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A Cognitive Framework to Plan for the Future of Transportation

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Abstract

Automated, connected, electrified, and shared mobility will be cornerstones of the transportation future. Research to quantify the potential benefits and drawbacks of practice, and to identify barriers to adoption is the first step in any strategic plan for their adoption. However, uncertainties, complexity, interdependence, and the multidisciplinary nature of emerging transportation technologies make it difficult to organize and identify focused research. The contribution of this work is a cognitive framework to help planners and policy-makers organize broad topics, reveal challenges, discover ideas for solutions, quantify potential impacts, and identify implications to guide preparation strategies. The authors provide example cognitive frameworks for connected, automated, and electrified vehicles.

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1.0 Introduction

Recent advancements in automated, connected, electrified, and shared (ACES) mobility have spurred a mix of excitement and concern about the future of transportation (NGA, 2018). As of 2018, more than 40 companies worldwide have collectively invested more than $80 billion to develop and launch ACES vehicles and related mobility services (Shaheen, Totte, & Stocker, 2018). Most of the companies stated that by 2021, they expect to be selling vehicles that do not require a human driver (Liljamo, Liimatainen, & Pöllänen, 2018). Industry dominant companies such as General Motors, Waymo, Uber, and Baidu have been conducting high profile testing on public roads (Perkins, Dupuis, & Rainwater, 2018). Nevertheless, the timing of adoption remains uncertain (Akar & Erhardt, 2018). One forecasting model indicated that, depending on the assumptions, the penetration levels for self-driving vehicles could be between 25% and 87% by the year 2045 (Bansal & Kockelman, 2017). Another study found that the penetration level could be near 100% by 2050 if the annual price reduction is 15% to 20% (Talebian & Mishra, 2018).

Although most transportation agencies acknowledge that ACES will be in their near future, many are unprepared for their deployments. Budget shortfalls are among the factors that hinder preparation actions and strategies (Zmud, Goodin, Moran, Kalra, & Thorn, 2017). Furthermore, without having a significant proportion of autonomous vehicles in the traffic mix yet, it is difficult to predict impacts on society. Consequently, uncertainties about the anticipated benefits, concerns about their safety, and doubts about their readiness result in a wait-and-see disposition (NAS, 2017). Subsequently, research about new challenges, opportunities, and policy needs lags (Fagnant & Kockelman, 2015).

The level of potential benefits and possible drawbacks of new transportation technologies depend on the setting (for example rural, suburban, or urban), demographics, and regional weather cycles. There are more than 90,000 state and local governments in the United States alone (Barnett, Sheckells, Peterson, & Tydings, 2014). That is, the capabilities and resources needed to strategically plan for adoption can vary widely among jurisdictions of a country, and across nations. These differences suggest that there will be no unique planning strategy to fit the needs of all situations (NLC, 2017). With growing evidence of impending deployments, the demand for guidance on both general and specific preparation strategies has been accelerating. This demand spurred a set of National Cooperative Highway Research Program (NCHRP) research projects in 2018 to survey agency needs and inform preparation strategies (NCHRP, 2018).

Research to assess the present situation is the first step in an effective strategic plan, but knowing where to start in an arena of high uncertainty can be daunting. There is lack of guidance in the current literature about a systematic method to identify and organize research in this vast multidisciplinary area to yield jurisdiction-specific recommendations. Such capabilities require local expertise with interdisciplinary backgrounds in all disciplines of engineering (for example electrical, mechanical, civil, and environmental), computer science, data science, economics, social science, and policy-making, just to name a few. Concurrently, rapid changes in the pace of technology evolution, performance, costs, market attitudes, application developments, and deployment variations quickly outdate the relevance of current findings. Uncertainties about performance in different situations, and the variety of assumptions made have led to large variations in research outcomes, for example, those about impacts on traffic (Zhang, Guhathakurta, & Khalil, 2018). Therefore, a cognitive framework to help planners and practitioners organize topics for research will be helpful. Previous work found that similar frameworks have been successful as a workshop tool because they can open up discussion around varying characteristics, help planners think more broadly, and provide a structured and coherent process for recording outcomes (Chatterton & Wilson, 2014).

The goal of this paper is to share the development of a cognitive framework that can help researchers and agencies organize time-sensitive topics, reveal challenges, bring out ideas for solutions, quantify potential impacts, and identify actions needed to plan strategically for practice. The main contribution of this paper is a systematic method of constructing cognitive frameworks that help tailor topics to the unique needs of a jurisdiction. Constructing a cognitive framework for one of the major technology trends requires three important steps. The first is to identify key enabling technologies and their derivative applications. The second is to map the technologies and applications to potential transportation benefit areas. The third is to map the technologies and applications to action areas that target the enhancement of identified benefits and the removal of barriers to adoption.

The authors contribute general frameworks for connected, automated, and electrified vehicles that researchers can expand or refine. Transportation agencies can use each framework and the general examples to identify and quantify potential benefits that are unique to their jurisdiction. Researchers and agencies can use the framework to identify specific needs in planning, engineering, policy-making, and standardization. In practice, educators, planners, engineers, and policy-makers can use the framework to identify related training materials, outreach materials, and other opportunities to help agencies plan strategically for adoption.

The organization of the remainder of this paper is as follows: Section 2 uses the three steps described earlier to create the general framework. Section 3 draws from the literature the potential benefits quantified and classifies them as *push* or *pull* factors in adoption. Similarly, section 3 classifies the potential drawbacks or concerns as *impedance* factors in adoption.

Section 4 populates frameworks for connected vehicles, automated vehicles, and electrified vehicles with research areas to quantify the push or pull factors, identify specific actions that jurisdictions could consider to enhance the push and pull factors, and to minimize the impedance factors identified. Section 5 contemplates impacts and implications from some of the suggested research areas, and illustrates the utility of the framework by highlighting planning actions and policies implicated for infrastructure adaptation. Section 6 offers some consideration for generalizing the framework to research the adoption of other future transportation technologies such as flying taxis and Hyperloops.

2.0 Methods

As shown in Fig. 1, the general cognitive framework organizes topics within a two-dimensional matrix. The row and column labels intersect cells to identify potential impacts on anticipated benefits and implications for actions needed to remove impedances to adoption. Subsequently, the lists of potential impacts and implications suggest multidisciplinary research areas to quantify the factors that affect adoption. The row labels are enabling technologies and derived applications. The matrix has two column sections. The labels of the first and second column sections are the potential benefit areas and the action areas, respectively.

The following four classifications help to define the specific row and column labels of cognitive frameworks for each major technology trend:

1. Enabling technologies and applications within a major technology trend
2. Anticipated or perceived transportation benefit areas
3. Key action areas that can influence potential benefits and impedances
4. Factors in adoption

The next subsections propose the four classifications for each of three major technology areas.

2.1 Enabling Technologies and Applications

Some of the important technologies that connected vehicles enable or relevant application areas are real-time travel advisory, active traffic management, pre-clearance systems, smart parking, platooning, the Internet-of-Things, data science, and remote sensing. For automated vehicles, important technologies or applications are the various levels of automation, operational characteristics, and shared mobility. For vehicle electrification, important technologies or applications are the types of vehicles and the types of charging facilities.

2.2 Potential Benefit Areas

The recognized benefit areas for all types of transportation technologies are safety, mobility, accessibility, and the environment (USDOT, 2015). Safety benefits involve the potential to reduce crashes, prevent injuries and fatalities, and avoid property damage in all modes of transportation. Mobility benefits are reductions in travel delay, travel time reliability, congestion mitigation, and efficiency gains in moving people and freight. Mobility benefits also involve solutions that maintain the multimodal transportation infrastructure in good condition. Accessibility benefits involve solutions that provide affordable and equitable transportation options for everyone. In particular, ACES promotes accessibility for the mobility disadvantaged such the disabled, the young, and the aged. Environmental benefits include the creation of green spaces for pedestrians, reduced energy consumption, and the elimination of unhealthy emissions.

2.3 Action Areas

The action areas implicate needed activities by governments, organizations, and professionals to realize the identified benefits and remove barriers to adoption. Action areas proposed in the example frameworks are planning, engineering, policy-making, and standardization. Planners need to identify implications of the technology deployment so that they can propose short- and long-term strategies to encourage adoption. Engineering involves the creation of new infrastructure elements or the removal of existing elements to better accommodate a transition to the new technologies. Policy-makers need to identify and modify existing laws or regulations that impede attainment of the anticipated benefits or that adversely affect technology adoption. Policy-makers can use the framework to identify new laws that the impending technologies will require for adoption and use. Standardization bodies can identify and create new standards that will facilitate the interoperability, scaling, and cost reduction of the new technologies.

2.4 Adoption Factors

The cells within the first column section of the framework identify potential impacts within the anticipated benefit areas and suggest multidisciplinary research areas to identify and quantify potential benefits or drawbacks of the enabling technology. The cells of the second column section of the framework implicate actions needed to remove impedances to adoption, and suggest multidisciplinary research areas to define actions needed to realize the potential benefits, mitigate potential drawbacks, and remove possible impedances to adoption.

Either or both the technology provider and members of society can reap benefits or experience drawbacks from the technology deployments. To organize the forces affecting adoption rates, it is helpful to classify the adoption factors into *push*, *pull*, and *impedance* categories. Fig. 2 illustrates how the net force from push, pull, and impedance factors can quantify the rate of adoption. In this scenario, the bottom and the top of the hill that the sled is traversing represents zero and full adoption levels, respectively. This visualization suggests that the sum of forces from push and pull factors can potentially overcome impedances to move the sled (technology) forward to full adoption levels.

Push factors generally arise from the potential to attain business benefits such as revenue generation, efficiency enhancements, risk reduction, and external investments. Companies push new technologies to create new markets, grow existing market shares, and expand their business scope. New products that reduce manufacturing costs, diminish risks, and perform better can enhance business efficiencies. Quantifying these factors requires research to interpret evidence of investment levels, procurement activities, and anticipated business gains.

Pull factors generally arise from the anticipated or perceived benefits of adopting new technologies. Benefits of new transportation technology could be safety enhancements through crash avoidance, greater mobility through congestion mitigation, improved accessibility for all population demographics, environmental stewardship through pollution reduction, and reduced cost of mobility services. Quantifying these factors involves research to understand impacts on traffic safety, infrastructure capacity, net emissions, and costs.

Impedance factors generally arise from fear of the new, uncertainty about potential impacts or implications, doubt about advertised benefits, and new resources needed to accommodate deployments. Lack of activities in the implicated action areas can strengthen impedances to adoption. The general cognitive framework shown in Fig. 1 does not show the last column for standards development. The final procedure to populate the cognitive framework involves two steps:

1. Identify *push* and *pull* factors of adoption at the intersection of the enabling technologies or applications and the potential benefit areas, and define research areas to quantify those factors.
2. Identify *impedance* factors at the intersection of enabling technologies or applications and the action areas to define actions needed to realize the potential benefits, mitigate the potential drawbacks, and to remove the impedances to adoption.

3.0 Data

This section extracts some data from the literature to provide initial examples of research that quantified push, pull, and impedance factors. For future econometric analysis, all factors can translate into monetary values. Depending on the source of the technology development, the levels of push factors were different among countries. Similarly, the intensity of pull factors could differ among jurisdictions. Academic publications that quantify push factors in terms of investment levels are generally scarce and outdated. Therefore, some investment and adoption level data comes from projections scattered among research reports from various commercial consulting and technology adoption-forecasting firms that cater to the investment community.

3.1 Safety Benefits

According to the Association for Safe International Road Travel (ASIRT), nearly 1.3 million people die each year in road crashes (ASIRT, 2018). Analysts anticipate that at full adoption, connected and autonomous vehicles (CAVs) could potentially eliminate more than 94% of crashes that are due to human errors (USDOT, 2015). Fewer crashes will also eliminate incident-induced congestion. Subsequently, an increasing number of cities are pulling for CAV adoption as part of their “vision zero” initiative to eliminate highway deaths (GAO, 2017). Although most of the adoption factors in safety are pull types, there are some push types such as savings from the reduction of liability and insurance costs.

3.2 Mobility Benefits

With scarce room to build more transportation infrastructure, urbanization and population growth will worsen congestion in cities (UN, 2018). Therefore, cities are pulling for solutions to mitigate congestion without requiring significant resources or room for infrastructure expansion. A 2018 California Department of Transportation-sponsored study suggests that the price reduction of automated vehicle (AV) technologies will encourage greater private ownership and subsequently generate more vehicle miles travelled (VMT) per capita (Gordon, Kaplan, Zarwi, Walker, & Zilberman, 2018). However, other studies found that VMT would actually decline because the projected expansion of shared mobility services will move more people in fewer vehicles (Arbib & Seba, 2017). It is evident that generalized assumptions may not account for the unique situations within different jurisdictions, and research can result in contradicting outcomes.

CAVs can eliminate the need for traffic signals by coordinating vehicle speeds and flows through intersections (Tonguz, 2018). One experiment demonstrated that just a single AV in the traffic stream could dampen traffic waves (Stern, et al., 2018). Another study found that CAVs could potentially increase throughput by more than 25% (Moavenzadeh & Lang, 2018). Various studies suggest that CAVs can increase throughput and reduce fuel consumption by forming platoons (Boysen, Briskorn, & Schwerdfeger, 2018). Early adopters in the trucking sector will likely push for platooning because of the potential for substantial cost reduction and gains in operational efficiencies. The trucking industry forecasts that their freight movements will increase 42% by 2040 (Boris & Murray, 2018). Industry research quantified the push factor for autonomous trucks at $168 billion in annual savings (Morgan Stanley, 2013). A McKinsey study quantified a push factor of business expansion whereby AVs will make up 85% of last-mile deliveries by 2025 (Joerss, Schröder, Neuhaus, Klink, & Mann, 2016). Such deliveries will include small packages, food, and medicine.

3.3 Accessibility Benefits

The general findings are that, in addition to providing public transportation services, CAVs will become a vessel for digital service provisioning and consumption. Hence, technology and service providers are pushing to gain early shares of the growing market for in-vehicle digital services such as entertainment, social media, education, and online shopping. Companies can tap a market of tens of millions of Americans who are unable, unwilling, or prohibited from driving because of age, medical conditions, or other reasons (USDOT, 2018).

An ability to eliminate the cost of a human driver will enable traditional vehicle manufacturers to encroach on the mature and lucrative ride-sharing market. The rapidly growing demand for shared mobility services has lured both information technology giants (for example Waymo and Baidu) and traditional vehicle manufacturers (for example GM and Ford) into developing new autonomous fleet services that transport passengers, food, packages, and freight. The evidence of push factors is that companies have invested more than $100 billion from 2014 to 2018 in relevant technology developments (Kerry & Karsten, 2017). By 2040, manufacturers expect to sell 33 million highly and fully automated vehicles worldwide (NGA, 2018).

A study commissioned by Intel Corporation found that autonomous driving technology will enable a new “passenger economy” worth $7 trillion in 2050 (Lanctot, 2017). For perspective, that amount is more than the combined 2017 gross domestic product (GDP) of Japan and Brazil. A Bloomberg research forecasts that three-fourths of new cars sold in 2023 will come with cellular connections (Moritz & Coppola, 2018). A study from Victoria Transport Policy Institute (VTPI) found that trip cost with shared AVs would be an order of magnitude lower than that of a human-driven taxi (Litman, 2017). The cost reduction and enhanced convenience of ride sharing can result in more trips completed with fewer vehicles, and subsequently a reduced demand for parking spaces (Sperling, 2018). A recent study estimated that 15% of the traffic in Stuttgart was cruising for parking (Hampshire & Shoup, 2018). Early adopters are currently deploying autonomous micro-transit to shuttle people across the campuses of retirement communities, colleges and universities, and large corporations (Nasser, Brewer, Najm, & Cregger, 2018).

3.4 Environmental Benefits

According to the International Energy Agency (IEA), 125 million electric vehicles (EVs) will be on the road by 2030 (IEA, 2018). This push hinges on the perceived demand for EVs, proven cost reduction in manufacturing, and financial incentives towards environmental stewardship. Cities pull for electric trucks and buses because of the expected reduction in harmful emissions. A Bloomberg study estimates that by 2025, those push and pull factors will result in the electrification of half of the buses in the world (Chediak, 2018). Subsequently, many cities are ramping up deployments of battery charging facilities to accommodate all types of vehicles (Litman, 2017).

3.5 Impedance Factors

This section introduces a limited number of impedance factors. They include infrastructure incompatibilities, potential traffic interference from behavioural differences between human and robotic drivers, uncertainties about liability in a crash, privacy concerns about corporate access to personal data, cybersecurity implications, and general consumer discomfort about interacting with new or advanced technologies.

3.5.1 Incompatible Infrastructure

AVs use a variety of sensors to determine their positions on the road by identifying pavement markings, guardrails, medians, and other elements of the infrastructure. Even within a state, pavement markings differ in reflectivity and spacing. Worn, poorly removed, or missing markings could challenge the safety and efficiency of AV operation. Potholes increase navigational challenges. One study suggests that AVs will accelerate damage to the road infrastructure because of changed behaviours such as wheel wandering and traffic speed (Chen, Balieu, & Kringos, 2016). However, many jurisdictions cannot afford to keep up with such infrastructure repair needs (USDOT, 2015). Even so, the demands for infrastructure modernization will tax already limited resources. For example, the installation of additional roadside equipment and sensors may be necessary to leverage the full capabilities of CAV technologies. These potential issues have implications for planning, engineering, and policy-making with regard to improving the frequency and affordability of roadway condition monitoring and repairs.

3.5.2 Interference and Co-existence

In the early stages of deployments, CAVs will need to co-exist with other people and things on the road that are not connected. Examples include pedestrians, bicyclists, motorcyclists, and wildlife. Predicting the movements of pedestrians and wildlife can be challenging even for humans. CAVs must also be able to identify obstacles such as wind-blown objects, tree shadows, and debris on the roadway. This implicates actions in engineering and standardization to prepare CAVs for such situations.

3.5.3 Insurance and Liability

CAVs consist of materials that are subject to wear and tear. Snow, fog, dust, dirt, and electro-magnetic interference can hamper the operational safety of CAVs. Therefore, adverse weather conditions can result in property damage and fatalities. Hackers will likely attempt to disable or take control of a CAV. Failures due to blocked sensors or damaged tires will require intervention. Therefore, the need for insurance will continue. A Harvard Business Review study suggests that insurance liability will shift away from individual owners and toward vehicle or mobility service providers (Cusano & Costonis, 2017). This implicates policy-making to ensure that travelers have proper coverage and protection.

3.5.4 Privacy

An ability to capitalize on the digital marketplace of CAVs relies heavily on the mining of data about riders and their activities. Companies will have the ability to track the origin and destination patterns of every rider. The frequency of high profile data breaches has generated concerns about the possible misuse of tracking data (Li, Lu, Misic, & Mahmoud, 2018). These concerns implicate policy-making and standardization to protect users.

3.5.5 Security

CAVs rely on a plethora of connected sensors and actuators to operate. Sensors such as LiDARs are vulnerable to interference and spoofing (Shin, Kim, Kwon, & Kim, 2017). Cyber-attackers can gain access to the wireless networks of CAVs and control their behaviour (Bonilla, Parra, & Forero, 2018). These issues implicate a need for cybersecurity standards and related policy-making to deter those types of threats.

3.5.6 Consumer Discomfort

There is evidence that high profile crashes have increased public fear about AVs (Kortum & Norman, 2018). Most surveys conducted around the world found that a majority of the respondents are not willing to ride in an automated vehicle without a human driver (Liljamo, Liimatainen, & Pöllänen, 2018). Traffic safety and ethical considerations were the biggest concerns (Liljamo, Liimatainen, & Pöllänen, 2018). Subsequently, many cities hesitate to invest in adoption planning because of the general lack of private-sector interest, low trust in radically new technologies, and uncertainties about their readiness for deployment on public roads.

4.0 Results

This section completes the four classifications to develop individual frameworks for the three major technology trends of connected, automated, and electrified vehicles. Although a separate framework for shared mobility can capture independent research areas, the authors define it as an enabled application within the automated vehicle framework. This approach unmasks possible interdependencies and synergies from removing the human driver.

4.1 Cognitive framework for Vehicle Connectivity

Fig. 3 shows an example framework to identify impacts and implications from connected vehicle deployments. The enabling technologies classified in this example are real-time travel advisory, active traffic management, pre-clearance systems, smart parking, platooning, internet-of-things (IoT), big data, and remote sensing. Researchers can expand the framework by identifying additional enabling technologies and applications.

In this framework, the term “accessibility” has broad meaning. It can relate to the ease of accessing a vehicle from a particular location, or the complexities of human interaction with systems inside a vehicle. It can also relate to the ability to use the enabled applications in certain locations. For example, when forming truck platoons, there may be some exceptions because of traffic restrictions in business districts, or weight restrictions at roadway sections such as weak bridges.

4.2 Cognitive framework for Vehicle Automation

Fig. 4 is an example framework to identify impacts and implications from automated vehicle deployments. The enabling technologies in this example are the levels of vehicle automation, robotic mobility systems that users can share, and the operating characteristics that can evolve over time. As an example, researchers can study the sensitivity of vehicle load efficiency on congestion within their jurisdiction. As another example, researchers can assess the technology readiness by simulating or testing performance in snow, flood, and fog.

4.3 Cognitive framework for Vehicle Electrification

Fig. 5 shows an example framework to identify impacts and implications from electric vehicle deployments. The enabling technologies classified in this example are the types of vehicles and charging facilities. As an example, researchers can quantify the potential benefits of electric trucks in the area of safety and mobility. Such studies can seek to measure the power consumption profile in different situations, and the effects on battery range.

5.0 Discussion

This section focuses on the highlighted research areas (black boxes) to illustrate further the utility of the framework. The highlighted areas are planning actions implicated for infrastructure adaptation. The cognitive framework for **connected** vehicles identified planning considerations to modify lane use, intersections, ramp meter positions, toll gantry location or their elimination, site selection for preclearance systems, the location of smart parking facilities, and other factors that can affect land-use planning. Heavy snow, flooding, dust, and other environmental conditions that lead to poor road conditions can diminish the performance of vehicle cameras, LiDAR, radar, and ultrasonic sensors. This implicates planning to install sensors that can guide automated vehicles when dust, fog, or precipitation compromises the visibility of road markings and guardrails. Roadside or embedded pavement sensors could detect vehicle position and report any issues such as stalling due to a mechanical failure, tire damage, or computer failure. Data from infrastructure and vehicular sensors can enable the prediction of traffic flows and improve adaptive traffic controls.

The cognitive framework for **automated** vehicles implicates planning to modify lane use for conflict reduction with human drivers, to accommodate an optimum distribution of recharging stations, to dedicate spots for shared mobility pick-up/drop-off, and to accommodate sensors in places where they can be most effective. Creating AV-only lanes too soon in the adoption cycle can waste capacity. However, capacity can increase in the long term if AVs do not require shoulders, medians, and wide lanes to operate at peak performance. If research for a particular jurisdiction finds that shared AVs will move more people in fewer vehicles, then their need for parking could decline. Such an outcome will implicate planning to eliminate and repurpose street parking, parking lots, and parking structures. CAVs can drive themselves to parking facilities that are further away from the urban centre (Liu, 2018). Research found that reserving space for opening doors and human manoeuvrability is unnecessary, so the space required for parking can decrease by an average of 62% (Nourinejad, Bahrami, & Roorda, 2018). The availability of automated dispatching for shared mobility vehicles implies that dedicating spaces for pick-up/drop-off can improve their navigational accuracy and remove conflicts with adjacent traffic flows.

The cognitive framework for vehicle **electrification** implicates planning to meet the different requirements for cars, buses, and trucks by optimally distributing the appropriate type of charging stations. For example, cars could use standard wireless charging pads in parking spaces whereas trucks and buses will require fast chargers along their routes to charge batteries while they move. Several countries have been experimenting with solar roads because of the order of magnitude price drop for solar panels (Samuel, Razak, Prabhu, Shaheem, & Jerath, 2018). This implicates planning to assess the potential for deploying solar roads in jurisdictions that could best accommodate them.

6.0 Conclusions

Planning strategically for the future of transportation is difficult because of the uncertainties involved. Preparation strategies will require additional resources to retrain the workforce, plan new initiatives to spur adoption, enact policies to remove impedances, and develop new standards to enable interoperability and scalability. Furthermore, the major transportation technology trends of vehicle automation, connectivity, electrification, and sharing (ACES) bring new challenges. Understanding the major trends require baseline knowledge about many topics that are complex, interrelated, and multi-disciplinary. Therefore, to identify strategies and orchestrate plans for action, organizations need to acquire professionals with interdisciplinary talents. These individuals are rare and expensive.

Technology suppliers generally guard their proprietary and confidential data. Hence, very little information is available to the academic community for researching potential impacts. Scenario simulations can result in conflicting outcomes because of differences in the underlying assumptions. Even so, assumptions must change as the technology evolves, converges, operates more robustly, and becomes more affordable. Hype and press releases about impending deployments introduce further scepticism and doubt. Altogether, these challenges impede preparation strategies for the future of transportation.

Research is the first step in identifying preparation strategies and actions needed to accommodate adoption. However, the topics are complex, multidisciplinary, interrelated, and vast. This makes it difficult to identify focused research to understand potential changes in impacts and implications as the technologies mature and spur new applications. Hence, this paper shares a general method for systematically constructing cognitive frameworks to help identify and organize focused research to determine potential jurisdictional-specific impacts and implications of emerging transportation technologies. Frameworks for each major technology trend classify enabling technologies and their derivative applications to form the row labels. The example frameworks provide a starting point for researchers to expand on. The first column section promotes research ideas to identify and quantify push and pull factors of adoption based on the anticipated benefits within areas of safety, mobility, accessibility, and the environment. The second column section promotes research ideas to identify potential drawbacks to deployment or barriers to adoption, and to identify actions needed by planners, engineers, policy-makers, and standards bodies to mitigate negative impacts.

After populating the framework, researchers can gain a better understanding about the state of the technology and their potential deployment horizons. The needed actions identified, based on the potential for jurisdiction- or industry-specific benefits, will support cost estimates, justifications, and plans for preparation. A limitation of this work is the lack of rigour in quantifying push, pull, and impedance factors. The framework provides a starting point for identifying broad research areas and actions needed to spur adoption and remove impedances. Therefore, future work will integrate the framework with quantitative methods to evaluate the net forces that are driving adoption, and to link the result to a suitable diffusion model of adoption.

7.0 Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

8.0 Authors' Contribution

R Bridgelall: Literature search and review, manuscript writing, and editing; DD Tolliver: Content planning.

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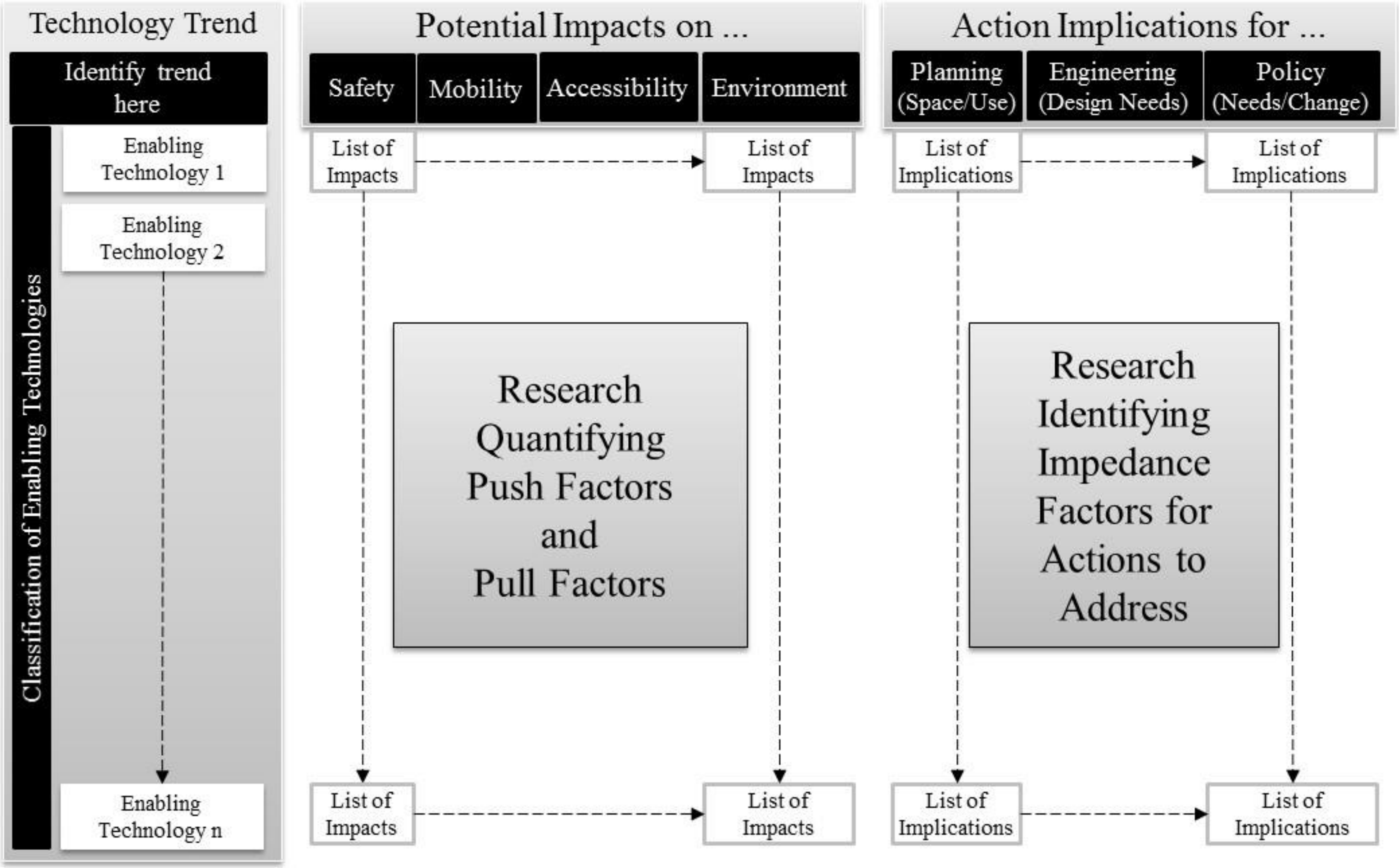
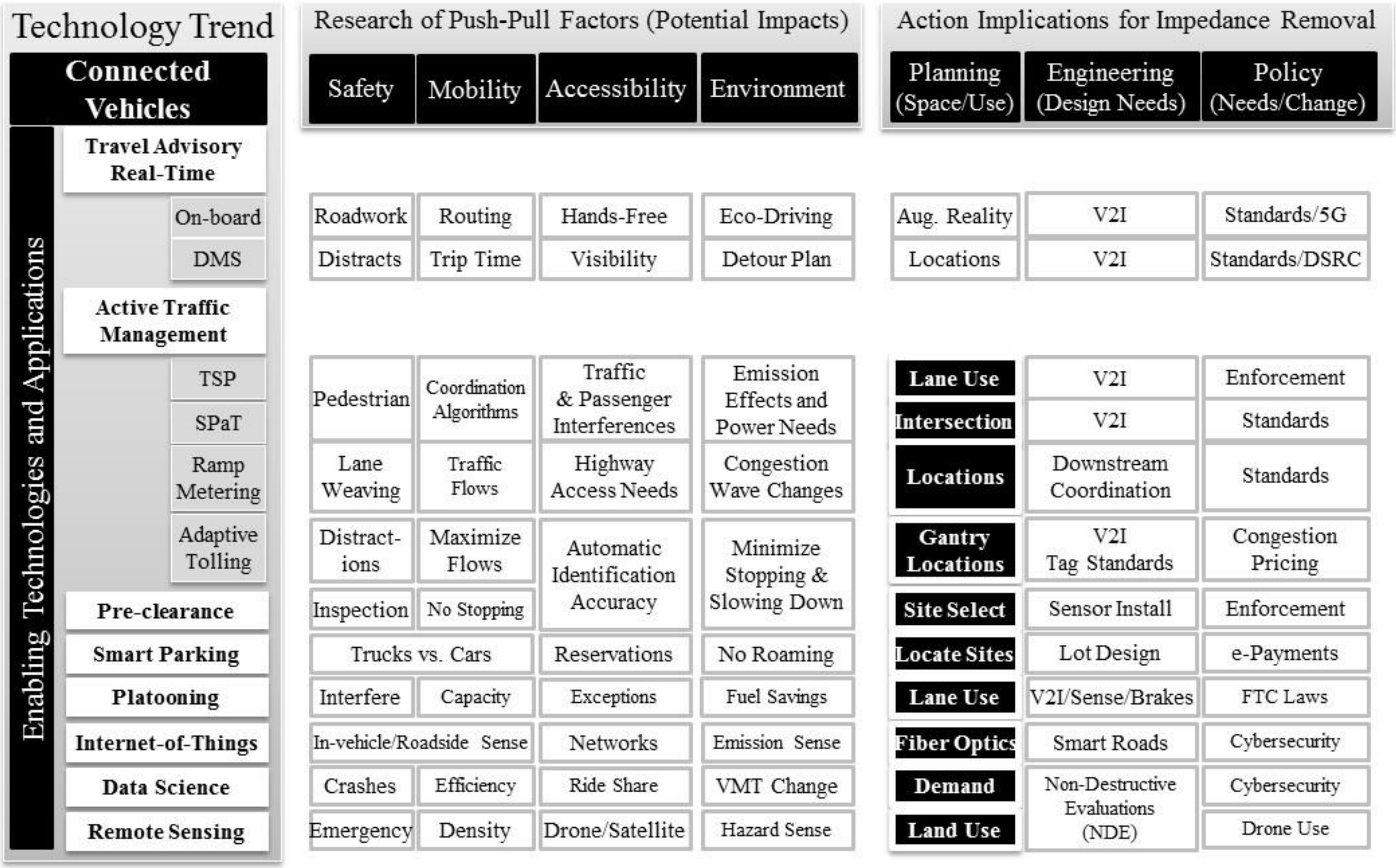


Fig. 1 General cognitive framework

Push Factors	Pull Factors	Impedance Factors
• **Revenue generation** from new markets, new products, and business expansion. • **Efficiency enhancements** of business operations. • **Risk reduction** from product liability and shareholder losses. • **Investments** (entrepreneurs, military).	• **Safety** enhancement by crash avoidance. • **Mobility** enhancement by mitigating congestion. • **Accessibility** for everyone. • **Environment** benefits through clean fuels, and redesigning for people. • **Cost** reduction.	• **Fear** of change/new, loss of jobs, loss of revenue (parking, gas, fines, etc.), hacking. • **Uncertainty** about liability, safety, security, legality, registration, privacy, and network reliability leads to lack of policies. • **Doubt** about benefits hype. • **Cost** increment and effort needed to change.

Fig. 2 Classification of factors in technology adoption



Technology Trend		Research of Push-Pull Factors (Potential Impacts)				Action Implications for Impedance Removal		
Connected Vehicles		Safety	Mobility	Accessibility	Environment	Planning (Space/Use)	Engineering (Design Needs)	Policy (Needs/Change)
Enabling Technologies and Applications	Travel Advisory Real-Time							
	On-board	Roadwork	Routing	Hands-Free	Eco-Driving	Aug. Reality	V2I	Standards/5G
	DMS	Distracts	Trip Time	Visibility	Detour Plan	Locations	V2I	Standards/DSRC
	Active Traffic Management							
	TSP	Pedestrian	Coordination Algorithms	Traffic & Passenger Interferences	Emission Effects and Power Needs	Lane Use	V2I	Enforcement
	SPaT					Intersection	V2I	Standards
	Ramp Metering	Lane Weaving	Traffic Flows	Highway Access Needs	Congestion Wave Changes	Locations	Downstream Coordination	Standards
	Adaptive Tolling	Distract-ions	Maximize Flows	Automatic Identification Accuracy	Minimize Stopping & Slowing Down	Gantry Locations	V2I Tag Standards	Congestion Pricing
	Pre-clearance	Inspection	No Stopping			Site Select	Sensor Install	Enforcement
	Smart Parking	Trucks vs. Cars		Reservations	No Roaming	Locate Sites	Lot Design	e-Payments
	Platooning	Interfere	Capacity	Exceptions	Fuel Savings	Lane Use	V2I/Sense/Brakes	FTC Laws
	Internet-of-Things	In-vehicle/Roadside Sense		Networks	Emission Sense	Fiber Optics	Smart Roads	Cybersecurity
	Data Science	Crashes	Efficiency	Ride Share	VMT Change	Demand	Non-Destructive Evaluations (NDE)	Cybersecurity
	Remote Sensing	Emergency	Density	Drone/Satellite	Hazard Sense	Land Use		Drone Use

Fig 3. Cognitive framework focused on connected vehicle topics highlighting infrastructure adaptation

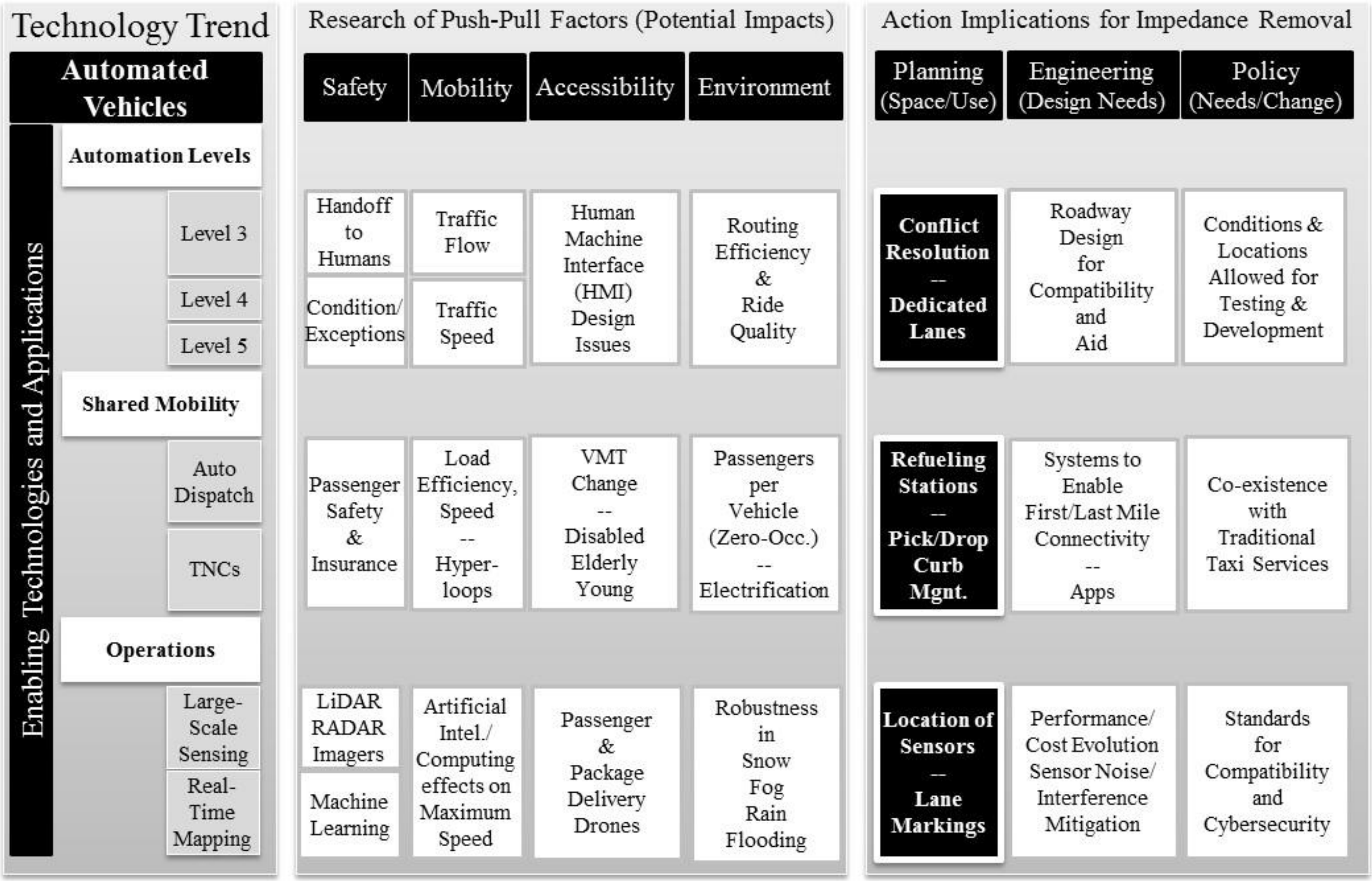


Fig. 4 Cognitive framework focused on automated vehicle topics highlighting infrastructure adaptation

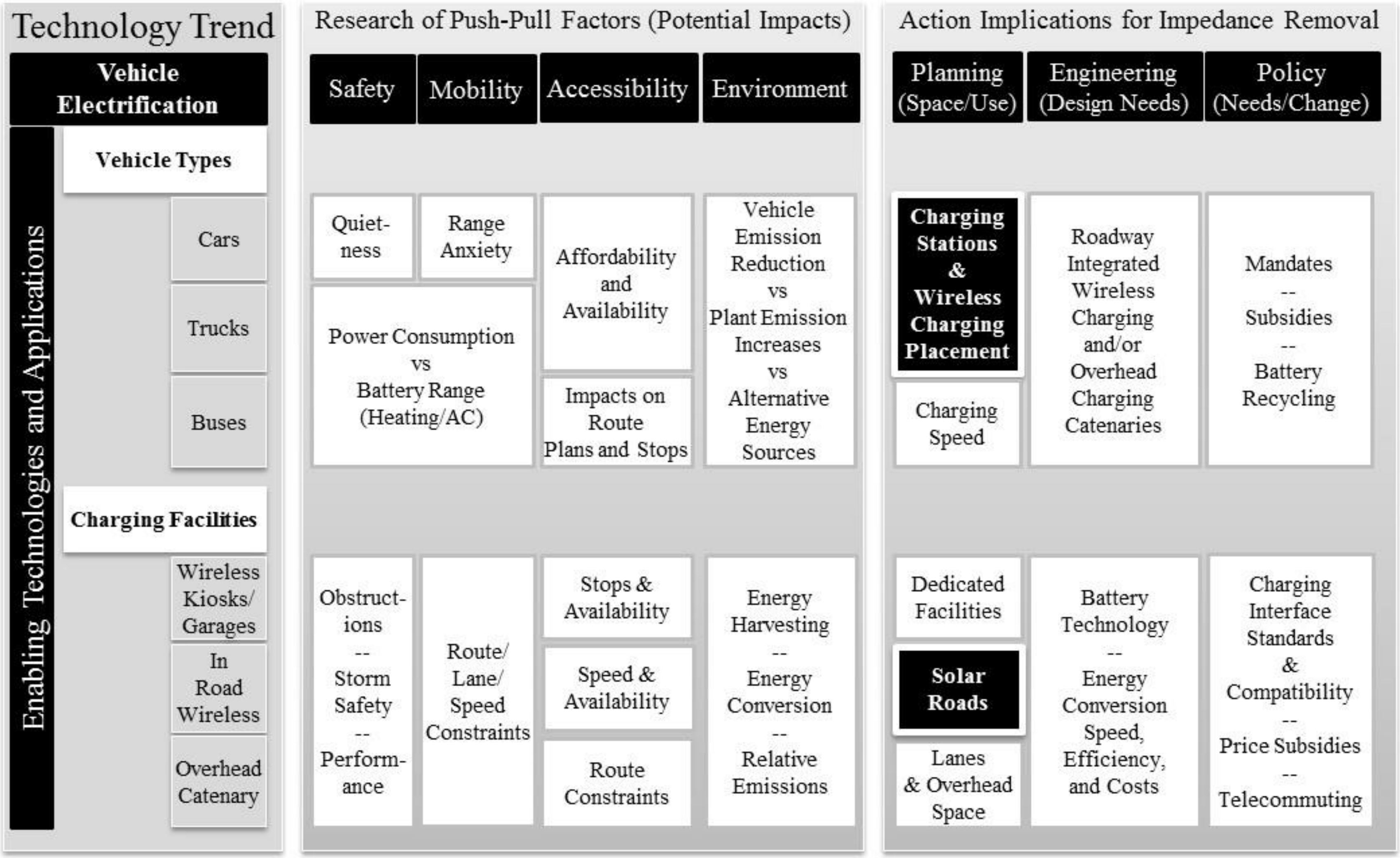


Fig. 5 Cognitive framework focused on topics in vehicle electrification highlighting infrastructure adaptation