.org

[19] Rebuilding From the Failures of Vision Zero: https://www.planetizen.com/news/2021/05/113209-rebuilding-failures-vision-zero

flow/frequency. Companies, such as Street Simplified[20] and Derq[21], conduct video surveillance for a given amount of time (typically, 24 hours) at requested locations and employ computer vision techniques for object classification and tracking. The subsequent processing of resulting trajectories enables identification of conflicts and potential crashes (i.e., near misses).

One Berkeley Deep Drive (BDD) project[22] developed a toolchain for automatic generation of hazardous scenarios that arise because of shortage of information (e.g., occlusions) and incorrect interpretation of the other object's actions. Some of these risky scenarios can be avoided by employing connected vehicles and infrastructure.

Connected Vehicles and Infrastructure

In complex environments, such as intersections, challenges arise from complicated vehicle trajectories; occasional absence of lane markings to guide vehicles; split phases that prevent determining who has the right of way; invisible vehicle approaches; illegal movements; simultaneous interactions among pedestrians, bicycles and vehicles. Intelligent intersection improves awareness of drivers, bicyclists and pedestrians when they maneuver through the junction.[23] Intelligent intersection technology has four critical components: (1) sensing; (2) interpretation of sensor measurements; (3) anyone-to-infrastructure (X2I) connectivity, extending the concept of vehicle-to-infrastructure (V2I) connectivity; and (4) signal phase prioritization. It has the potential to remove spatial and temporal uncertainties that lead drivers, cyclists and pedestrians to wrong decisions resulting in accidents.

This research is directly related to AV safety. It was recently shown that even with perfect onboard sensing AVs without connectivity cannot be safe.[24]

Safety of Rail Crossings

Safety at highway-rail crossings is an issue that affects many travelers using various modes in various locations, from unsignalized crossings in rural locations to signalized crossings in dense urban areas where both light and heavy transit rail are operated in the same right-of-way as vehicular traffic.

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[20] Street Simplified: https://www.streetsimplified.com

[21] Derq: https://derq.com

[22] Varaiya, P., Seisha, S. Generation and Mitigation of Hazardous Scenarios at Traffic Intersections. https://deepdrive.berkeley.edu/project/generation-and-mitigation-hazardous-scenarios-traffic-intersections

[23] Varaiya, P. Which Intersections Need I2V and When? https://deepdrive.berkeley.edu/project/which-intersections-need-i2v-and-when

[24] Shetty, A., Yu, M., Kurzhanskiy, A., Grembek, o., Tavafoghi, H., Varaiya, P. Safety challenges for autonomous vehicles in the absence of connectivity.
Transportation Research. July 2021. https://doi.org/10.1016/j.trc.2021.103133

In 2018, more than half of public at-grade crossings had automatic warning systems (flashing lights and/or gates) but very few private at-grade crossings did. Still, more than 60% of collisions occurred at crossings with automatic warning systems. A study on driver behavior using cameras installed in cars found that 46% of the time, drivers were likely engaged in secondary tasks and 35% of the time, drivers failed to look either left or right on approach to passive grade crossings. In general, 94% of train-vehicle collisions could be attributed to driver behavior or poor judgment. An advanced warning system that provides another source of information to travelers, perhaps an in-vehicle notification to immediately and directly alert the driver, could help further improve safety. This could also be a valuable data source for automated vehicle systems.

While rail intersection safety applications have been recently demonstrated in operation, they have rarely included connected vehicle technology. There are also limitations on the ability to expand existing systems due to the lack of data sharing agreements and other coordination with private railroad companies.

Due to the difficulty of coordinating with the railroad industry, it is unlikely that connected rail crossing safety applications will be based on direct vehicle-to-train communication. The most feasible solution would be to extend the intelligent intersection and X2I concept to include rail crossings. Thus, the communication between vehicles and trains would occur through the infrastructure.

Parking and Curb Management

Urban congestion is largely a result of parking shortage. Drivers arrive at their destination and then start circling around blocks in search of street parking - this adds to VMT, emissions, delay, and safety risks, as drivers searching for parking are distracted. Another big problem facing cities is double parking by delivery vehicles and Transportation Network Companies (TNCs) such as Uber and Lyft. Trying to solve these problems, cities embark on experiments that lead to a transformation in urban curb management. Curb space is increasingly becoming a dynamic interface between people and vehicles, bikeways, bus lanes, street vendors (e.g., food trucks), and paratransit picking up and dropping off passengers with disabilities.

How cities manage this public asset and resource for local economies is a timely problem, whose solution relies on first understanding the emerging usage patterns over time and space. Currently, there is no systematic method for identifying these patterns and there is great untapped potential for doing so with emerging machine learning technologies and nontraditional data sources, such as dashboard cameras mounted on shuttle buses, parking enforcement and other vehicles that routinely travel a geographic area of interest. When combined with stationary cameras, these provide an excellent

data source covering broad ranges of time and space. Recent advances in deep learning provide an opportunity to learn usage patterns from such data.

Smart Parking

Smart parking is a technological approach to improve the parking process and the cars' positioning in a city with a shortage of space. Its main purpose is to spare time for drivers who want to leave their cars close to their destinations. It effectively reduces the number of vehicles in the streets, which in turn improves the environment.

Any smart parking initiative implies the use of additional smart devices starting from a regular smartphone to special sensors and cameras in the parking areas. Also, AI takes its place among smart parking solutions. In other words, smart parking is a highly diverse branch using the latest tech advancements. Smart parking technologies include:

- IoT smart parking sensors. The sensor is positioned in a parking space, underground. Before the work starts, the sensor should be properly calibrated. The vehicle located in a parking space changes the earth's magnetic field, and the sensor tracks this change. The occupation status is then sent to the cloud.

  Users can track the sensors' signals in real-time from a PC or smartphone. First and foremost, drivers see all parking areas around them along with free spots they can take - it looks like an interactive map. The interface of such a tool is usually simple and user-friendly. Quick navigation is essential when driving: no extra taps on the smartphone screen - only minimalistic and understandable navigation symbols (big icons, vivid arrows, etc.). Smart cities parking usually involves third-party integrations. For instance, an app developed for a certain company should be easily integrated with the devices of the city's authorities.

- The counter system is another smart device that detects when a car appears in the parking lot and when it leaves. This data is then processed by the IoT device, and it can identify free parking spots at any given moment. The data from the counters is stored in the cloud, so parking managers can use it later for analysis and demand predictions.

- Control systems have several features that make them more complex than sensors or counter systems. A control system detects if someone breaks parking rules, then it registers the violation and stores the evidence (a photo or a video), plus, it can issue a ticket and inform the violator. This way, smart parking solutions exclude the human component and contribute a lot to reducing the city's expenses and increasing safety as they often have to work tirelessly 24/7.

- Parking lifts are aimed to optimize parking spaces by increasing the capacity of the parking lot. Lifts help optimize even the tiniest spaces by exploiting vertical space, allowing the placement of up to three cars on the same parking spot.
- Parking robots serve as valets that take your car and place it with maximum efficiency. Robotic car parking is complex and involves several components. It works similarly to AI robots but involves lifts, shelves, and other similar tools. In other words, this is a robotic system that simplifies and organizes the parking process.

These solutions require significant capital spending. The return on investment should come from parking fees. To maximize it, flexible pricing can be used:

- The pollution level. High pollution is an enormous challenge for lots of big cities, so authorities opt for modern technologies to encourage people to drive “greener” cars. Pollution-based fees is another way smart parking technology helps us to take care of the planet. The system checks the car’s year and engine, then calculates parking fees based on this information. As a result, the owners of hybrid and diesel vehicles pay a 20% lower price, while for electric cars it is completely free. This should encourage citizens to drive eco-friendly cars in the city area.
- The car’s length. Do you prefer bigger cars? You should be ready to pay more for their parking. This is a democratic way to support the owners of smaller cars, whose vehicles take less space. In other words, you pay not only for the time but also for the space occupied. And, of course, smaller cars are another eco-friendly option.
- The driver’s citizenship. If you live in this city, you pay taxes for its maintenance, including parking facilities, so citizens do not have to pay the same parking fees as tourists. Governors can create “residential parking” areas throughout the city to support taxpayers and help them in a constant battle for a parking spot with tourists.

Curb Management

In Las Vegas, Cox Communications[25] has entered a pilot partnership with the city to introduce its Cox2M curb management system to help manage downtown congestion. Curbside kiosks collect video data, making vehicle type and license plate information to

[25] Cox Communications. https://www.cox.com

kick off a countdown clock alerting drivers when they've spent too much time on a curb.[26]

Another project in Aspen, Colorado, established "smart zones" where delivery drivers use an app to book small delivery reservations. The technology, provided by Coord,[27] has made for a smoother orchestration of goods coming into the city's small downtown. In Aspen, 11 popular loading zones were converted to the new smart zones, which the city charges $2 per hour to use. Nearly 120 delivery drivers have signed up to use the zones. The move has ostensibly reduced congestion and double-parking.[28]

Other cities like Columbus, Ohio and Omaha, Nebraska, have also embarked upon curb management initiatives that use technology.

Equity

Transportation equity means accessible and affordable transportation for everyone in the community resulting in fair distribution of transportation resources, benefits, costs, programs and services based upon differences in income, ability and other factors affecting transportation choice and impact. In that respect, public transportation and mobility services for elderly and disabled are the pillars of equity. Public transportation was discussed in the previous section. We can add that the reachability and accessibility analysis, described in the section Transit Performance Assessment, should be combined with the Census data on income, number of cars per household, housing cost, education, unemployment, and the land use data characterizing job-rich areas. In this section we will focus on mobility options for the elderly and disabled.

Possible Future of Paratransit

Private companies that are managing health care are finding that the lack of access to transportation is costing them big money; therefore, they are looking for ways to improve this situation. Some are even investing substantial funding into coordinated transportation partnerships because the cost of fulfilling an evening trip to take a patient home from the hospital is a fraction of the cost of an additional night's stay. Additionally, the cost of missed appointments alone is in the billions of dollars, again prompting health care organizations to take more than a passing interest in how medically related transportation services are provided. They are beginning to seek out public transit as a

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[26] City of Las Vegas Launches Smart Curbside Management Corridor with Cox. Nevada Business, Mar. 2021. https://www.nevadabusiness.com/2021/03/city-of-las-vegas-launches-smart-curbside-management-corridor-with-cox

[27] Coord.com. Curb management for fast-changing cities. https://www.coord.com

[28] Coord.com. Smart Zones Deliver: Full Aspen Case Study. Coord Blog, Mar. 2021. https://www.coord.com/blog/aspen-smart-zone-case-study

partner to remedy this situation, and slowly but surely, we are beginning to see integration of paratransit with non-emergency medical transportation (NEMT) resources.

In Richmond, Virginia, the Greater Richmond Transit Company (GRTC)[29] has established one such arrangement in which a private-sector broker, RoundTrip,[30] was hired to integrate health care related transportation with ADA[31] paratransit. RoundTrip enables transportation for medical appointments to be arranged through third parties, which include health care organizations. RoundTrip in turn distributes the ensuing trips to various fleets which are inclusive of vehicles owned by the transit agency and others that are not. These are the seeds of coordination being planted, and the future of paratransit beckons us to continue in this direction to include referrals to services that are operated separately from the transit agency altogether. Meanwhile, GRTC built a highly successful bus rapid transit service, Pulse,[32] which has achieved national recognition for generating ridership increases as other agencies struggle to retain ridership.

Mobility on Demand (MoD) for Disabled Riders

MoD with wheelchair-accessible vehicles (WAVs) not only increases mobility options for individuals with disabilities, but also allows for better overall service delivery by freeing up resources and increasing productivity.

The expertise of transit providers assists clients in identifying areas that can benefit from microtransit services, design parameters of service delivery, choose appropriate technology tools, and develop successful marketing of new initiatives to increase public awareness.

In one successful example in Redding, California, First Transit[33] and Far Northern Regional Center (FNRC),[34] a nonprofit organization, worked together to improve access to jobs for individuals with disabilities. In 2018, First Transit began providing an on-demand program, Redi-Ride, for FNRC clients needing transportation to and from work or employment-related functions. As job opportunities increased for the community, the need for safe and reliable on-demand transportation quickly arose. The program now provides 600 rides per month, opening up opportunities for FNRC clients that did not previously exist.

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[29] Greater Richmond Transit Company.com. http://ridegrtc.com
[30] RoundTrip.com. https://roundtriphealth.com
[31] Americans with Disabilities Act: https://www.ada.gov
[32] GRTC Pulse: http://ridegrtc.com/brt
[33] FirstTransit.com. https://www.firsttransit.com
[34] FarNorthRegionalCenter.com. https://www.farnorthernrc.org

Digital Companion for Disabled Riders

Spatial mismatch is the mismatch between where low-income households reside and suitable job opportunities. Disabled people who can and want to work are dramatically affected by the spatial mismatch. Generally of lower income, these people have to compromise on choosing where to work or find an appropriate, and sustainable for them, means of transportation. For most of them, public transit, and occasionally paratransit, is the only way to get to and from work. The main pain points of the disabled travelers include the inability to get a door-to-door ride, long waiting and travel times, risk of ending up stranded away from home due to changing services or lack of after-hours service, and COVID-19 related safety concerns due to rising crime and rioting.

One way to help is to provide an app that would serve as a personalized digital companion to disabled travelers providing information about mobility options in trip planning, given travelers' circumstances. The goal is to build a working prototype system that would help generate a travel plan for a disabled person using available mobility options that include transit and paratransit but is not limited to those. In addition to the prototype, we will produce a concept design for the product that will describe how travelers and mobility services are added to the system and a path to deployment.

The core technology will be building a Knowledge Graph (KG) of disabled travelers with their needs, restrictions, preferences and points of interest (POIs); and mobility services including transit, paratransit and private companies such as Uber WAV with their schedules, coverage areas, cost, etc. As the KG grows, new relationships between existing entities may be discovered. A knowledge update engine will be a distinguishing feature of the system. A review-like function will be the core feature of the KG built on the semi-automatic collection of feedback, reviews and surveys. This will update user preferences. The information contained in the KG will be accessible through an API by a functional prototype user interface (UI).

Transportation Accessibility and Adoption of Shared Automated Vehicles (SAV) by Disabled Travelers

Automated vehicles (AVs) are one of the most significant technological advances to happen to our transportation systems - they are expected to save lives and provide enhanced mobility for all people. AV technologies also allow the emergence of novel business models such as shared automated vehicles (SAVs), which could provide more accessible on-demand mobility services and play a vital role in sustainable transportation. In particular, SAVs could be an attractive means to provide transportation access for those who cannot drive or face significant barriers to driving, including the elderly and people with disabilities.

Individuals with disabilities are a unique but sizable demographic in the United States. According to the 2018 disability status report, nearly 13% of the population has a disability. Unfortunately, many people with disabilities have limited transportation opportunities and adverse transportation experiences. We know that AVs have the

potential to transform personal mobility. Whether disabled travelers can benefit from this transformation depends on to what extent the accessibility is taken into consideration in the development and planning process of the deployment.

Research is needed to understand the transportation accessibility for people with disabilities, their future adoption of SAVs, and the potential change to their transportation mode choices. There is a knowledge gap in the literature that prevents us from understanding the specific transportation needs, preferences, and accessibility issues for these disadvantaged groups who could benefit from AV technologies' deployment. Therefore, to better understand this population's transportation needs and unique challenges, firstly, we need to carry out a thorough analysis of disabled travelers' transportation experience (particularly while using public transit and ride-hailing services). Research on user acceptance and interest in SAVs by the disabled population is also limited, so it is unknown what the key determinants would be for them to use SAVs. Therefore, we also need to investigate the technology acceptance of SAVs and what factors (e.g., safety, compatibility, trust, accessibility, and ease-to-use) will contribute to the intentions of using SAVs by disabled travelers.

Priorities of Cities and Transit Agencies - Survey

On numerous occasions during our conversations with representatives of various transit agencies we heard the notion that they were not lacking innovative ideas, and that when possible, were trying those out in pilot projects. Rarely, however, the implementation went beyond pilots - all due to the shortage of mainly operational budgets. This indicated the need for subsidies and a systematic view on things - namely, which projects could benefit multiple participating entities, as opposed just one particular agency.

To better understand the alignment of interest between cities and transit agencies, we conducted a survey about their priorities. The survey was targeted at three different groups of entities in the San Francisco Bay Area: 1) large cities; 2) small cities; and 3) transit agencies.

Each group was presented with a list of topic areas subdivided into individual topics. In each area the respondents had to choose 2 priority topics. And then, they selected the top 5 out of all chosen priority topics.

Next, we present the survey results. Topics in bold are the ones by the responders as their priorities. And those making it to the top 5 by the responders are indicated in blue. Essentially, in the lists below, bold font indicates interest in the topic, and blue color - readiness to dedicate resources.

The topics for large cities, including San Francisco, San Jose, Oakland and Concord, were specified and selected as follows:

- Congestion management
    - **Traffic monitoring and pattern analysis**
    - **Identifying major bottlenecks**
    - Intersection modification to improve efficiency
    - Signal timing optimization
    - Installation and maintenance of signal priority systems
    - Managing queue spillbacks at on-ramps
    - **Reducing traffic on certain streets**
    - **Area tolls**

- Safety management
    - Vision Zero site selection and design
    - **Vision Zero implementation**
    - **Vision Zero project assessment**
    - **Identifying hazardous hotspots**
    - **Intersection improvement through technology - smart signals, connected infrastructure**

- Public transportation
    - Improving transit accessibility - ensuring that certain parts of the city are properly serviced
    - **Bus Rapid Transit / Transit Signal Priority**
    - **Exclusive bus lanes / Bus on shoulder**
    - Public health & transit - social distancing, sanitizing, etc.
    - **Creating/ maintaining/ improving park & ride facilities**
    - Change/ increase/ reduce stop locations
    - **Mobility hub**
    - Transit connection protection
    - Dynamic personal micro-transit or personal rapid transit
    - Demand responsive transit

- Street parking and curbside management
    - **Monitoring curbside usage - pattern inference and violation hotspot identification**
    - Curb painting
    - **Technology for curb reservation and enforcement**
    - **Double parking detection and elimination**
    - **Smart parking technologies**

    - Identifying transportation network companies (TNCs) - Uber, Lyft, etc. - pick-up and drop-off locations

- Emergency preparedness
    - **Flood preparedness - identifying risk areas, sewage system improvement**
    - **Planning for power outage**
    - Inventory registry
    - **Evacuation planning**

- Other
    - **Maintenance and repair of roads**
    - **Reducing violent crime**
    - Reducing vandalism
    - Improving sanitary conditions
    - Waste management
    - Street cleaning
    - **Maintenance of parks and recreation areas**

The topics for small cities, including Brentwood, Campbell, Livermore, Orinda, Pleasant Hill, Pleasanton, San Leandro, San mateo, San Pablo, Union City and Walnut Creek, were specified and selected as follows:

- Congestion management
    - **Intersection modification to improve efficiency**
    - **Signal timing optimization**
    - **Installation and maintenance of signal priority systems**
    - Managing queue spillbacks at on-ramps
    - **Reducing traffic on certain streets**
    - **Reducing traffic through the city**

- Safety management
    - **Vision Zero site selection and design**
    - **Vision Zero implementation**
    - **Vision Zero project assessment**
    - **Identifying hazardous hotspots**
    - **Intersection improvement through technology - smart signals, connected infrastructure**

- Public transportation
    - **Improving transit accessibility - ensuring that certain parts of the city are properly serviced**

    - **Bus Rapid Transit / Transit Signal Priority**
    - Public health & transit - social distancing, sanitizing, etc.
    - **Creating/ maintaining/ improving park & ride facilities**
    - **Change/ increase/ reduce stop locations**
    - **Mobility hub**
    - Transit connection protection
    - Dynamic personal micro-transit or personal rapid transit
    - **Demand responsive transit**

- Street parking and curbside management
    - **Monitoring curbside usage - pattern inference and obstacle detection**
    - **Curb painting**
    - Technology for curb reservation and enforcement
    - Double parking detection and elimination
    - **Smart parking technologies**
    - Identifying transportation network companies (TNCs) - Uber, Lyft, etc. - pick-up and drop-off locations

- Emergency preparedness
    - **Flood preparedness - identifying risk areas, sewage system improvement**
    - **Planning for power outage**
    - **Inventory registry**
    - **Evacuation planning**

- Other
    - **Maintenance and repair of roads**
    - **Reducing violent crime**
    - **Reducing vandalism**
    - **Improving sanitary conditions**
    - Waste management
    - **Street cleaning**
    - **Maintenance of parks and recreation areas**

The topics for transit agencies, including AC Transit, County Connection, SFMT, Solano Transportation Authority, Tri-Delta and VTA, were specified and selected as follows:

- Operations efficiency
    - **Optimize (reduce) number of stops**
    - Deal with blocked lanes and bus stops
    - **Transit signal priority**
    - **Dedicated bus lanes**

    - Speed-up vehicle boarding - level boarding, lower vehicle floors
    - Connection protection
    - **Coordination with TNCs (Uber, Lyft, etc.) and micro-mobility providers**
    - Coordination with other transit agencies

- Operations safety
    - **Improving transit stop safety**
    - Improving safety at critical junctions - e.g., during intersection crossing
    - **Improving safety of vulnerable road users (VRU)**
    - **Monitoring driver behavior - drowsiness detection**
    - **Advanced driver assistance systems - collision warning, VRU detection, V2X technology**

- Fare collection
    - New payment methods
    - **New fare collection methods**
    - **New ways of fare calculation**

- Equity and environmental impact
    - **Improving paratransit operation**
    - Improving efficiency of eligibility check for special services, such as paratransit
    - **Transportation service(s) for disadvantaged populations - e.g., elderly and disabled**
    - **Improving transportation accessibility for communities of concern - door-to-door solutions, coordination with TNCs and micromobility providers**
    - Flex routes
    - **Monitoring emissions**
    - **Plan and build charging infrastructure**
    - Parking pricing based on vehicle emissions type
    - Area tolls based on vehicle emissions type

- Data collection and analysis
    - Making sure all vehicles report AVL
    - **GTFS reporting**
    - **GTFS-RT (real time) reporting**
    - **Improving performance measurement and tracking**
    - Improving APC collection
    - Improving APC quality
    - Reporting APC in real time

    - Improving inventory management
    - Monitoring equipment health

- Other
    - **Zero emission vehicles**
    - **Charging/hydrogen infrastructure**
    - Planning to use transit fleet in evacuations
    - **Public health - e.g., COVID-inspired measures**
    - **Vehicle automation - e.g., driverless technology**

Being transportation authorities in addition to just transit providers, SFMTA and VTA indicated several other topics they were focusing on:

- Demand management and methods of estimating the induced demand - induced by various factors, such as Vision Zero, pandemic, changes in transit operation.
- Improving safety of pedestrians and bicyclists in the context of overall encouragement of active transportation.
- Adding high quality transit to historically marginalized communities and expanding our fare programs better serve those in need. As part of this activity, riders' and drivers' safety in the context of their exposure to violent crime is being addressed.
- Parking management is also in the focus of these two agencies.

Conclusion

Both cities and transit agencies have common interests where they could work together. Specifically, this concerns congestion management, safety of vulnerable road users, transit reachability and infrastructure for clean air vehicles. The synergies are summarized below.

Congestion Management

Transit providers desire travel time reliability, so they can maintain their schedules. Therefore, they would love to get rid of congestion, which makes travel time less predictable. Cities are also interested in removing or reducing congestion. Therefore, they need to know the locations of bottlenecks and their causes, but they cannot afford ubiquitous detection or CCTV cameras to monitor traffic and parking situations. Transit buses equipped with dash cameras can provide regular monitoring of city streets along transit routes.This kind of data would help with identifying parking violations, double parking hotspots, dedicated bus lane violations, as well as causes of some bottlenecks.

Safety

Intersections present a very demanding environment for all the parties involved. Challenges arise from complex vehicle trajectories; occasional absence of lane markings to guide vehicles; split phases that prevent determining who has the right of way; invisible vehicle approaches; illegal movements; simultaneous interactions among pedestrians, bicycles and vehicles. The safety of vulnerable road users (VRU) can be improved by investing into connected sensing infrastructure at intersections where it makes most sense. On bus routes the deployment of such an infrastructure should go hand-in-hand with BRT and signal priority.

Transit Reachability

To ensure the sustainability of the transportation system in terms of congestion, environmental impact and equity, one of Caltrans' priorities is to encourage travel mode shift – from private cars to public transit. This can be achieved once public transit presents a competitive alternative to private vehicles in terms of accessibility (should be close by, easy to use and affordable) and reachability – that is, the desired destination should be reachable within reasonable time from the moment one wants to start their journey.

Transit agencies do not address this problem. Their main performance metric is ridership. Based on this metric, they optimize their routes and schedules. Many of them also consider accessibility an important factor. Reachability, however, cannot even be assessed by an individual agency. It requires an approach on the level of a **regional transit system**. Reachability should be an important factor in determining locations for mobility hubs.

Charging and Hydrogen Infrastructure

Current charging and hydrogen infrastructure in California is not sufficient for the projected growth of clean-air transportation, and it needs significant expansion. 2. The Administration's Justice40 Initiative directs at least 40% of the overall benefits of Infrastructure Investment and Jobs Act (IIJA) investments flowing to disadvantaged communities. To ensure an equitable deployment of clean-air infrastructure, the corresponding portion of new chargers must serve disadvantaged communities. It would be wise for transit agencies and cities to coordinate the build-out of the charging infrastructure based on the assessment of which communities would benefit most from this expansion.