NCTCOG AUTOMATED TRANSPORTATION SYSTEM DEVELOPMENT

North Central Texas Council of Governments

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PREPARED IN COOPERATION WITH THE REGIONAL TRANSPORTATION COUNCIL, **NCTCOG**, THE FEDERAL HIGHWAY ADMINISTRATION, AND THE TEXAS DEPARTMENT OF TRANSPORTATION.

1. INTRODUCTION

As the population in the Dallas-Fort Worth (DFW) Metroplex grows and the need for flexible mobility options increases, addressing the first mile / last mile connectivity and related mobility limitations has been the focus of several studies. Recent innovations in transportation technologies may offer potential solutions to this issue. The North Central Texas Council of Governments (NCTCOG) is leading the region's effort to monitor and evaluate emerging technology innovations that promise to advance the efficiency and effectiveness of passenger and supply chain transportation systems and services in north Texas.

NCTCOG is exploring the feasibility of implementing Automated Transit Systems (ATS) as state-of-the-art connectivity solutions for passenger mobility and supply chain applications in activity centers and/or as connections to other forms of transportation. Previous solutions to the need for district-wide transportation in campus or dense urbanized areas, serving as circulators or regional connectors, have typically been capital-intensive infrastructure projects which end up locked into a specific technology or mode of transportation. While these projects may succeed at first, they prove to be difficult or expensive to maintain as components for the transportation system become more difficult to source, let alone attempt to expand.

With this in mind, NCTCOG's efforts to evaluate emerging technology innovations have focused on achieving economies of scale through modular infrastructure that is paved for use by any independent-running vehicle, "future-proofing" the infrastructure and providing users with demand-responsive transportation. This approach, the core vision of NCTCOG's Automated Transportation System (ATS) Initiative, reduces long-term risks of obsolescence of the infrastructure while providing maximum opportunity to use any current and future vehicle technology depending on the changing transportation needs. In other words, the "smart technology" is removed from the infrastructure and secured wholly within the vehicle. This type of system – smart vehicle and paved guideway infrastructure – allows for leveraging of technology advances in ATS vehicles without simultaneously sacrificing the infrastructure investment.

Previous work in this initiative has included the development of the Last Mile Transit Connections Concept Study (2015/2016): a regional exploratory analysis of people movers and other local-scale transit options, the development of Geographic Information Systems (GIS) mapping and data algorithms to determine feasible locations within the region that might benefit from an ATS deployment. Building on this exploratory effort, the study of the Dallas International District (previously Midtown) advanced the initiative through the Dallas Midtown Autonomous Transportation System and Shared Parking Feasibility Study (2019): a planning study integrating the ATS route planning with parking management and land use considerations, including a separate technology scan of available ATS vehicles. These previous efforts serve as a foundation for this study, ATS Development, to focus on the three main components of an ATS: vehicles, charging systems for the vehicles, and guideways.

This ATS Development Study expands on the previous work and envisions the use of ATS technologies for both passenger and cargo/goods movement that would provide connectivity to local, regional, and national transportation systems. The scope of the study is illustrated in Figure 1-1. The ATS Development Study explores independently running ATS vehicle technologies for transporting both passengers and cargo/goods; reviews cutting-edge options for wireless Electric Vehicle (EV) charging technologies, with a focus on dynamic charging; and develops modular guideway infrastructure design guidelines using the latest advances in technologies. To future-proof infrastructure investment for grade-separated (elevated) guideways, these structures must not preclude utilization by various types of ATS vehicles. In kind, the ATS vehicles themselves must be able to traverse a simple, paved guideway without relying on guideway-mounted equipment for propulsion or vehicle guidance that would be technology-specific to each vehicle.

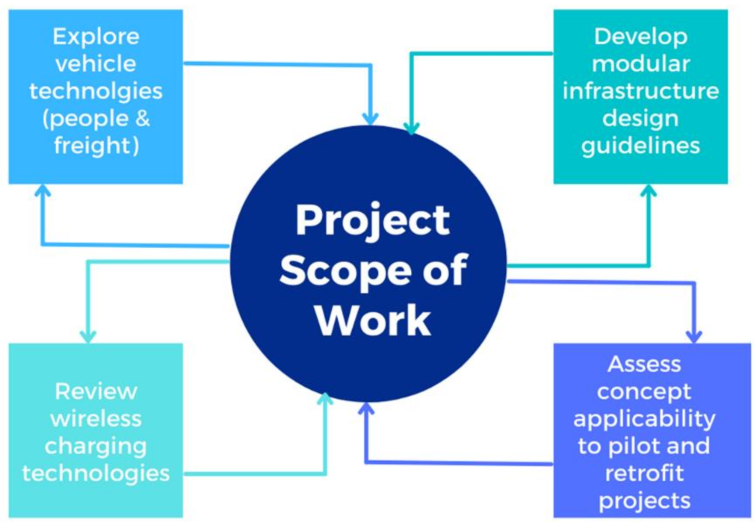


Figure 1-1: ATS Development Study Scope of Work

This ATS Development study provides a compendium of currently available ATS technologies that are suitable for first and last mile passenger and cargo/goods movement and state-of-the-art Electrical Vehicle (EV) charging technologies that can be updated in the future with technological advances. In addition, this study also provides design guidelines for a modular elevated guideway structure that serves as a dedicated right-of-way for the ATS. The modular guideway is envisioned to provide a) a signature streamlined appearance, b) a means for efficient assembly with standardized components readily available, and c) economies of scale to potentially reduce construction costs, process and time. Additionally, this ATS development study uses pilot projects and case studies within the region to inform the analysis of vehicles and charging systems and the development of guideway design guidelines. Retrofit opportunities for existing people mover systems within the region will also be explored to determine if these structures can be adapted and reused for application of the ATS concept.

The results of this study are intended to provide a flexible guideline that can be updated as technologies evolve, and new technologies emerge so that it will be a useful and relevant planning tool for the design of future ATS systems and to assist public agencies with laying the groundwork for future mobility as a service transportation system for the region.

NCTCOG established an ATS Study Steering Committee comprised of city leaders and transit officials to provide feedback and assist the NCTCOG ATS Development Study team in optimizing the usefulness of the study to address regional needs and provide guidance in accomplishing the study goals. The ATS Steering Committee was comprised of representatives from the City of Dallas, Dallas County Utility and Reclamation District (DCURD), DFW Airport, the City of Arlington, and the study team and leadership from NCTCOG. The ATS Steering Committee met periodically to provide feedback on the progress and direction of the study.

The ideas and solutions in this study were developed with operational feasibility, streamlined construction and low cost in mind while also including innovation and creativity. The fundamental aim of this program is to develop broad performance guidelines that will provide support for projects in the future as well as a toolkit to assess applicability for site specific applications. The methodology developed in the study provides the means to evaluate technology candidates as they evolve and emerge to maintain relevancy for the future.

2. BACKGROUND AND STUDY APPROACH

Two operating environments were identified as example applications and were used in developing the basis of this study. Operating Environment A (OE-A) is a manufacturing environment involving the transportation of cargo/goods within a manufacturing complex. Operating Environment B (OE-B) is focused on transporting passengers in a dense urban environment. To support the development of the ATS system guidelines for applicability in any future passenger or cargo/goods movement within the parameters of OE-A and OE-B, the study considered two specific potential pilot systems and two retrofit applications of existing people mover systems within the region. The pilot locations used for the study were the Dallas International District and the General Motors (GM) manufacturing facility located in Arlington. The retrofit projects considered were the Las Colinas Urban Center Area Personal Transit (APT) and Dallas-Fort Worth (DFW) International Airport Skylink Automated People Mover (APM). It was important to review the applicability of the concepts with both new systems and retrofit of existing systems to assess the viability of both approaches.

The following general assumptions were made to facilitate reaching the study goals:

- The ATS covers short distance connections (first/last mile) between various forms of transportation.
- The ATS uses state-of-the-art technologies.
- Passenger carrying capacities are between 6 and 25 passengers per vehicle.
- Cargo/goods carrying vehicles maximum carrying capacity is 6,500 pounds per vehicle.
- ATS vehicles are rubber-tired.
- ATS vehicles utilize on-board batteries for propulsion.
- ATS vehicles do not rely on guideway-mounted equipment for guidance or propulsion.
- ATS vehicles will be low speed.
- Tools developed for this study will have the ability to be updated as technologies evolve.
- The guideway design guidelines are for an elevated guideway that is a dedicated-right-of-way.
- This study provides a guideline for the purpose of defining a guideway concept. Construction drawings and final design are not provided in this document. All structures must have a final design performed, sealed, and signed by a Texas Professional Engineer.
- The guideway design concept is developed for simple span units.
- General span lengths are limited to 60 feet for small water crossings and roadways, 90 feet for crossing arterials, and 120 feet for crossing major thoroughfares and highways.
- Design guidelines are based on current standards at the time of the study.
- Station design and at-grade design guidelines are not included in this study.

The study began with a series of outreach activities with NCTCOG staff to ensure that the study considered regional goals and needs, that pilot and retrofit project considerations were appropriately incorporated and that the latest developments in the technologies and demonstration programs were understood. These outreach activities included tours of the GM manufacturing facility in Arlington, Las Colinas APT facilities in Irving, the Mobility Innovation Zone (MIZ) in Alliance (north Fort Worth); discussion with representatives from the Advancing Sustainability through Powered Infrastructure for Roadway Electrification (ASPIRE) initiative by the National Science Foundation (NSF); outreach to regional partners as part of steering committee meetings; and outreach to various vehicle and EV charging equipment manufacturers through Requests for Information (RFIs) and subsequent virtual meetings and email correspondence. These initial meetings and tours helped define the study approach and understanding of the current state of development of some of the technologies.

The study approach is listed below, and a graphical representation is shown in Figure 2-1.

1. Consider operating environments for people and cargo/goods movement.
2. Consider a wide range of capacities and operating scenarios for possible future regional applications.
3. Inventory state-of-the-art technologies:
    - AV
    - EV charging
    - Lightweight modular guideway structure
4. Assess market readiness and applicability.
5. Develop an evolving/flexible vehicle technology evaluation tool.
6. Develop design guidelines for an economical, light weight, modular/component-based, elevated, dedicated guideway.
7. Explore mobility-as-a-service.
8. Ensure flexibility to operate ATS system in dedicated right-of-way (ROW) and mixed traffic in the future is not precluded.
9. Visualize the integration of systems.
10. Consider retrofit potential and other applications for regional pilot programs.

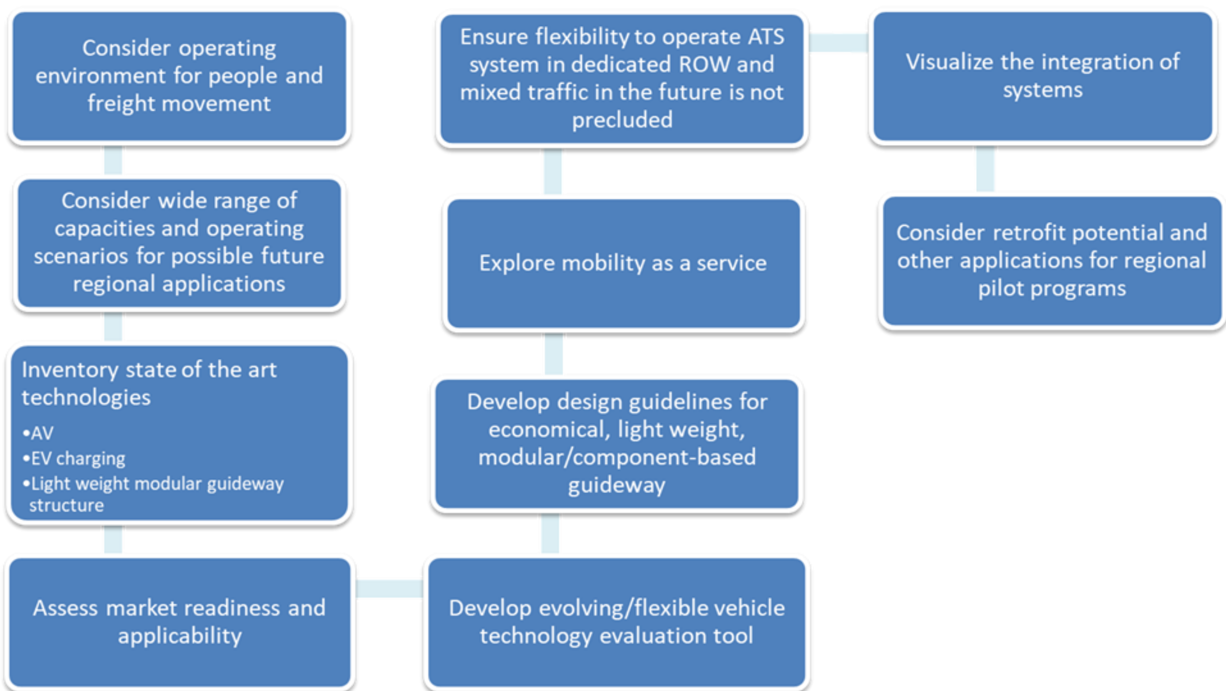


Figure 2-1 ATS Development Study Approach

Given the complexity of the study goals, visualizing the integration of systems was paramount to the success of the study. The various vehicle and EV charging technologies were accommodated in the generic guideway design guidelines so as not to preclude any range of technologies from participating in the future procurement of the ATS.

The following sections detail the technology evaluation for both the people and cargo/goods moving vehicles, the EV charging technology evaluation, the development of the guideway design guidelines, and the ideas for pilots and retrofit applications.

3. TECHNOLOGY IDENTIFICATION AND REPRESENTATIVE TECHNOLOGY SUPPLIERS

Part of the focus of this study is to identify and evaluate the field of rubber-tired ATS technologies and EV charging systems to find appropriate candidate technologies for this study. Many automated transit systems have a guideway which contains numerous system components including, but not limited to, electric power rail, guide rail, train control equipment, and switches. The rubber-tired ATS vehicle technologies considered in this study are those ATS vehicles that do not rely on guideway-mounted rails for propulsion and do not rely on guideway-mounted equipment for vehicle guidance. These vehicles, commonly referred to as Autonomous Vehicles (AVs), utilize on-board batteries for propulsion, other guidance/navigation methods, radio communication, and on-board switching.

Utilizing AVs has the potential to offer benefits, such as:

- Flexibility to right size the technology to the demand.
- Operate in a platoon or as independent vehicles.
- Ability to route vehicles around other vehicles.
- Ability to bypass stations.
- Offer point-to-point service.
- Decrease the capital and O&M costs associated with the guideway infrastructure.
- Flexibility to permit shared use of the guideway for one or more system technologies initially or in the future.
- Potential to replace the vehicles with updated technology as the technology evolves without major guideway infrastructure modifications.

The technologies considered in the study were selected based on their applicability for either OE-A (cargo/goods movement in manufacturing environment) or OE-B (passenger movement in dense urban environment). To support the development of the ATS system guidelines for applicability in any future passenger or cargo/goods movement within the parameters of OE-A and OE-B, the study considered two specific potential pilot systems and two retrofit applications of existing people mover systems within the region. These pilot and retrofit projects, which are discussed in more detail in Sections 5 and 6 of this report, helped to shape the vehicle, guideway, and EV charging analysis and guidelines in a practical way.

The study also involves reviewing the feasibility of using wireless EV charging systems to help optimize the ATS operations. Ideally, the ATS technologies identified for this study will be capable of using a state-of-the-art wireless EV charging technology, immediately or in the near future.

3.1 ASSESSMENT OF ATS VEHICLE TECHNOLOGIES

Extensive research was conducted to compile an inventory of state-of-the-art ATS vehicle technologies that allow for a wide range of capacities and operating scenarios for potential future regional applications for people and cargo/goods movement. Appendix A contains more specific vehicle information.

The initial research and industry outreach revealed that at the time of this study, the field of technologies is evolving rapidly: during the course of the study the candidate technologies were updated several times. Even though at this time most technologies are not able to operate in mixed traffic, some are currently being developed and tested for such operations. For the purpose of this study, given the current state of development of the ATS technologies, it is assumed that the ATS vehicles would operate on an elevated guideway that is a dedicated right-of-way. However, it is envisioned that with advances in technologies, it is possible that ATS vehicles could operate in mixed traffic. To accommodate the fast-paced evolution of the AV technologies, it was necessary to develop tools that could be used by NCTCOG to continue to evaluate the readiness of these technologies for future implementation projects. A technology evaluation plan was developed to assist the user to assess market readiness and applicability of technologies within the available inventory that provide the required parameters for each specific use.

To augment the database of technologies and current information available regarding the specific vehicles, an RFI was issued to get additional information from emerging ATS technology suppliers. The results of the RFI and additional details are discussed in Section 3.3.2.

The initial list of technologies included all available AV technologies that were identified during the search without any restrictions. The plan to assess these technologies for applicability for this study is explained below, see Figures 3.1-1 and 3.1-2 below.

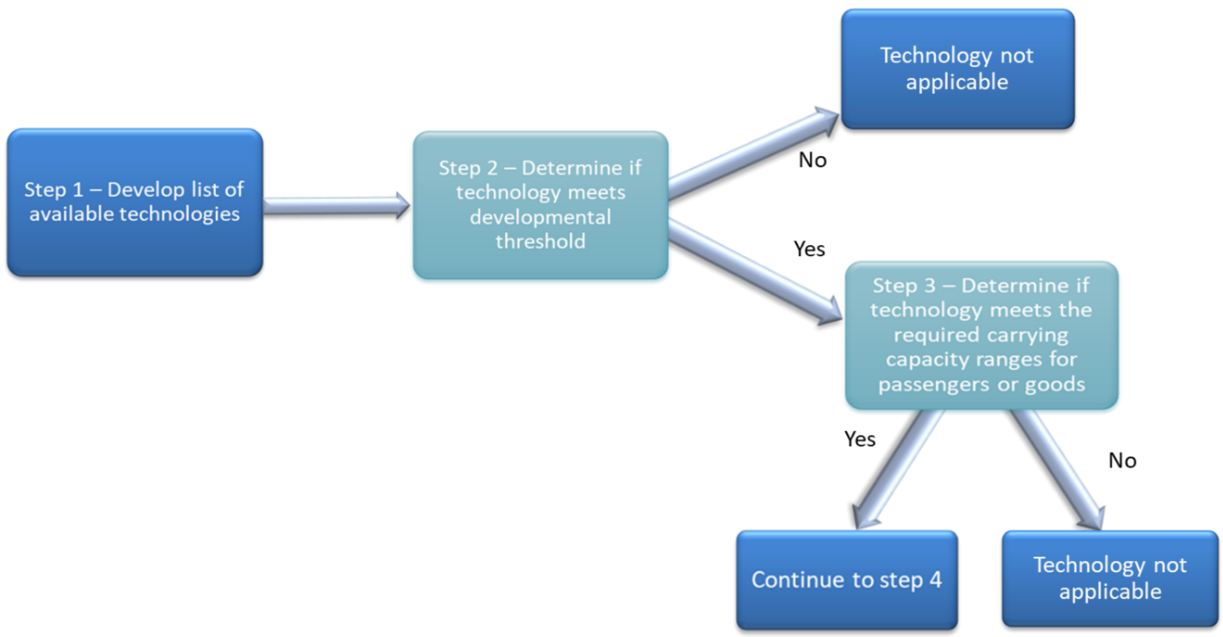


Figure 3.1-1 Steps for ATS Vehicle Technology Assessment

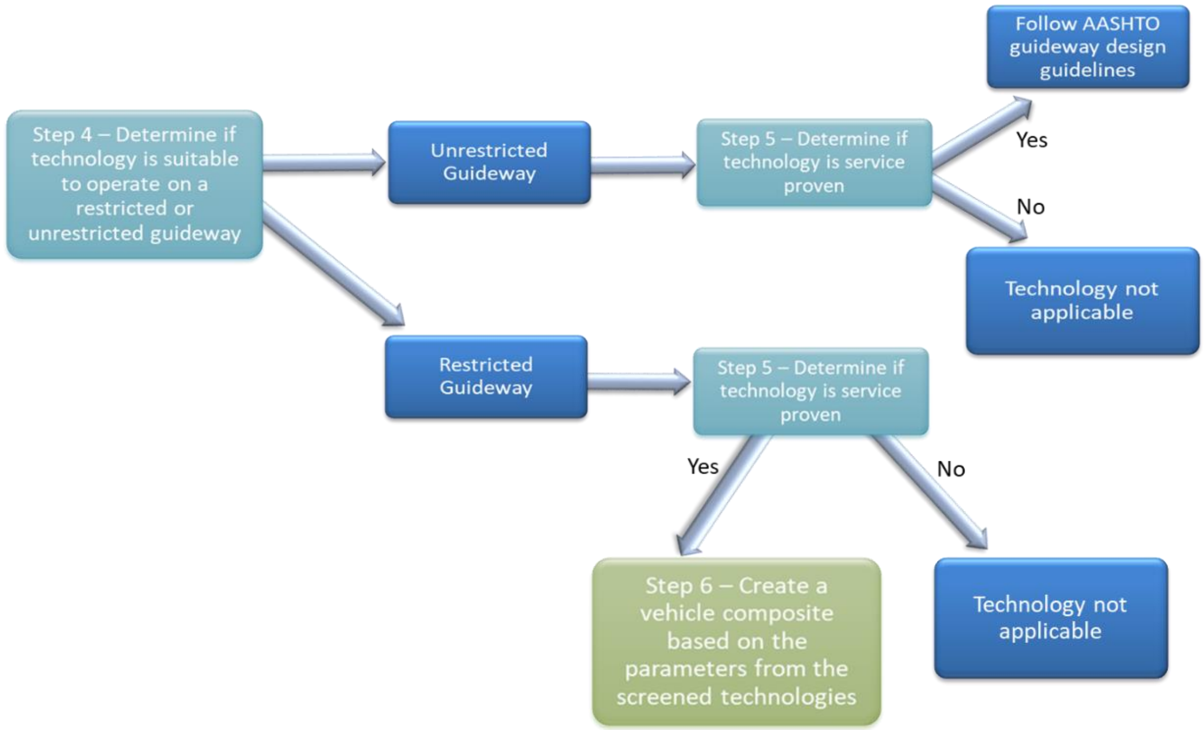


Figure 3.1-2 Steps for ATS Vehicle Technology Assessment (Continued)

Step 1: The initial list of AV technologies was developed by using Lea+Elliott, Inc.'s existing database of technologies and doing research to find any technologies not already in the database.

Step 2: Since most of the AV technologies are nascent technologies, the technologies in the initial list were studied to see if they met a pre-determined developmental threshold. The NASA technology readiness levels shown in Figure 3.1-3 were the basis for the technology readiness definitions used for this study, see Figure 3.1-4.

Based on the definitions below, the categories that were indicated as service proven were chosen as the pool of candidates for this study. The vehicles that were categorized as in development or concept were not ideal candidates for this study. These vehicle technologies were kept in the study database since they are evolving and could move up to the service proven category in the near future.

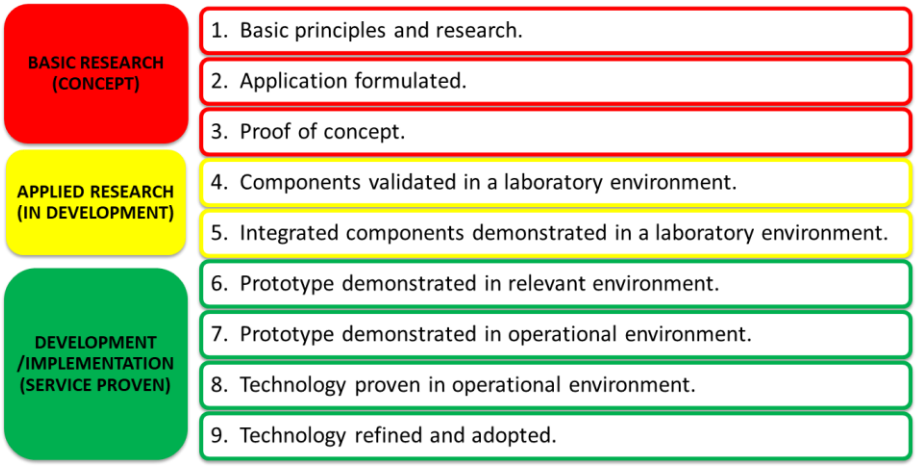


Figure 3.1-3: NASA Technology Readiness Scale (Image: NASA)

<u>Service Proven</u>: The autonomous vehicle must have been successfully operated as an integrated, functioning system for either passenger or freight service, including pilot or demonstration projects, for a period of time sufficient to demonstrate satisfactory operation.

<u>In Development</u>: The autonomous vehicle must have been developed beyond the concept phase into working physical prototypes that are fully functional and are being tested but have not yet been successfully operated as an integrated functioning system, including pilot or demonstration projects, for a period of time sufficient to demonstrate satisfactory operation.

<u>Concept</u>: An autonomous vehicle that has not been developed beyond the concept phase into working physical prototypes that are fully functional and are being tested.

Figure 3.1-4 Technology Readiness Categories

Step 3: The next step was to determine if a technology meets the required carrying capacity ranges for passengers and/or goods. The minimum carrying capacity for the passenger vehicles was established as six passengers per vehicle and for the cargo/goods carrying vehicles it was 6,500 pounds.

Step 4: As stated before, the AV technologies considered for this study are in different stages of development, with most not being able to operate in mixed traffic. For future projects, AV technologies that are capable of operating in mixed traffic should be able to operate on any typical American Association of State Highway and Transportation Officials (AASHTO)-designed guideway or road. This study calls for guideway design guidelines for vehicle technologies that can operate on a dedicated right-of-way or restricted guideway.

Step 5: The vehicle technologies that were categorized as service-proven and can provide the required service were chosen as the basis of the guideway design guidelines.

Step 6: The ATS technologies chosen in step 5 were used to develop two different composite vehicles, one for cargo/goods movement and one for passengers. The dimensions and weights of these composite vehicles were used as the basis of design for the guideway design guidelines.

The objective is to develop guidelines that can be used by a future designer to accommodate any size vehicle technology by scaling up or down. If there is a future vehicle that is not within the generic vehicle parameters used for this study, the guideway design could be resized accordingly.

The following section expands on the vehicle technology evaluation and selection by providing a broad look at the various technologies considered for this study.

3.2 TYPES OF ATS VEHICLE TECHNOLOGIES CONSIDERED

The Autonomous Vehicle technologies considered for this study are generally grouped into the following categories:

- Group Rapid Transit (GRT)
- Automated Vehicle Shuttle / Autonomous Vehicle (AV)
- Next Generation Automated People Mover (APM)
- Autonomous Bus
- Other Autonomous Technologies

Based upon the study's technology goals described above, the AV technology categories that could meet the requirements of OE-B (passenger movement in dense urban environment) are GRT, AVs, emerging Automated People Mover (APM) technologies that could in the future operate without rail-based propulsion and guideways, and Autonomous Buses.

The vehicle technologies that are applicable for OE-A (cargo/goods movement in manufacturing environment) are categorized as Other Autonomous Technologies since they are all very different. The following subsections identify representative technologies within these technology categories.

3.2.1 Group Rapid Transit (GRT)

Group Rapid Transit systems group passengers with either the same destination or potentially different origin-destination pairs, depending on the GRT's control system and vehicle assignment algorithm. Such systems have fewer average stops than conventional transit, acting more as an automated shared taxi system. A GRT system could have a range of vehicle sizes to accommodate different passenger load requirements, for example at various times of day or on routes with less or more average traffic.

GRT has principally been proposed as a corridor service, where it can potentially provide a travel time improvement over conventional rail or bus. However, GRT's potential grouping of passengers makes it much less attractive in applications with lower passenger density or where few origin-destination pairs are shared among passengers. 2getthere (in partnership with Oceaneering) is a GRT supplier that has several deployments of their technology, such as the vehicle shown in Figure 3.2.1-1. 2getthere technology uses magnets embedded on the guideway to aid in navigation.

Figure 3.2.1-1 2getthere GRT Vehicle, Brussels Airport

3.2.2 Automated Vehicle Shuttle / Autonomous Vehicle (AV)

An Automated Vehicle Shuttle or Autonomous Vehicle (AV) is a vehicle technology that can sense its environment and navigate without human input or guideway equipment such as embedded magnets (in contrast with the previously discussed GRTs). AVs combine a variety of technologies to perceive their surroundings including radar, lidar, GPS, odometry, mapping and cameras. Advanced control systems interpret the information received to identify appropriate navigation paths as well as obstacles.

AVs are used to move passengers or cargo/goods with a level of automation. They are classified into six distinct levels of automation, as defined by the Society of Automotive Engineers (SAE). The first three levels of automation (Levels 0-2) require a human driver to monitor the environment, while the last three levels (Levels 3-5) allow an automated system to perform driving tasks. Shared Automated Vehicles are level 4 and higher and are small (typically 8-15 passengers), battery-powered, electric vehicles. These vehicles aim to transform transportation by significantly improving safety and mobility, improving the efficiency of rides on demand, reducing carbon footprints of cities, and solving the public transportation problem of the first and last mile connectivity. Shared automated vehicle shuttles are being deployed for use in non-fixed, nonetheless still contained, environment. Most AV shuttles are equipped with SAE Level 4 control.

While all automated shuttle service pilot demonstration programs are in the initial testing phase at the time of this study, some are offering rides to the public. These pilot programs are testing the feasibility of automated vehicle technology for public transit and user acceptance. EasyMile and NAVYA are major manufacturers of low-speed (12-15 mph) AVs. Other emerging manufacturers include Mobileye, GM Cruise, and May Mobility. A few examples of these vehicles are shown below.

Figure 3.2.2-1: EasyMile EZ10 Vehicle

Figure 3.2.2-2 NAVYA Autonom Shuttle

3.2.3 Next Generation Automated People Mover (APM)

APMs are not considered AVs, but they are included here as a special category. APMs are distinguished by their ability to be operated fully automated without drivers. Automatic operation requires an exclusive right-of-way as well as fixed structures that keep the vehicle on track. Examples of how guidance can be provided are by horizontally-mounted guide wheels that track side-mounted guide rails, guideway-mounted center guidebeam, the guidebeam itself, guideway-mounted center guide rail or traditional rails. The guideway of the APM system refers to the track or other running surface (including supporting structure) that supports, powers, contains, and physically guides APM vehicles designed to travel exclusively on it. The APM guideway can be elevated, at-grade (fenced or otherwise protected) or in tunnels. One example of an existing APM is the Skylink at DFW International Airport.

APM suppliers are keenly aware of the rapid development of AVs, which do not require mechanical guidance or guideway-supplied electrical power. This awareness and understanding that the future is changing and the desire to remain relevant in a world that is embracing Autonomous Vehicles, is driving APM suppliers to consider how to adapt their technologies to become Autonomous Vehicles. Non-mechanical guidance is in development by many of the APM suppliers. With the rapid advancement in battery technology, some suppliers are also considering how batteries might be used to power APMs since this is still under development and the details of the technological advances are not known. APM technology suppliers include Alstom and Mitsubishi, among others.

3.2.4 Autonomous Bus

Autonomous buses are equipped with an array of different types of sensors, including cameras, LiDAR, and radar. Currently, Autonomous buses are limited to a specific Operational Design Domain (ODD), but within that ODD, they are generally able to operate without a driver on-board. In order to accommodate disabled passengers, Autonomous buses are equipped with a wheelchair ramp. Bus manufacturers include Irizar Autonomous Bus (shown in Figure 3.2.4-1), among others.

Figure 3.2.4-1 Irizar Autonomous Bus

3.2.5 Other Autonomous Technologies

ATS cargo/goods movement technologies are included in this section. Several technologies that could meet the requirements of OE-A (cargo/goods movement in manufacturing environment) were considered. Some manufacturers of these technologies indicated that they could retrofit their existing technologies to fit a specific application, if required. Stanley Robotics, Outrider, Oceaneering, and Kodiak Robotics were some of the technologies reviewed. Representative images are shown below.

Figure 3.2.5-1 Stanley Robotics

Figure 3.2.5-2 Oceaneering

Figure 3.2.5-3 Outrider

Figure 3.2.5-4 Kodiak Robotics

3.3 VEHICLE TECHNOLOGY EVALUATION

The initial list of technologies evolved into a database that includes various levels of information for all the technologies considered. Several technologies are in such a nascent state of development that not much information is readily available. The study team contacted most of the technology suppliers in the list to request additional information that is not provided on their websites. A few technology suppliers were very helpful and provided all the requested information while others did not respond to our informal requests for information (see later discussion on RFI in section 3.3.2). The database includes the following information:

- Identification (ID)
- Technology Name
- Cargo Type
- State of development
- Vehicle length
- Vehicle width
- Vehicle height
- Vehicle weight – empty
- Vehicle capacity (number of passengers or cargo weight)
- Maximum speed
- Minimum horizontal curve radius
- Fully bidirectional
- Doors on both sides or one side
- Restricted or non-restricted guideway
- Website

The technologies were then categorized as service proven (currently in use for passenger or goods movement applications), in development or concept, see Figure 3.1-4 for definitions. It was important to include information on whether the vehicles have doors on one or two sides and if they are fully bidirectional because these features impact guideway design and system operations.

The technologies are also categorized as either Group Rapid Transit, Automated Vehicle Shuttle/Autonomous Vehicle, Automated People Mover, Autonomous Bus, and Other Autonomous Technologies. A partial database is included in Table 3.3-1.

It is important to note that this is a snapshot in time of the technology development. It is not intended to show preference toward any technologies.

Table 3.3-1 ATS Vehicle Technology Partial Database

ID	Technology	Cargo Type	State of Development	Vehicle length (ft)	Vehicle width (ft)	Vehicle height (ft)
1	**Group Rapid Transit (GRT)**					
1.1	2getthere/Oceaneering GRT	People	Service Proven	19.7	6.9	9.2
2	**Automated Vehicle Shuttle / Autonomous Vehicle (AV)**					
2.1	EasyMile EZ10	People	Service Proven	12.9	6.5	9.0
2.2	Local Motors Olli	People	No longer in service	12.9	6.7	8.2
2.3	NAVYA AUTONOM Shuttle (ARMA)	People	Service Proven	15.6	6.9	8.7
2.4	NAVYA AUTONOM CAB	People	Service Proven	15.3	6.4	6.9
2.5	Applied EV and Oxbotica	Palletized Freight/Large Items	In Development			
2.6	Schaeffler and Mobileye	Palletized Freight/Large Items	Concept			
2.7	AURRIGO AUTO-SHUTTLE	People	Service Proven	19.0	7.5	8.3
2.8	AURRIGO AUTO-DOLLY	Palletized Freight/Large Items	Service Proven			
2.9	Einride	Palletized Freight/Large Items	In Development			
2.10	Toyota e-Palette	People	In Development	17.2	6.8	9.0
2.11	Westfield POD	People	Service Proven	12.1	5.4	6.9
2.12	e.GO MOOVE (previously ZF e.GO Mo	People/Large Items	In Development			
2.13	Continental CUbE	People	Service Proven			
2.14	IAV HEAT	People	Service Proven			
2.15	Cruise Origin	People	In Development			
2.16	Zoox	People	In Development			
2.17	REE Automotive e-Shuttle	People/Large Items	In Development	23.6	7.9	10.0
2.18	REE Automotive Leopard	People/Large Items	In Development	11.5	5.9	7.2
2.19	Baidu Apolong II	People	In Development	14.2	7.0	8.9
2.20	May Mobility	People	Service Proven	17.25	7.6	6.6
3	**Automated People Mover (APM)**					
3.1	Alstom Innovia APM 200	People	Service Proven	41.8	9.4	11.1
3.2	Mitsubishi Crystal Mover	People	Service Proven	37.6	8.9	12.1
4	**Autonomous Bus**					
4.1	New Flyer Autonomous Bus	People	In Development	41		11.1
4.2	Irizar Autonomous Bus	People	Service Proven	40		
4.3	Volvo Autonomous Bus	People	In Development	40		
4.4	Iveco Autonomous Bus	People	In Development	40		
5	**Other Autonomous Technologies**					
5.1	Stanley Robotics	Palletized Freight/Large Items	Service Proven			
5.2	Oceaneering	Palletized Freight/Large Items	Service Proven	20	7	9
5.3	Citroën Skate	People/Large Items	Concept	5.2	8.5	1.6
5.4	Outrider	Palletized Freight/Large Items	Service Proven			
5.5	Kodiak Robotics	Palletized Freight/Large Items	Service Proven			
5.6	Honda Autonomous Work Vehicle	Palletized Freight/Large Items	Service Proven	9.5	4.9	5

3.3.1 Composite Vehicles

The vehicle technology database was used to find current candidate vehicles that meet the requirements of either OE-A (cargo/goods movement in manufacturing environment) or OE-B (passenger movement in dense urban environment) for use in this study. Dimensional data from the candidate vehicles was analyzed to develop "design values" to create the composite vehicles that were used as the basis for the development of the guideway design guidelines discussed in Section 4 of this report. Figures 3.3.1-1 and 3.3.1-2 show the dimensional data for the passenger ATS vehicle and the cargo/goods ATS vehicle.

Table 3.3.1-1 Passenger Vehicle Composite Data Dimensions

Vehicle Composite - People	Value
Design vehicle length	19.7 ft
Design vehicle width	7.5 ft
Design vehicle height	9.0 ft
Design vehicle weight (unloaded)	8,818 lbs
Design vehicle capacity	22 pax
Maximum design speed	55 mph

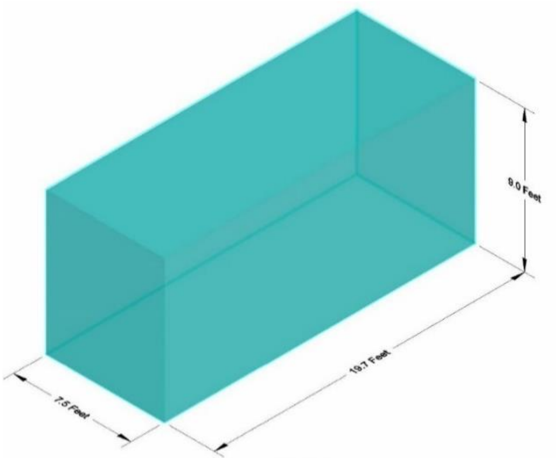


Figure 3.3.1-1 Passenger Vehicle Composite

Table 3.3.1-2 Cargo/Goods Vehicle Composite Data Dimensions

Vehicle Composite - Cargo	Value
Design vehicle length	20 ft
Design vehicle width	7 ft
Design vehicle height	9 ft
Design vehicle weight (unloaded)	8,500 lbs
Design vehicle capacity	6,000 lbs
Maximum design speed	25 mph

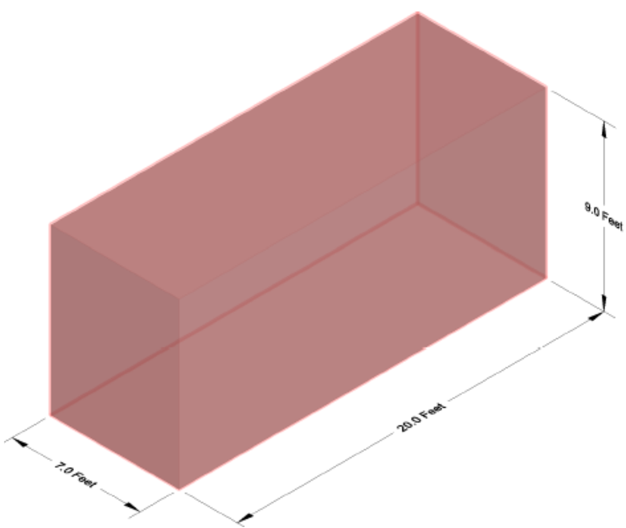


Figure 3.3.1-2 Cargo/Goods Vehicle Composite

Dynamic envelope consideration for these vehicles resulted in the dynamic envelope dimensions shown in Figure 3.3.1-3 below. The passenger and cargo/goods movement vehicles were combined into one dynamic envelope since the dimensions for both vehicles are similar.

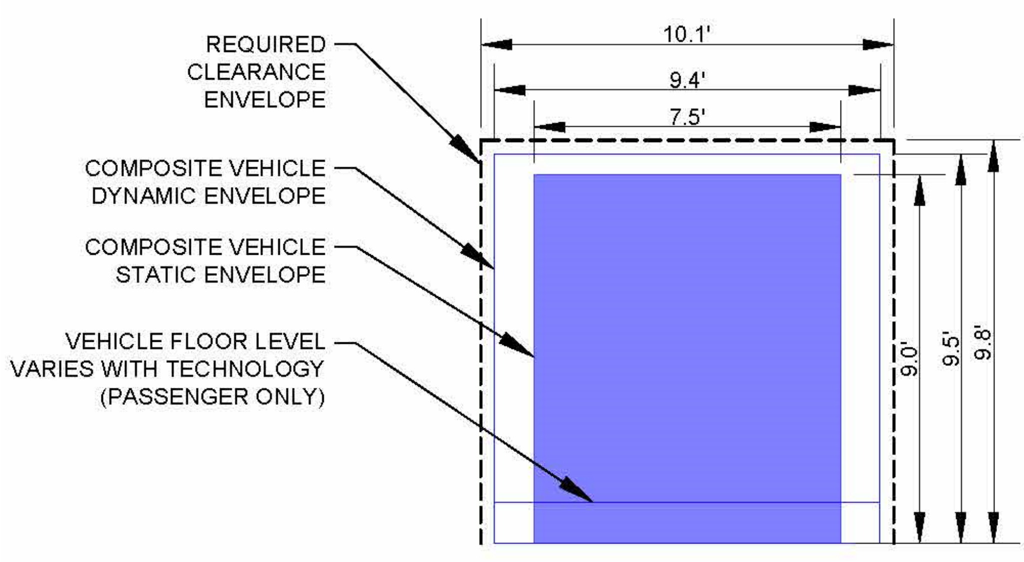


Figure 3.3.1-3 Composite Vehicle Dynamic Envelope

Architectural renderings of the composite vehicles were created to help visualize future deployments of the ATS. The vehicle renderings are shown in Figures 3.3.1-4 through 3.3.1-7 below.

Figure 3.3.1-4 Passenger Vehicle Front

Figure 3.3.1-5 Passenger Vehicle Rear

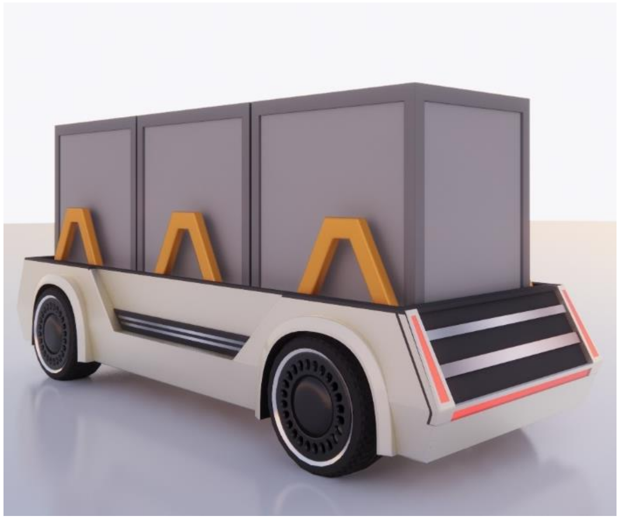


Figure 3.3.1-6 Cargo/Goods Vehicle Front

Figure 3.3.1-7 Cargo/Goods Vehicle Rear

3.3.2 AV Technologies Request for Information

NCTCOG issued an RFI requesting information and input for innovative ATS vehicles that could be implemented in various locations throughout the Dallas-Fort Worth region to carry passengers and/or cargo/goods.

The RFI requested that the identified ATS vehicles be able to run on flat surfaces rather than traditional track-based infrastructure to provide for future route flexibility and scaling. NCTCOG requested solutions that can operate in both an exclusive right-of-way but also have the capability to operate in mixed traffic if desired at some point in the future. Additionally, while each vehicle should be capable of operating as a stand-alone unit, when deployed as part of an ATS system, it is anticipated that system control software may be necessary to ensure proper operations within the deployed site.

The RFI was issued on July 8, 2022, with responses due August 5, 2022. NCTCOG received three responses from ATS vehicle technology suppliers; these responses confirmed the vehicle research completed for this study.

3.4 ASSESSMENT OF WIRELESS ELECTRIC VEHICLE CHARGING TECHNOLOGIES

A primary goal of this study is to investigate the use of dynamic wireless EV charging (charging on-the-fly) technology.

There are three EV technology options currently available or in development:

- Stationary plug-in EV charging
- Stationary opportunity EV charging (wireless)
- Dynamic wireless EV charging (wireless)

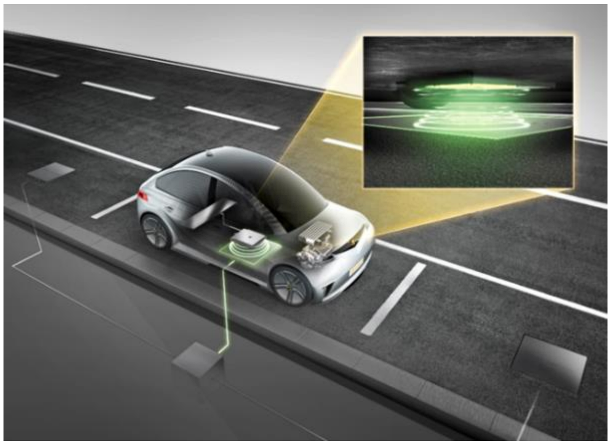


Figure 3.4-1 Continental AG Automated Wireless Charging Technology

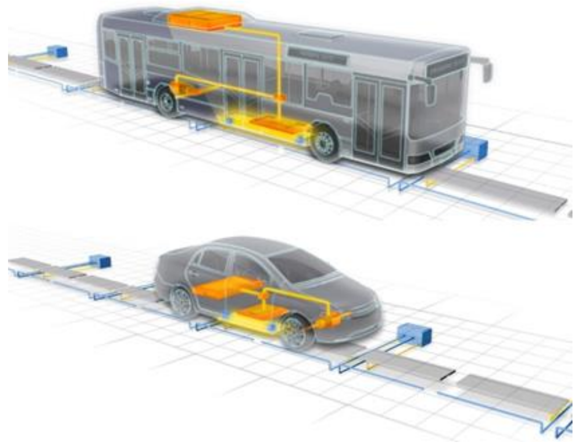


Figure 3.4-2 IPT PRIMOVE Dynamic Charging

Currently, Stationary plug-in charging is currently the most common charging method used by EV technologies – it is widely available.

There are two types of Stationary Opportunity EV Charging: inductive charging or contact charging. Inductive charging consists of a charging plate embedded in the surface of the guideway or roadway that the vehicle stops over, which allows charging while parked. This type of charging has been used as a way of providing supplemental charging during short stops, such as while stopped at a bus stop or bus station. Dynamic wireless EV technology, on the other hand, is embedded along the guideway or roadway in a way that permits vehicles batteries to be charged while the vehicle is moving. This technology is currently under development or being tested in various pilot programs.

The goal of this study is to investigate the use and potential benefits of dynamic EV technology. Potential benefits could be significant, especially in applications where there is a desire to minimize downtime, such as would be desired for around-the-clock operations. Potentially, continuous charging could reduce the burden on electrical grid during charging cycles as compared to stationary charging alternatives. After conversations with industry experts regarding the first and last mile nature of the applications for this study and based on the state of development of the dynamic EV charging technologies, it was decided to broaden the EV charging technology investigation to also include stationary opportunity wireless charging in addition to dynamic charging. Since the dynamic wireless EV charging technology has not been widely deployed, opportunity EV charging offers a more viable alternative for near-term ATS deployments.

For purposes of this report only wireless charging, both stationary and dynamic, were reviewed in any detail. To create a baseline for the current state of the development of EV charging technologies an inventory of state-of-the-art technologies for both stationary charging and dynamic charging was compiled (see Appendix B for additional information regarding EV charging technologies). The technologies were assessed on current market readiness and applicability for this study.

This discussion is limited to a high-level overview of the companies, based on publicly available information. Due to the startup nature of many of these companies, as well as the nascent nature of the industry, many companies require Non-Disclosure Agreements (NDAs) before providing more detailed information, which created a challenge in obtaining data and information that is usable for comparative purposes for a report of this nature.

3.5 EV CHARGING TECHNOLOGIES CONSIDERED

The following is a compilation list of roadway/in-guideway electric vehicle charging technologies and descriptive information regarding these technologies. The compilation is divided into two primary categories: 1) Stationary wireless electric vehicle charging technologies that require the electric vehicle to remain stationary over charging equipment embedded below the roadway surface and/or guideway surface; 2) Dynamic wireless electric vehicle charging technologies permit vehicles to charge while the vehicles are in motion over the charging equipment embedded below the roadway surface and/or guideway surface.

3.5.1 Stationary Wireless Electric Vehicle Charging Technologies

Wireless power transfer uses electromagnetic coils in or on the ground, and on the underside of the EV, which transmit power through free air using resonant magnetic induction (or similar). To enable wireless power transfer, most EVs would require an aftermarket modification to be compatible with this technology as most EV manufacturers do not yet offer this as an option. Some wireless power transfer companies work directly with EV manufacturers to install the coils on the EV while still in the factory, making for a more integrated installation. In the future, wireless charging technology is expected to be an option directly from the EV technology supplier.

With this technology, charging begins automatically when the receiving coil is stationary over the transmitting coil. All moving parts are eliminated, and all electrical equipment is located either underground or at a location away from the EV. The EV must position the receiving coils over the sending coils for power transfer to begin. Wireless power transfer enables the potential for truly autonomous charging as no interaction is needed to begin charging, unlike with a plug-and-cord solution. All stationary wireless power transfer equipment has a certain tolerance with which misalignment will prevent power transfer. There is an air gap between the inductive coils in the ground and on the bottom of the EV, resulting in some power loss. To mitigate this, wireless power transfer companies shape the electromagnetic wave form between the coils and keep the distances at a minimum.

As with plug-and-cord solutions, the rate at which EVs charge is dependent on the capacity of the charger. Additionally, the charge time for a full battery is dependent on the size of the battery of the EV. Stationary wireless power transfer technology has been deployed for several years in real-world applications. Most applications to date have been in the bus fleet industry. The predictability of bus route timing and distance traveled makes for an excellent application of electric vehicles and wireless power transfer. Stationary charging could be a great fit for an ATS since the distances between stations are relatively short.

Table 3.5.1-1 Capabilities of Stationary EV Charging Technologies

Capabilities of Stationary EV Charging Technologies	
Level of Automation	High
Vendor Diversity	Low
Power Levels	Up to 450 kW
State of Technology	Limited commercial deployments, additional pilot projects
Applicable Standards	SAE J2954. However, not all manufacturers comply with the standard, and technologies from different manufacturers are not cross compatible.

Vendor Examples

- WiTricity
- InductEV
- Continental AG
- Plugless Power
- HEVO
- WAVE
- Electreon

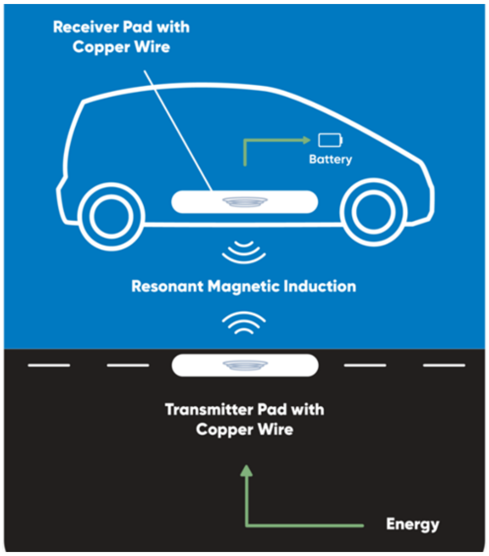
Stationary wireless electric vehicle charging technologies are listed within this Section 3.5.1.

3.5.1.1 WiTricity

In 2007, WiTricity was founded by a team of MIT physicists to commercialize a new wireless electricity technology. Their magnetic technology allows power transfer between devices with a high degree of efficiency over a practical distance applicable to real-world applications.

WiTricity has been tested by the US Department of Energy and WiTricity claims that it was demonstrated to be very efficient.

3.5.1.2 InductEV



InductEV (formerly Momentum Dynamics) has been working on commercializing wireless power transfer since 2014. They have developed what they refer to as "dual-power" mode, which allows their system to detect the vehicle's charging capabilities, and charge at an optimal charge rate Their modular solution can achieve higher power by adding additional charging pads – up to six charging pads can be added which permits a charge capacity of up to 450kW. Their charging pad can be installed directly into the ground, flush with the surrounding grade.

Figure 3.5.1.2 -1 Conceptual Diagram Illustrating Components in Roadway and Vehicle

3.5.1.3 Continental AG

At the 2017 IAA Frankfurt Motor Show, Continental showcased their inductive charging technology installed in an electric vehicle. Continental has an innovative approach, where the driver parks over the charging pad, guided by a Continental navigation system. The way it works is that the vehicle approaches the parking position where an authentication dialog is automatically executed with the charging station. The system gives an indication of when the driver has reached the proper parking position – the system also confirms when charging has begun.

3.5.1.4 Plugless Power

Plugless Power is focused on Level 2 (L2) Stationary Wireless Charging. This type of charging occurs at 208V or 240V single phase. While L2 charging has a slower charging rate compared to a Direct-Current Fast Charger (DCFC), this type of charging at 208V or 240V is widely available in virtually all residential and commercial facilities. Each charging station serves only one passenger Electric Vehicle. Plugless Power are developing an in-ground charging station installation, but currently only have above-ground installations.

Figure 3.5.1.4-1 Plugless Power wireless charging technology

3.5.1.5 HEVO

With the aspiration of helping to increase the rate of adoption of electric vehicles, HEVO was founded in 2011. HEVO has a licensing agreement with the U.S. Department of Energy's Oak Ridge National Laboratory (ORNL) for its wireless charging technology for electric vehicles. HEVO continues to try to develop this technology to achieve higher power levels and improve efficiency while continuing to work with ORNL.

HEVO is focused on Level 2 (L2) Stationary Wireless Charging. HEVO technology has only been applied to passenger vehicles. The HEVO charging pad can be installed flush with the floor or attached directly on top of the floor.

3.5.1.6 WAVE

The WAVE charging pad is installed directly into the ground and installed flush with the surrounding grade. WAVE offers systems ranging from 125kW to 500kW, but their 250kW charger is their most widely used offering.

WAVE focuses on in-route opportunity charging, where the vehicle will charge for a short period (20 minutes or less) to receive a boost in charge to further increase range. They are also capable of supporting depot charging where overhead or plug-in type chargers are typically installed.

WAVE has several installations already in use with multiple transit authorities in the United States including the Twin Transit Authority in Chehalis, Washington, Pinellas Suncoast Transit Authority in Pinellas County, Florida, and the Antelope Valley Transit Authority outside of Los Angeles. The Antelope Valley Transit installation has been in operation since 2018 and they have achieved over 7 million miles with their all-electric fleet. All WAVE installations have obtained UL Field Certification approval for their equipment.

3.5.1.7 Electreon

Electreon has been at the forefront of implementing wireless electric vehicle charging for both dynamic and stationary applications. This company will be discussed more in depth in Section 3.5.2.3 herein.

3.5.2 Dynamic Wireless Electric Vehicle Charging Technologies

Wireless power transfer of vehicles in motion is unique among all other charging technologies. It uses sending and receiving coils in the EV and in the roadway or guideway to provide resonant magnetic inductive charging while the EV is in motion. EVs would require an aftermarket modification to be compatible with this technology as it is not yet offered by EV manufacturers as an option.

Similar to stationary wireless power transfer, charging takes place autonomously, all moving parts are eliminated, and all electrical equipment is located either underground or at a location away from the EV. An array of coils placed in a series embedded in the road/guideway provide the power to charge the vehicle in motion. The EV must pass over the coils within a certain tolerance, and because there is an air gap between the inductive coils, some power loss does occur. To mitigate this, wireless power transfer companies shape the electromagnetic wave form between the coils and keep the distances at a minimum. Additional efficiency issues with dynamic wireless power transfer include the rapid on-off switching of the sending coils, resistive losses due to long runs from electronics to coils, and less optimized magnetic field shaping. The same receiver coil can also be used in a stationary wireless power transfer application. This technology has been installed in several test and data collection applications, almost exclusively outside of the United States.

Table 3.5.2-1 Capabilities of Dynamic EV Charging Technologies

Capabilities of Dynamic EV Charging Technologies	
Level of Automation	High
Vendor Diversity	Low
Power Levels	Up to 250 kW
State of Technology	Developmental level
Applicable Standards	None

Vendor Examples

- Magment GmbH
- Electreon
- IPT Technology
- Integrated Roadways

Dynamic wireless electric vehicle charging technologies are listed within this Section 3.5.2.

3.5.2.1 Magment GmbH

Magment is focused on using magnetizable concretes for their dynamic wireless charging. Their magnetizable concrete is composed of cement and magnetic particles of electronic waste that has been recycled. Magment permits other entities to produce their product. These entities include concrete pre-casting companies, specialized cement manufacturers, or industrial flooring providers with specialized training. Magment's goal is to offer power levels from 200W to 250kW.

Current projects in development that include the use of Magment technology include a collaboration with the Indiana Department of Transportation (DOT) and Purdue University in three phases. Phases one and two will include testing of pavement, analysis, and optimization research to be conducted at Purdue University. In the third phase, a quarter-mile long test bed will be constructed that will permit engineers to test the concrete's capacity to charge heavy trucks operating at high power (higher than 200kW). This technology is planned to be implemented for a stretch of highway in Indiana.

Also, the State of Michigan is planning an Inductive Vehicle Charging Pilot in the Greater Detroit area for one mile roadbed made from magnetizable concrete by Magment.

3.5.2.2 Electreon

Electreon is an Israel-based firm developing wireless charging technology. Electreon's technology utilizes under-road units built of rubber-coated copper coils embedded approximately four inches under the asphalt. A management unit transfers the energy from the electrical grid to the road infrastructure and manages communication with approaching vehicles. Vehicle units have receivers installed on the vehicle floor to transmit the energy directly to the battery while driving. The central control unit operates on a cloud, enabling it to communicate with all management units and all registered vehicle units. Each roadside management unit can cover up to 110 yards of road, charging multiple vehicles simultaneously. Roadway infrastructure coils can be retrofitted within an existing guideway where reinforced concrete is not in conflict with coil locations and space is available for charging management infrastructure.

Currently deployed projects include one in Tel Aviv, Israel and another in Gotland Island, Sweden. Smartroad Gotland is a 1.6 km stretch of electric roadway between the airport and town center of Visby on the Swedish island of Gotland. The project is financed by the Swedish Transport Administration (Trafikverket) as part of their goal to reduce CO_2 emissions from heavy transportation. The coil segments are designed to be durable for 15 years, while the management unit will undergo periodic maintenance every 2 years for dynamic charging and 5 years for static charging.

Projects in deployment are in Karlsruhe, Germany and the A25 Toll Road in Lombardy, Italy. These projects have sought to demonstrate how Electreon technology can charge multiple EV types, including light, medium, and heavy duty vehicles, and allow for lower-capacity batteries within these vehicles. The company also announced its first U.S. roadway project with the Michigan Department of Transportation (MDOT) and expects to break ground in the summer of 2023. Electreon recently announced a 5-year agreement with MDOT to expand beyond the Detroit project and to develop an electric road system for the state of Michigan.

Electreon also has an operational demo track at Utah State University, dynamically charging a Kenworth truck. Recently, Electreon and ASPIRE announced a 1-mile project for dynamic charging at the Utah Inland Port, as well as partnership on wider fleet electrification in Utah and establishing electric road corridors to west-coast states.

3.5.2.3 IPT Technology

IPT PRIMOVE wireless charging technology works via magnetic inductive power transfer, with current flowing from ground winding coils to a receiver pad located beneath a vehicle.

IPT PRIMOVE's dynamic wireless charging concept has been tested at various sites in Belgium and Germany utilizing various vehicle types ranging from conventional passenger cars to buses and trucks.

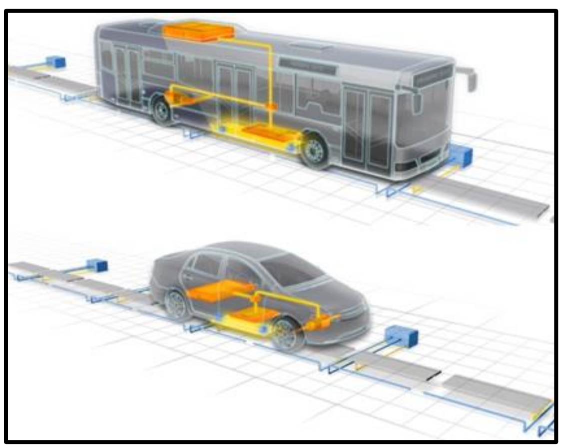


Figure 3.5.2.3-1 IPT PRIMOVE Dynamic Charging

3.5.2.4 Integrated Roadways

Integrated Roadways is developing precast concrete sections called Smart Pavement. Smart Pavement is embedded with digital technology and fiber optic connectivity, that will allow for such things as collection of traffic data, wireless EV charging, assisted autonomy, and wireless networking. Key characteristics of Smart Pavement slabs include modularity, accessibility, removability, and upgradability. They are designed to meet local paving requirements.

The Brighton Blvd. Project is a pilot project in Denver, CO that commenced in September 2018. At this location, the first Smart Panels were installed to capture traffic data. Integrated Roadways plans to have another pilot project with wireless charging capability included in 2023.

3.6 EV CHARGING TECHNOLOGY EVALUATION

A wide range of EV charging technologies are included in this report since these technologies are evolving and technology manufacturers are continuously making strides in their development.

NCTCOG issued an RFI requesting information and input for innovative wireless charging technologies that could be implemented to provide dynamic charging to rubber-tired ATS technologies that would operate on dedicated guideways. Based on the stage of development of dynamic charging, static/opportunity wireless charging for the same types of vehicles and applications was included in the RFI.

The RFI was issued on July 8, 2022, with responses due August 5, 2022. NCTCOG received two responses from wireless EV charging technology suppliers; these responses confirmed the EV charging research completed for this study. The responses also provided additional detailed information regarding the wireless charging equipment that informed the guideway design guidelines.

The intent of the wireless charging research was not to evaluate each individual technology, but rather to learn about the state of the industry, providing a set of recommendations for how to include this technology in future regional transportation planning. Figure 3.6-1 depicts the fundamental questions used to obtain information from technology manufacturers.

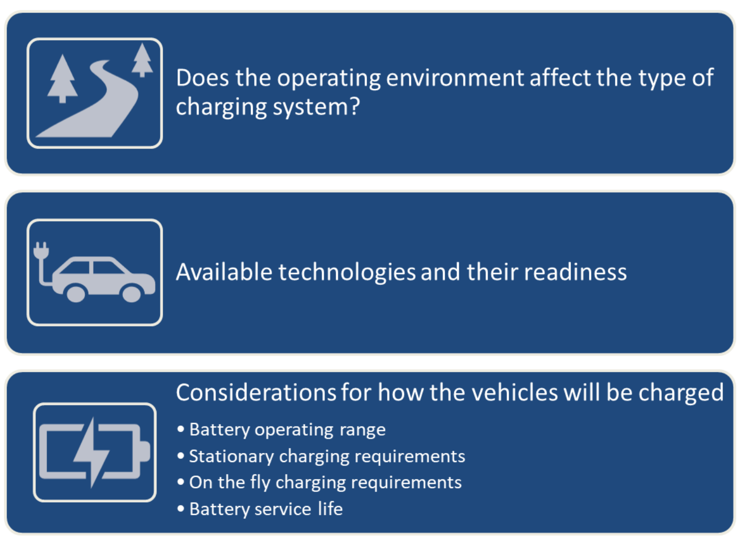


Figure 3.6-1 Guidelines for Assessing EV Charging Technologies

Currently, dynamic EV charging technologies are not yet ready for commercial use, though the pilot projects underway aim to make these technologies more commercially available in the near future. Results from these pilot projects may help advance the technology to make it suitable for use in the region and make it adaptable for different vehicles. Static/opportunity wireless charging is commercially deployed and could be a good option for near-term ATS projects.

4. GUIDEWAY DESIGN GUIDELINES

The development of the ATS guideway design guidelines is included in this section of the report. The task was to develop guidelines for a simple, paved guideway with a streamlined lightweight appearance that uses modular construction and innovative design materials and methods. Other practical considerations included environmental sustainability, initial cost, lifetime maintenance costs, consideration of business risk (consideration for other factors not included in this list such as fire ratings, etc.), availability of materials, and geometric compatibility (curvature). For the guideway system to be modular and streamlined, weight was a major consideration. Complementing the streamlined visuals of an ATS vehicle, the guideway structure was designed to have a signature look; the structural components were designed to be modular (so they can be prefabricated to the extent possible), understanding that there are situations that preclude any bridge element preconstruction. New information regarding design and materials becomes available every day as Accelerated Bridge Construction (ABC) becomes more common.

4.1 GUIDEWAY DESIGN ALTERNATIVES AND EVALUATION

A key requirement is to create a somewhat standardized, modular system without excessive delays for design and construction, understanding that there are limitations to this concept. The concept for the substructure and superstructure components is to design them so that each component can be prefabricated in multiple pre-designed sections that can be stockpiled if desired. Then the sections can be assembled on site to create the completed guideway component and ultimately, the finished guideway. For the purposes of guideway design, the component structure can be thought of as a long bridge hence the terminology is used interchangeably herein.

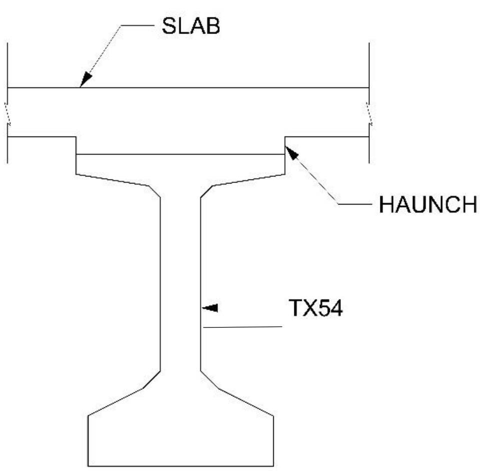


Figure 4.1-1 Haunch

Certain details in the design process cannot be standardized. These details cannot be developed without knowing site-specific details of the alignments and major components of the specific bridge. One example is the haunch illustrated in Figure 4.1-1. The haunch may seem like a minor detail, but it is used to adjust for differences in elevations between the top of the girder and the deck. The haunch height varies along the length of the girder and is affected by girder camber, superelevation and vertical and horizontal curvature. The average haunch height is estimated by the designer but is adjusted and cast by the contractor to accommodate the varying conditions. However, where possible, this study seeks to create a guide to start from for site-specific design, creating a theme/similar look for future ATS guideways throughout the region.

4.2 COMPONENTS AND MATERIALS CONSIDERED

The possibilities for modular elevated ATS guideway structures were examined based on ABC principles. Structure types, materials, methods of construction, and configurations were evaluated based on criteria derived from the above goals and design guidelines. Every feasible option was considered.

4.2.1 Assumptions

Because of the infinite possibilities for configurations of the structures, assumptions were made to determine an initial concept. Some assumptions will be included in the specific relative sections of this report, but the following overall assumptions are provided here:

- This is a guideline for the purpose of defining a guideway concept. Construction drawings and final design are not provided in this document. All structures must have a final design performed, sealed, and signed by a Texas Professional Engineer.
- This concept is developed for simple span units.
- All foundations will be individually designed based on site-specific soil conditions, which are highly variable.
- Because of variability in horizontal and vertical alignments, there will be some elements that must be individually designed.
- General span lengths are limited to 60 feet for small water crossings and roadways, 90 feet for crossing arterials, and 120 feet for crossing major thoroughfares and highways.
- Designs will be based on current standards at the time of the study.
- Station design and at-grade design are not included in this study.

4.2.2 Bridge Types

A bridge consists of basic components, the deck which supports the vehicles, the superstructure (which includes the deck), the substructure (which supports the superstructure) and the foundation, which supports everything. For this report, the superstructure is referred to as “framing”.

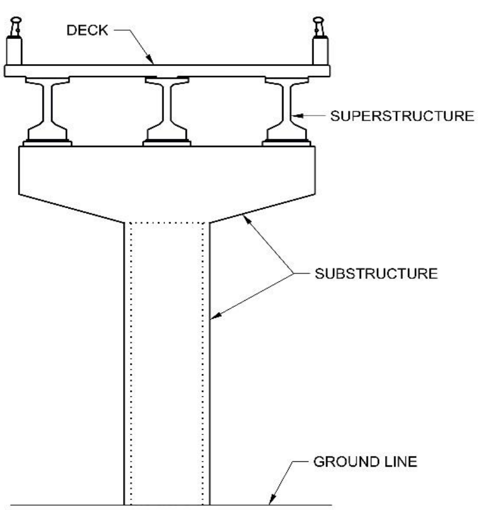


Figure 4.2.2-1 Bridge Components

Overall superstructure types for this study covered the spectrum of very complicated to very simple. The most complicated structures – cable stayed, suspension, arch and truss – were considered, but eliminated because of cost, not only in design and construction but also lifetime maintenance cost. These structures meet the streamlined criteria but fail in many others. Any structure that has limited redundancies for steel members in tension is considered fracture critical and requires hands on, biennial inspection. This means that any fracture critical members must be inspected close-up, close enough to touch. Although beautiful, these structures are not practical for this application. Short span superstructure elements, such as timber, were also not considered.

Innovative methods of construction were also considered. ABC is a relatively new concept that was developed to decrease impact on traffic due to construction. Bridge members are constructed or cast off-site and assembled on-site. For most bridge elements this would meet the innovative and modular criteria. The most innovative concepts, such as 3D printed bridges, have developed for concrete, plastic composites, and stainless steel, but have only been used for short span and pedestrian bridges. The concept has not developed enough to be practical for this study. Advances in bridge construction and materials are developing quickly so what cannot be considered today may be possible in the future. The bridge elements were evaluated in three categories, the superstructure broken up into framing (beam systems) and decking, with the main substructure element considered being columns (column caps were also considered).

4.2.2.1 Framing

The most common shape for bridge beams is the basic I shape. TxDOT has developed a concrete prestressed beam, called an I-Girder, with heights ranging from 28 in. to 62 in. and that can accommodate spans up to 135 feet. For this evaluation, built-up steel plate girders and all rolled steel shapes that have the basic I shape (WF, S, M, H and HB) are considered in the I-Beam/Girder category.

U-beams are another common shape. U-beams, tub girders, trapezoidal tub girders or any girder with a basic U shape is included in this category. U-beams are also common where a smooth edge shape is desired.

Other framing systems including trusses, cable-stayed and suspension systems were considered initially because of their unique appearance. Cable-stayed and suspension bridges also have a sleek and pleasing appearance. These structures are usually steel which have an increased lifecycle cost and fail in the areas of modular capability and geometric compatibility. Each of these structures requires individual and complex design and are generally straight spans accommodating very little to no curvature. There are locations where specialized designs may be considered, such as a guideway structure over a river or a park area.

4.2.2.2 Decking

Cast-in-place (CIP) concrete and precast/prefabricated deck panels were examined. Every configuration that is not CIP is considered a panel system.

4.2.2.3 Columns

Conventional cast-in-place (CIP) concrete columns, precast concrete columns and steel columns were considered. Fiber wrapped or concrete filled steel columns could be considered, but they generally increase the cost relative to the conventional column types.

4.2.3 Materials

Each material was evaluated considering how it would perform for its particular function. For the decking elements, CIP concrete and precast concrete panels, both normal and lightweight concrete mixes, were evaluated (see Appendix C for concrete property comparisons). Fiber Reinforced Polymer (FRP) and Recycled Structural Plastic Composite (RSPC) were two innovative products also considered. See Appendix D for innovative material information.

For the superstructure framing elements, concrete, steel, FRP and RSPC materials were considered.

For the substructure components, only concrete (CIP and precast) and steel were considered. Fiber wrapped columns or concrete filled steel columns would provide little additional benefit and would add to the cost but may be practical in high seismic areas. Steel pipe columns are designed as compact sections, and to be a compact section, the unbraced height of the column is limited. Each bridge type was also evaluated by material type and in the case of 3D printing, construction type.

RSPC is made from plastic waste and is conceptually ideal for short span bridges, but do not meet the span requirements for this study. The elements are lightweight, could be easily stockpiled, can be altered on site, and use a waste product that could alternatively contaminate waterways and fill landfills. However, construction of bridge elements and investigations of the potential for spans longer than about 40 feet has stopped, making it not a viable alternative. RSPC planks, which are currently being manufactured for railroad ties could be used for deck planking but would not be a preferred deck configuration. The Easter Dawick Bridge in Scotland (Figure 4.2.3-1) was constructed with approximately 2205 pounds of waste plastic consisting of deck planks and built-up I section superstructure. It is the longest RSPC bridge overall at 90 feet with short spans of 30 feet each.

Figure 4.2.3-1 Easter Dawick Bridge, Scotland

FRP is also a lightweight, innovative material considered. While FRP was not considered for substructure elements, it was considered for both beams or decking material (see Figure 4.2.3-2 and 4.3.2-4). Although a manufacturer in Maine (AIT Bridge) ensures their “GBeam”, an FRP U-Beam that spans up to 120 feet, can maintain its structural integrity for one hour at 2,000°F, there is some concern that this innovative material may not stand up to certain risks that traditional materials are periodically exposed to (i.e. vehicle fire near or under the FRP structure). Additionally, the limited number of manufacturers and suppliers may affect availability of the product, which is a significant criterion considered in material selection for this study. This material warrants further investigation and may be suitable for various ATS applications depending on the site constraints.

Figure 4.2.3-2 FRP Beam, Mostostal Warszawa

Figure 4.2.3-3 Construction of GBeam Bridge

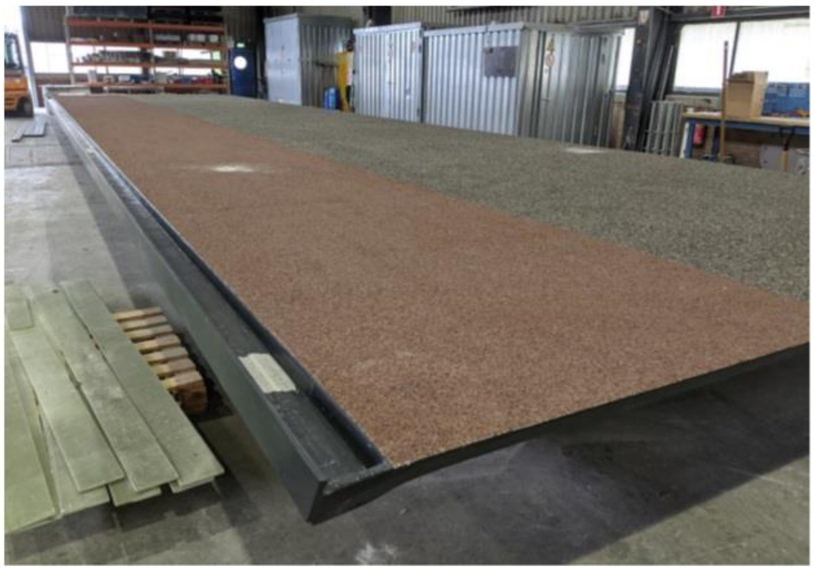


Figure 4.2.3-4 FRP Deck

Steel is one of the most common bridge materials, but it has higher lifetime maintenance costs than concrete. To prevent corrosion, it must be weathering steel or painted. Steel superstructure may be required because of length and/or curvature but is not cost effective for bridges that do not require steel.

Concrete is the most common bridge material in most of the US and is widely available. In addition, many precasting facilities are located in north Texas, so neither material availability nor manufacture of elements is problematic. Lightweight concrete is a more innovative material for bridges than normal weight concrete and is a great material for precast deck slabs, which have the advantage that they can be cast locally. For some beam designs, lightweight concrete should be used where possible to reduce construction crane capacity requirements and loads on foundations, and to modestly increase spans without increasing beam depths. For precast segmental column sections, normal weight concrete is the best option. Lightweight concrete may be used if it can achieve the required strength.

Common precast concrete beam/girder shapes are I-beams and U-beams. Local manufacturers are experienced in casting them, and local contractors are experienced with their installation. The most common materials are concrete and steel, with concrete being the most common material in the southern

US. Steel is generally used for long spans and curved bridges. Box beams of steel or concrete are often used for overcrossings with low clearance. Precast concrete beams can be used for a curved bridge if the curve radius is large enough to construct the bridge using straight, chorded beam sections.

4.3 METHODOLOGY FOR EVALUATION OF GUIDEWAY SYSTEM

A list of framing, decking and column elements was developed by material. During the investigation, it was important to acknowledge that each manufacturer has a vested interest in the sale of their product, so manufacturers' opinions were discounted, and performance was evaluated by test results, maintenance, and estimated service life as provided by the vendors.

Initial evaluation of the concepts included performance in the following areas (see Tables 4.3-1 and 4.3-2):

- Modular Capability - ability to develop standardized sizes/shapes to fit together in a pre-defined fashion
- Streamlined Appearance – the preferred aesthetic is a sleek, streamlined guideway
- Weight - lighter weight materials are more preferrable to aid in streamlined appearance, constructability, and cost
- Availability – availability of materials within this region
- Geometric Capability (Curvature) – material must be able to conform to design geometry
- Business Risk Consideration - other elements like fire retardance or ability of material to corrode easily
- Innovation – new innovative materials are desired
- 60 feet Span – material must work for specific span length
- 90 feet Span - material must work for specific span length
- 120 feet Span - material must work for specific span length
- Initial Cost – implementation costs
- Lifetime Maintenance Cost – operation and maintenance costs
- Sustainability – it is desired to use sustainable materials when possible

Table 4.3-1 Initial Evaluation of Framing Elements

Elements Type & Material	Modular Capability	Streamlined Appearance	*Weight	Availability	Geometric Compatibility (curvature)	Business Risk Consideration	Innovation	60' Span	90' Span	120' Span	Initial Cost	Lifetime Maintenance Cost	Sustainability
Framing													
I-Beam/ Girder (Concrete)	★	▽**	●	★	▽	★	●	★	★	▽	★	●	●
I-Beam/ Girder (LTWT Concrete)	★	▽**	▽	★	▽	★	▽	★	★	▽	★	●	●
I-Beam/ Plate Girder (Steel)	★	▽**	▽	▽	★	▽	●	★	★	★	▽	●	★
I-Beam/ Girder (FRP)	★	▽**	★	●	▽	●	★	★	★	⊗	●	★	▽
I-Beam/ Girder (RSPC)	★	●	★	▽	▽	●	★	▽	⊗	⊗	●	★	★
Truss (Steel)	▽	▽**	▽	▽	⊗	▽	●	★	★	★	▽	●	★
Truss (RSPC)	▽	⊗	★	▽	⊗	●	★	▽	⊗	⊗	★	★	★
U-Beam (Concrete)	★	▽**	●	★	▽	★	●	★	★	▽	★	●	●
U-Beam (LTWT Concrete)	★	▽**	▽	★	▽	★	▽	★	★	▽	★	●	●
U-Beam (Steel)	★	▽**	●	▽	▽	▽	●	★	★	▽	★	●	●
U-Beam (FRP)	★	▽**	★	▽	▽	●	★	★	★	▽	●	★	★
Suspension (Steel)	⊗	●	●	⊗	⊗	▽	▽	★	★	★	●	●	★
Cable-Stayed (Steel)	⊗	●	●	⊗	⊗	▽	▽	★	★	★	●	●	★

*	Weight is included in the requirements because it will have a significant effect on the support system
**	Depends on type, span length and design criteria
UNK	UNKNOWN
LTWT	LIGHTWEIGHT

Rating Criteria

- ★ Meets the requirements without limitations
- ▽ Will meet the criteria with limitations or there are better options.
- ● Least advantageous
- ⊗ Does not meet Criteria

Table 4.3-2 Initial Evaluation of Decking, Columns, and 3D Elements

Elements Type & Material	Modular Capability	Streamlined Appearance	*Weight	Availability	Geometric Compatibility (curvature)	Business Risk Consideration	Innovation	60' Span	90' Span	120' Span	Initial Cost	Lifetime Maintenance Cost	Sustainabilility
Decking													
Precast Concrete Panels	★	★	▽	★	⊗	★	▽	N/A	N/A	N/A	★	▽	▽
LTWT Precast Concrete Panels	★	★	▽	★	⊗	★	▽	N/A	N/A	N/A	★	▽	▽
CIP Concrete	★	★	●	★	★	★	●	N/A	N/A	N/A	★	●	●
LTWT CIP Concrete	★	▽	▽	★	★	★	▽	N/A	N/A	N/A	★	●	▽
FRP Panels	★	★	★	●	★	⊗	★	N/A	N/A	N/A	●	★	★
RSPC Panels	★	★	★	●	★	⊗	★	N/A	N/A	N/A	●	★	★
Columns													
Concrete Columns	⊗	★	▽	★	★	★	●	N/A	N/A	N/A	★	★	●
Precast LTWT Concrete Columns	★	★	★	★	★	★	★	N/A	N/A	N/A	★	★	▽
Precast Concrete Columns	★	★	★	★	★	★	▽	N/A	N/A	N/A	★	★	▽
Steel Columns	★	★	★	▽	★	▽	▽	N/A	N/A	N/A	★	●	★
3D Printed Bridges													
Concrete	★	●	●	▽	★	●	★	★	▽	UNK	▽	▽	▽
Stainless Steel	UNK	★	▽	▽	★	●	★	UNK	UNK	UNK	●	▽	★
FRP	★	▽	★	▽	★	●	★	UNK	UNK	UNK	▽	★	★

*	Weight is included in the requirements because it will have a significant effect on the support system
**	Depends on type, span length and design criteria
UNK	UNKNOWN
LTWT	LIGHTWEIGHT

Rating Criteria

- ★ Meets the requirements without limitations
- ▽ Will meet the criteria with limitations or there are better options.
- ● Least advantageous
- ⊗ Does not meet Criteria

4.3.1 Evaluation Criteria and Weighting

The symbols were given a rating value, 0-3 (Table 4.3.1-1) and then an importance factor was applied to reflect the importance of each criterion (Table 4.3.1-2).

Table 4.3.1-1 Importance Factor Values

Rating Criteria	Symbols	
3	★	Meets the requirements without limitations
2	▽	Will meet the criteria with limitations or there are better
1	●	Least advantageous
0	⊗	Does not meet criteria

Each evaluation criterion was weighted for importance.

Table 4.3.1-2 Criteria Importance Factors

Guideway Criteria	Importance Factor (1-4)
Modular Capability	4
Streamlined Appearance	4
Weight	4
Availability	4
Geometric Compatibility (curvature)	4
Business Risk Consideration	4
Innovation	3
60' Span	3
90' Span	3
120' Span	3
Initial Cost	2
Lifetime Maintenance Cost	2
Sustainabililty	2

** A rating of 4 is the most important*

4.3.2 Evaluation and Recommendation for Guideway System

Recommendations from an extensive evaluation, based on the criteria identified above, resulted in the selection of lightweight concrete I-Beam/ Girder or U-beam if the concrete mix meets all design strength requirements (see Table 4.3.2-1). The beams recommendations are TxDOT I-Girders with girder depths determined by span length, with TX54 preferred. Lightweight concrete is preferred for all elements if the mix meets strength criteria. The FRP U-beam, which is now available in the United States, and steel I-Beam/Girder scored very close to the concrete beam ratings as well, providing options for future projects. For decking, the top-rated materials are FRP panels or lightweight precast concrete panels depending on the application. FRP panels were initially rated higher for the structure decking. However, discussions with the ATS Study Steering Committee highlighted concern for the business risk of FRP panels caused by external factors (e.g. personal vehicle fire underneath structure could create serious risk to structural integrity). For the columns recommendations are lightweight precast concrete columns, provided that the concrete mix meets all design strength requirements. Individual site parameters may alter the scoring for each material. 3D printed bridges were not given a final score since long-term performance information of these bridges was not readily available.

Table 4.3.2-1 Final Ratings Evaluation

Elements Type & Material	Modular Capability	Streamlined Appearance	*Weight	Availability	Geometric Compatibility (curvature)	Business Risk Consideration	Innovation	60' Span	90' Span	120' Span	Initial Cost	Lifetime Maintenance Cost	Sustainabililty	Total Rating
Framing														
I-Beam/ Girder (Concrete)	12	8	4	12	8	12	3	9	9	6	6	2	2	93
I-Beam/ Girder (LTWT Concrete)	12	8	8	12	8	12	6	9	9	6	6	2	2	100
I-Beam/ Plate Girder (Steel)	12	8	8	8	12	8	3	9	9	9	4	2	6	98
I-Beam/ Girder (FRP)	12	8	12	4	8	4	9	9	9	0	2	6	4	87
I-Beam/ Girder (RSPC)	12	4	12	8	8	4	9	6	0	0	2	6	6	77
Truss (Steel)	8	8	8	8	0	8	3	9	9	9	4	2	6	82
Truss (RSPC)	8	0	12	8	0	4	9	6	0	0	6	6	6	65
U-Beam (Concrete)	12	8	4	12	8	12	3	9	9	6	6	2	2	93
U-Beam (LTWT Concrete)	12	8	8	12	8	12	6	9	9	6	6	2	2	100
U-Beam (Steel)	12	8	4	8	8	8	3	9	9	6	6	2	2	85
U-Beam (FRP)	12	8	12	8	8	4	9	9	9	6	2	6	6	99
Suspension (Steel)	0	4	4	0	0	8	6	9	9	9	2	2	6	59
Cable-Stayed (Steel)	0	4	4	0	0	8	6	9	9	9	2	2	6	59
Decking														
Precast Concrete Panels	12	12	4	12	0	12	6	N/A	N/A	N/A	6	4	4	72
LTWT Precast Concrete Panels	12	12	8	12	0	12	6	N/A	N/A	N/A	6	4	4	76
CIP Concrete	12	12	0	12	12	4	3	N/A	N/A	N/A	6	2	2	65
LTWT CIP Concrete	12	8	8	12	12	4	6	N/A	N/A	N/A	6	2	4	74
FRP Panels	12	12	12	4	12	0	9	N/A	N/A	N/A	2	6	6	75
RSPC Panels	12	12	12	4	12	0	9	N/A	N/A	N/A	2	6	6	75
Columns														
Concrete Columns	0	12	8	12	12	12	3	N/A	N/A	N/A	6	6	2	73
Precast LTWT Concrete Columns	12	12	12	12	12	12	9	N/A	N/A	N/A	6	6	4	97
Precast Concrete Columns	12	12	12	12	12	12	6	N/A	N/A	N/A	6	6	4	94
Steel Columns	12	12	12	8	12	8	6	N/A	N/A	N/A	6	2	6	84
3D Printed Bridges														
Concrete	12	4	0	8	12	4	9	9	6	UNK	4	4	4	
Stainless Steel	UNK	12	4	8	12	4	9	UNK	UNK	UNK	2	4	6	
FRP	12	8	12	8	12	4	9	UNK	UNK	UNK	4	6	6	

4.4 GUIDEWAY DESIGN

As discussed in other sections of this report, the vehicles for this study are rubber-tired and will not be guided on rails. Because of this, the design criteria are a combination of Association of State Highway and Transportation Officials (AASHTO) Load-and-Resistance Factor Design (LRFD) Bridge Design Specifications and American Society of Civil Engineers (ASCE) Standard 21-21, Automated People Mover Standards (see Appendix E). The "roadway" area is wide enough to allow a passing vehicle in the event a vehicle stalls on the guideway. There is also sufficient guideway width for passenger emergency egress walk path. A composite vehicle was used to determine requirements, but design loads should be modified to use manufacturer's data when a vehicle is selected. Additional information and details can be found in Appendix C through Appendix H.

4.4.1 Basic Design Criteria

Basic design criteria include the following:

- Horizontal and vertical alignments shall be established to satisfy the vehicle ride quality requirements of ASCE 21-21.
- Structural design criteria shall be in accordance with AASHTO LRFD/ASCE LRFD Load Combinations (see Appendix E).
- Height of rectangular columns is anticipated to be 18 feet to 25 feet above ground.
- Maximum slope is 5% (based on ADA requirements).
- The unfactored composite vehicle weight is 18,000 pounds, fully loaded.
- Composite vehicle length 9 feet, axle spacing assumed to be 5 feet.
- Composite vehicle width 7.5 feet, wheel gauge assumed to be 6 feet.
- Tire contact area assumed to be 0.5 square feet.
- Guideway live load based on the composite vehicle and analysis was performed based on worst case moving loads and the multiple presence live load factors with a vehicle spacing of 50 feet between vehicles.
- Spiral transition curves are not required in the horizontal alignment.
- Tangent sections will have a normal crown not to exceed 2.0% cross slope.
- Deck will be superelevated in curves to allow for maximum speed in the curve (a superelevation table is provided in Appendix F-4).
- Deck panels will be leveled using bedding strips or leveling angles welded to angles cast into the girder top flanges.
- Deck slab thickness will be 8.5 inches to allow for diamond grinding at the joints, if necessary.
- Spans that incorporate sag or crest vertical curves will require special design for both the slab units and the exterior units.
- Curves with a radius less than what is shown below may require special design to configure the beam spacing and construction of the deck panels:

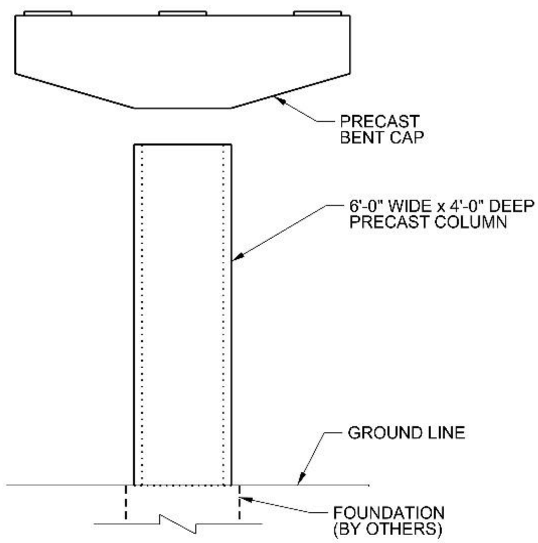
Table 4.4.1-1 Minimum Radius for Chorded Spans

Beam Spacing, S= 7.0 feet			
Minimum Radius for Chorded Spans			
Span Length (ft)	60	90	120
Minimum radius (ft)	1100	2200	4100
S/2 (ft)	3.4084	3.4385	3.44
	OK	OK	OK

Aesthetic details will be improved with architectural details including fascia panels to be determined at the time of project implementation.

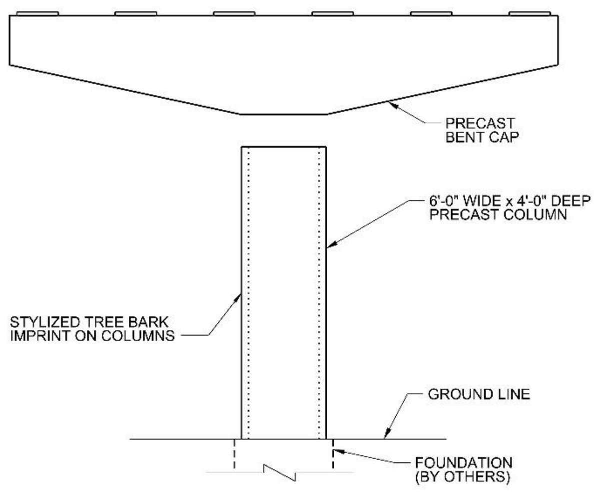
4.4.2 Structure Sections

The structures will be assembled from the ground up, with the foundations designed individually based on site-specific requirements. Foundation connections to columns will be designed in conjunction with the foundations.



SUBSTRUCTURE – The precast columns for both single direction and bidirectional structures are 6’-0” wide x 4’-0” deep and can be cast full length (height of column) by multiples of 5-’0”, for example, the precast columns would be 10’-0”, 15’-0”, 20’-0”, or 25’-0”. If the required height of the column is 17’-0”, the excess 3’-0” length would be buried. For aesthetic purposes, the foundation should not be exposed. The single direction cap is 20’-8” long, 4’-6” wide, 3’-6” deep at the ends and 5’-6” deep at the column. The cap for the bidirectional structure is 38’-10” long, 4’-6” wide, 3’-6” deep at the ends and 7’-0” deep at the column. Girder bearing pad details and elastomeric bearing details will be based on TxDOT standard designs for I-Girder structures. Grout pads over 4” high must be reinforced.

Figure 4.4.2-1 Single Direction Substructure Assembly



Both the single direction and bidirectional structures will require that the haunch (see Figure 4.1-1) be cast with the deck section on top of the girder. The exterior units will require special bracing at each stage - storage, transportation, and construction - because of their offset center of gravity. The slab sections will be levelled with bedding strips or welded angles and will be adjusted to accommodate the variable haunch height. To eliminate discontinuities in the surface of the deck, diamond grinding will be performed to smooth the surface. Precast full thickness overhang sections may be cast to eliminate the difficulties of precasting the haunch for exterior units. Modular details are provided in Appendix G and Girder Tables are provided in Appendix H.

Figure 4.4.2-2 Bidirectional Substructure Assembly

4.4.3 Final Structure Configuration

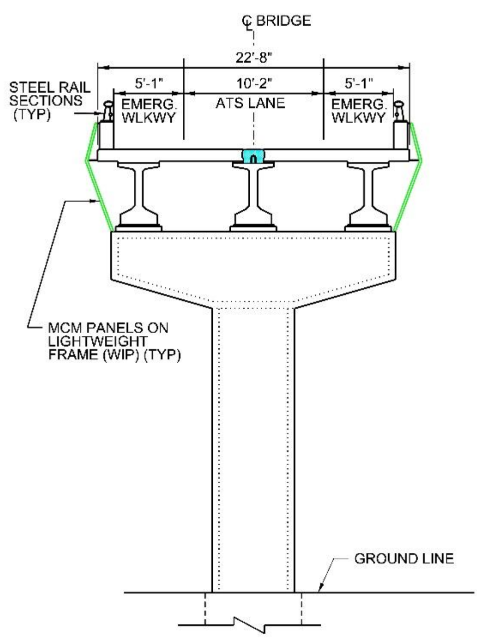


Figure 4.4.3-1 Single Direction Final Configuration

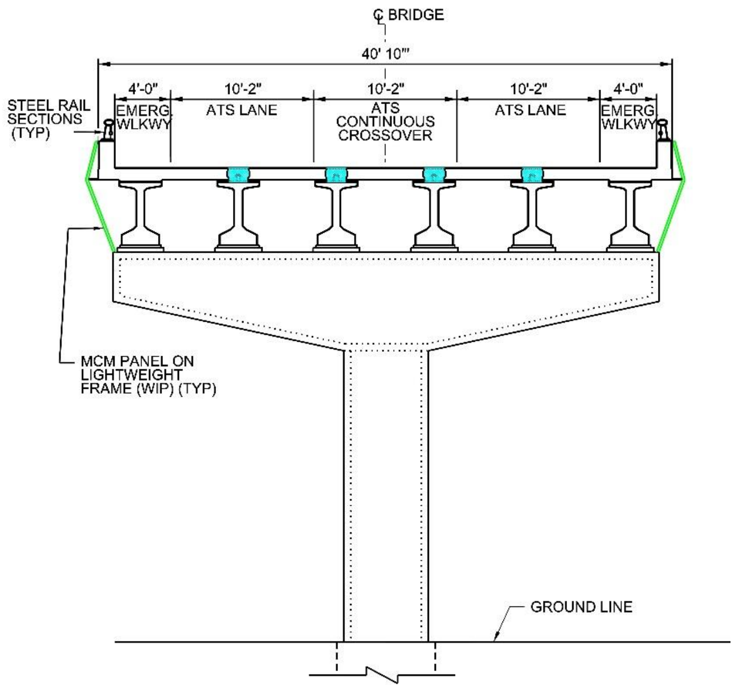


Figure 4.4.3-2 Bidirectional Final Configuration

Some AV technology suppliers recommend a physical barrier between lanes on which vehicles travel in opposite directions and there is currently no industry standard that provides definitive guidance. If required by the selected AV supplier, a barrier should be provided to satisfy their recommended safety requirements. Depending on the operational requirements, gaps in such barriers may be necessary to allow a vehicle to pass a stalled vehicle or otherwise provide for continued operations during vehicle failure conditions. Specific configurations should be coordinated during detailed design considering such operational and failure management requirements.

4.4.4 Aesthetic Considerations

To improve the aesthetics of basic concrete elements, there are multiple options from dyeing the concrete to adding appurtenances to the structure. One of the options includes designing form liners to cast a pattern into the columns and caps. Patterns can be designed to connect the structure and its use with the history or values of the surrounding community; the value added from simple enhancements can increase community adoption and acceptance of the new facility. Two example considerations for aesthetic concepts are provided here with a “sky” theme for a round column and a “forest” theme for a rectangular/square column. Panels of metal composite materials (MCM), as shown in Figures 4.4.4-1 through 4.4.4-6, or other lightweight fascia panels may be added to provide a signature look.

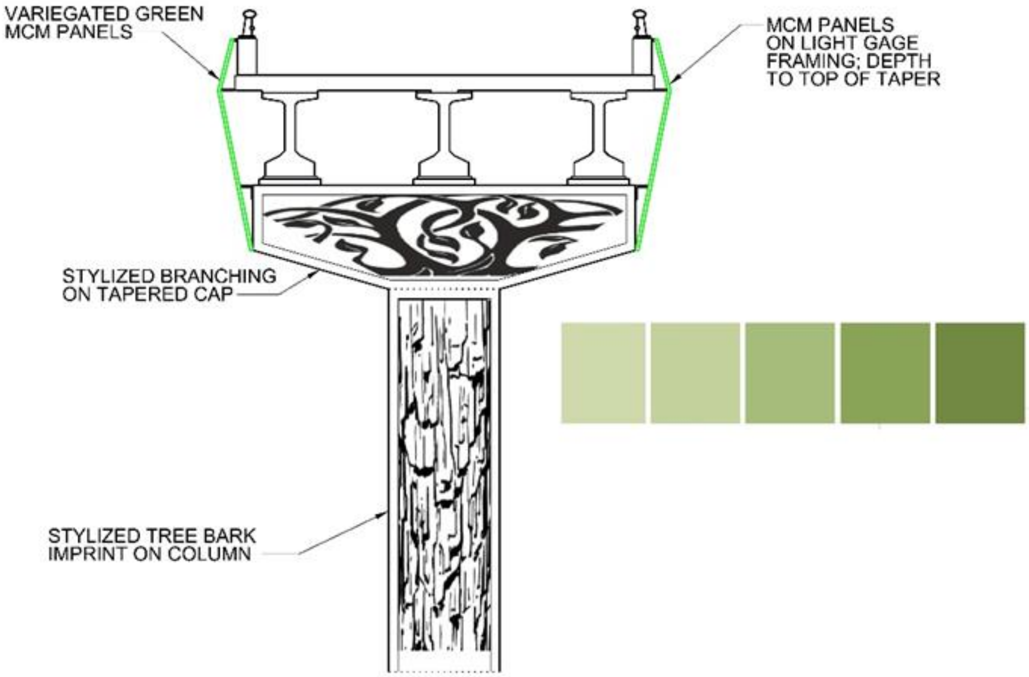


Figure 4.4.4-1 Forest Aesthetic for Single Direction Guideway

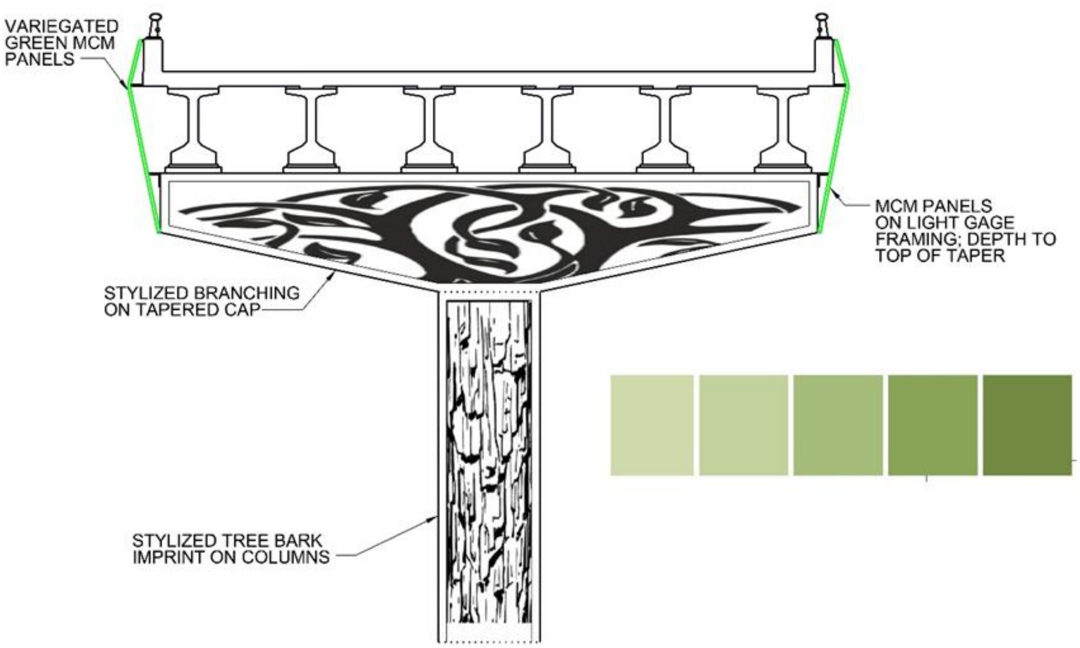


Figure 4.4.4-2 Forest Aesthetic for Bidirectional Guideway

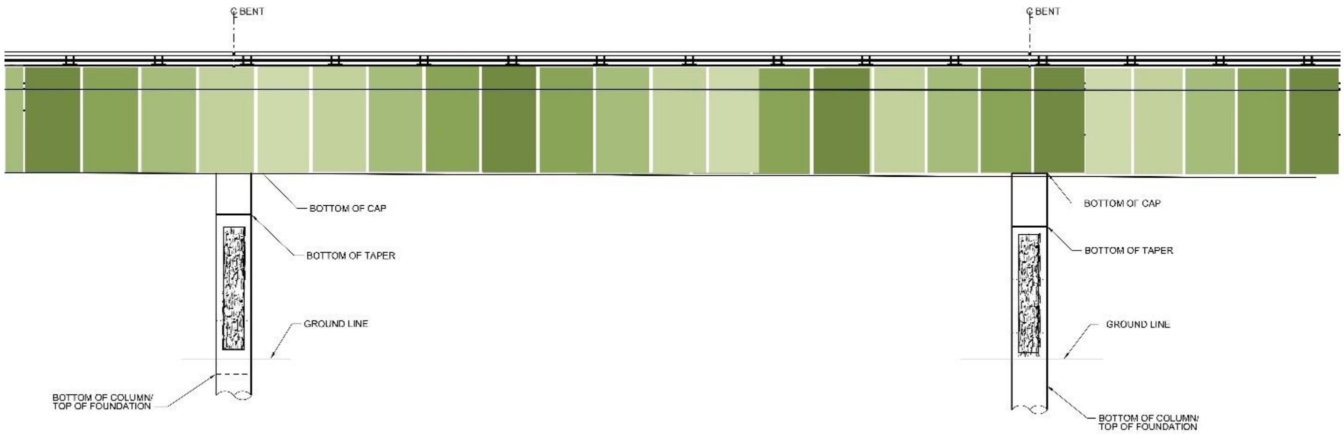


Figure 4.4.4-3 Side View of Forest Aesthetic

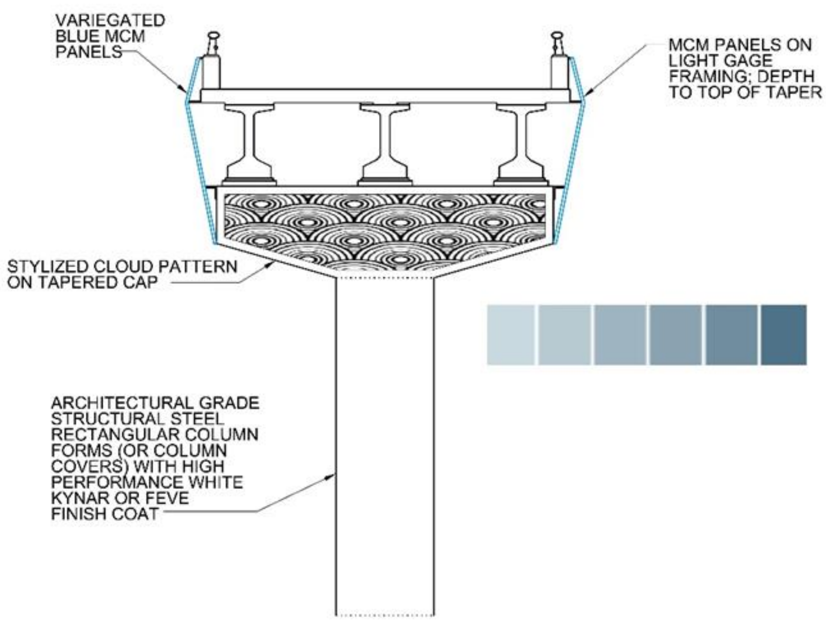


Figure 4.4.4-4 Sky Aesthetic for Single Direction Guideway

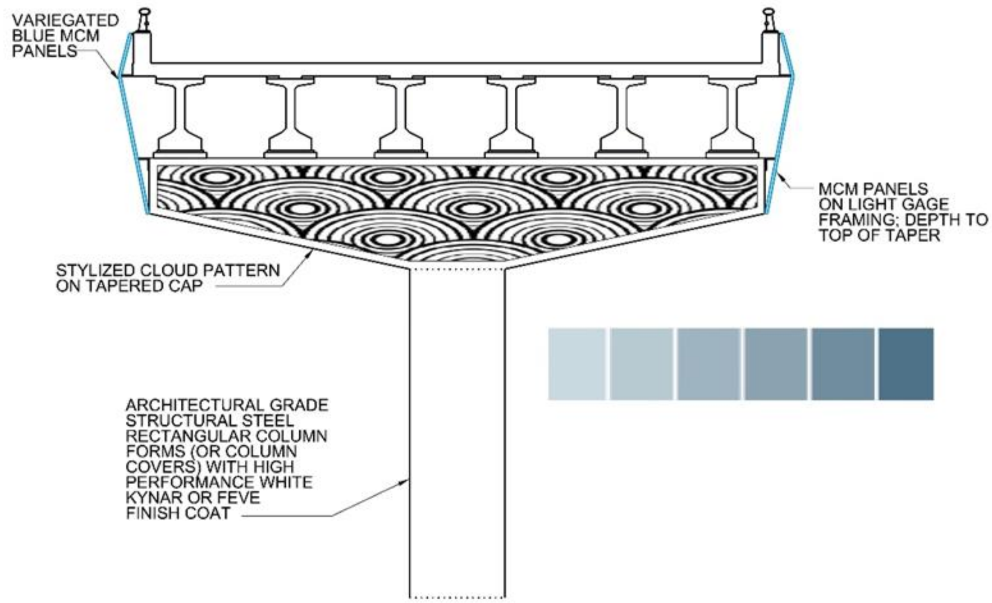


Figure 4.4.4-5 Sky Aesthetic for Bidirectional Guideway

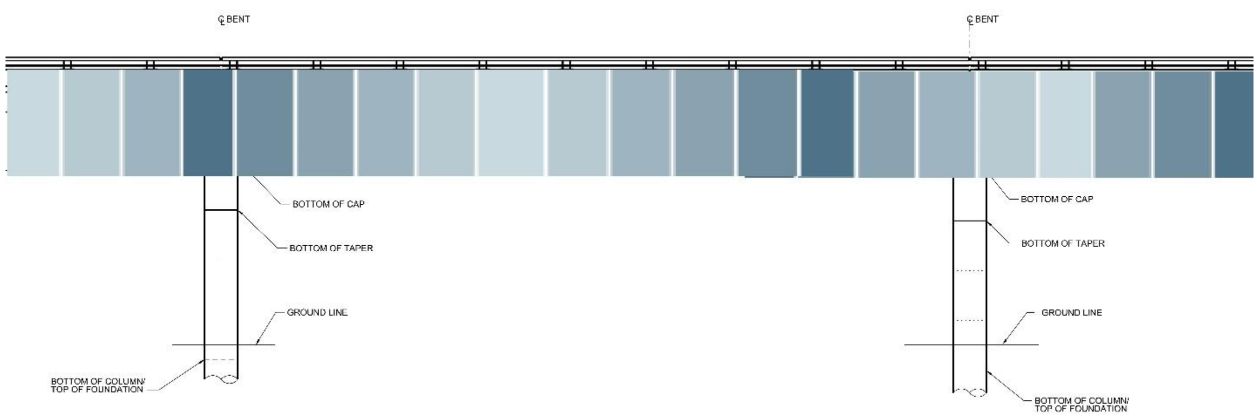


Figure 4.4.4-6 Side View of Sky Aesthetic

4.5 WIRELESS CHARGING CONCEPT

The following drawings present a possible concept for wireless charging installed in the superstructure. Power connections would be installed in the bridge rails and junction boxes could be installed intermittently over the girders in the UHPC joints as shown in the elevation view.

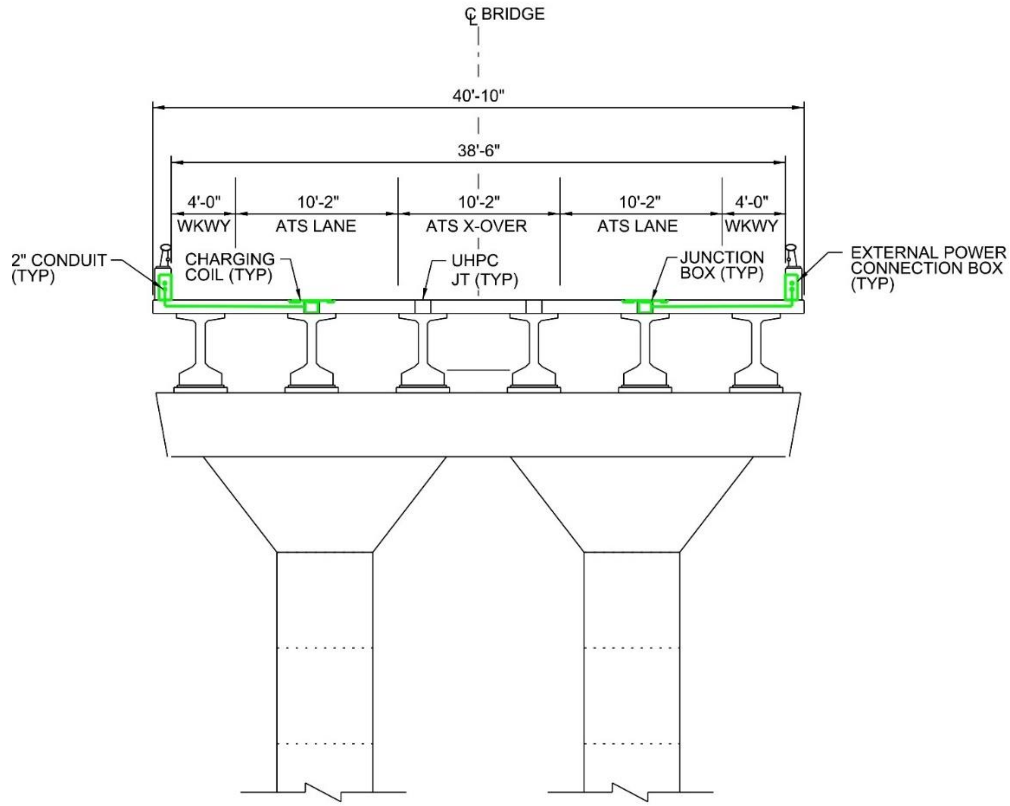
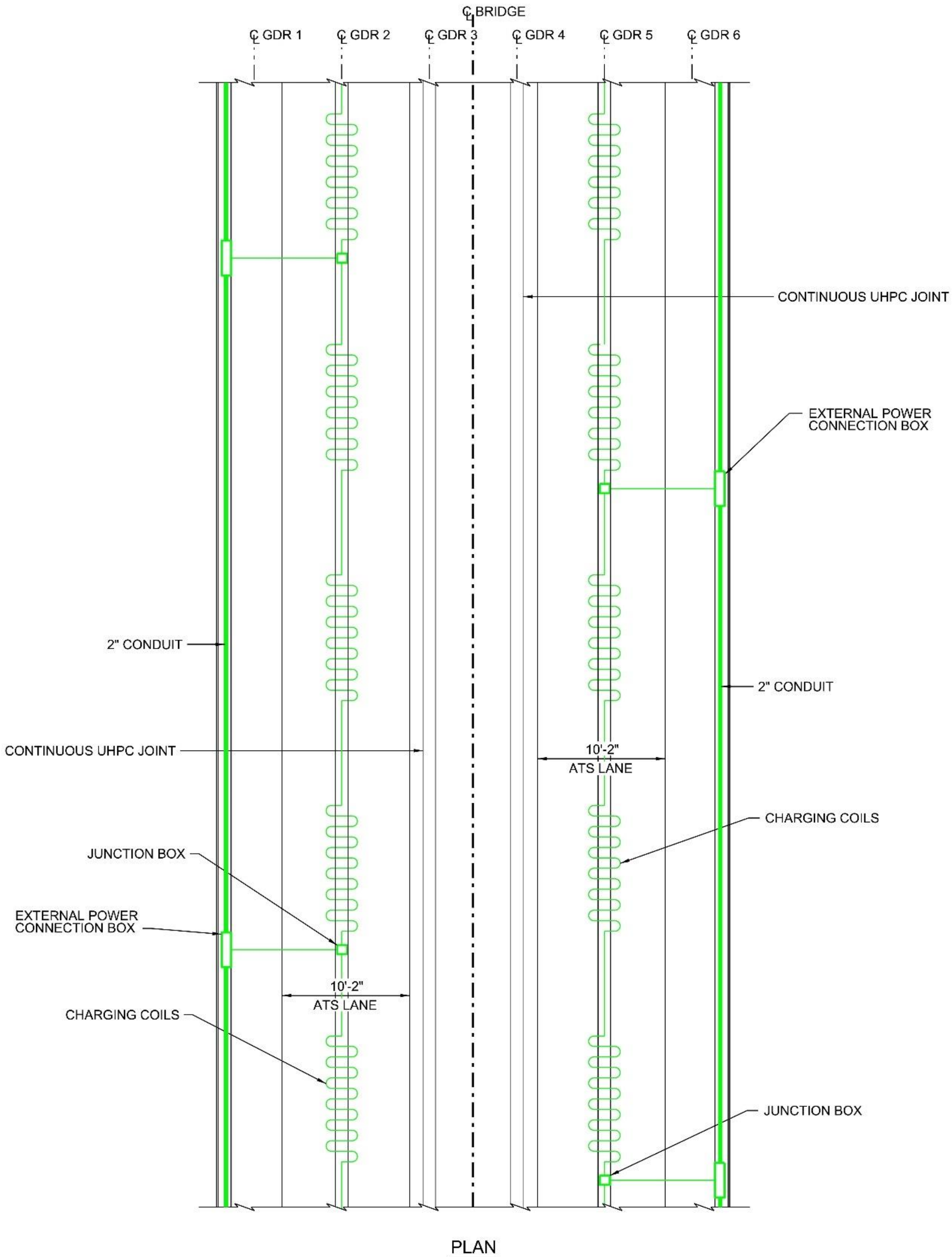


Figure 4.5-1 Section View of Charging Concept



THESE DRAWINGS REPRESENT CONCEPTUAL LAYOUT FOR WIRELESS CHARGING. THEY ARE NOT BASED ON ANY KNOWN SYSTEM OR CONFIGURATION. BECAUSE THE SYSTEM AND CONFIGURATION ARE NOT KNOWN, NO STRUCTURAL DESIGN CHECKS HAVE BEEN PERFORMED TO DETERMINE THE STRUCTURAL CAPACITY OF THE DECK OR THE UHPC JOINTS WHERE THE CHARGING MECHANISMS ARE SHOWN.

UHPC = ULTRA-HIGH PERFORMANCE CONCRETE

WIRELESS CHARGING ELEMENTS REPRESENTED IN GREEN.

Figure 4.5-2 Plan View of Charging Concept

5. FUTURE IMPLEMENTATIONS

This study offers broad performance guidelines that can help shape future projects. One of the primary goals of this study is to achieve an economy of scale by streamlining outcomes throughout the region. The sections below discuss ideas for possible implementations in the DFW area. The analysis for the options presented here was done primarily to obtain additional information regarding the possible fit of the inventoried vehicles in real-life scenarios and to calibrate the existing vehicle inventory as needed. The desired outcomes of these future implementation scenarios will have to be addressed by the owners of these sites/systems, and project parameters based on those desired outcomes will need to be established.

5.1 DALLAS INTERNATIONAL DISTRICT

The plans for the Dallas International District, located at the old Valley View Mall location north of IH 635 between the Dallas North Tollway and Preston Road, are under development. Previous efforts have advanced an ATS circulator integrated with parking strategies, multi-use and dense developments, and transit hub connections. However, at the time of this study, the plans for the new development are not advanced enough to engineer an ATS specifically for this site. As planning efforts continue for this site, the review of AV technology and wireless EV charging technologies, as well as the guideway design guidelines developed through this study can be used as a foundation for system design as the development advances to the next stage.

5.2 GENERAL MOTORS MANUFACTURING FACILITY IN ARLINGTON

Given the specific requirements of OE-A (cargo/goods movement in manufacturing environment) in Section 2 above, the General Motors manufacturing facility offers an opportunity to evaluate the feasibility of using AV technology to provide an efficient means of connecting products and supplies between a manufacturing facility and a heavy freight railhead. In this case, a direct and dedicated bridge/guideway could provide the opportunity for an ATS to provide reliable, frequent trips, replacing trucks carrying these goods on adjacent public roadways.

To support study development and ensure the vehicles inventoried provided a range of potential solutions in a goods movement environment, three operational configurations reviewing various AV technologies were developed for a high-level analysis. These vehicles are not indicative of final recommendations; they were chosen to provide variables for each scenario based on characteristics such as capacity and speed. The details of this analysis are included in Appendix I, and the results yield an estimation of the approximate number of vehicles, depending on the technology and route chosen, required for the ATS fleet to successfully meet the needs of the GM facility. Dynamic wireless charging, though not included in analysis here, could also play a role in fleet size as well as size of battery needed for each vehicle.

Table 5.2-1 below shows the results of the fleet analysis performed for each of the operational configurations. The results of the analysis are the approximate number of vehicles each option would require given all the assumptions based on the project team's understanding of the operational parameters and needs of the GM facility.

Table 5.2-1 Fleet Analysis for EO-A

Route / Autonomous Vehicle Technology	Total Round-Trip Distance (ft)	Total Round-Trip Time (min)	Operational Headway (min)	Operational Fleet Required	Total Fleet Required
OPTION 1 Stanley Robotics	10,449	22.3	1.5	15	18

Route / Autonomous Vehicle Technology	Total Round-Trip Distance (ft)	Total Round-Trip Time (min)	Operational Headway (min)	Operational Fleet Required	Total Fleet Required
OPTION 2 Kodiak Robotics / Outrider	11,919	25	6.1	5	6

Route / Autonomous Vehicle Technology	Total Round-Trip Distance (ft)	Total Round-Trip Time (min)	Operational Headway (min)	Operational Fleet Required	Total Fleet Required
OPTION 2 Oceaneering Cargo Rapid Transit (CaRT)	11,919	13	1.5	9	11

Route / Autonomous Vehicle Technology	Total Round-Trip Distance (ft)	Total Round-Trip Time (min)	Operational Headway (min)	Operational Fleet Required	Total Fleet Required
OPTION 3 Kodiak Robotics / Outrider	6,494	20.9	6.1	4	5

Route / Autonomous Vehicle Technology	Total Round-Trip Distance (ft)	Total Round-Trip Time (min)	Operational Headway (min)	Operational Fleet Required	Total Fleet Required
OPTION 3 Oceaneering Cargo Rapid Transit (CaRT)	6,494	8.9	1.5	6	8

6. APM SYSTEMS RETROFITS

The study goal of assessing concept applicability to retrofit projects in the region is directly linked to the vision of a regional standard for Automated Transportation Systems (ATS) that can withstand the test of time and continual advancement of technology. Creating an ATS that is "future-proof" includes reviewing yesterday's technology applications and ensuring the potential for upgrading those facilities to tomorrow's standards. A set of ATS design guidelines for new applications precluded from use on existing infrastructure within the region would have significantly less value than guidelines that could serve both purposes. The two existing retrofit opportunities within the north Texas region are the Las Colinas Urban Center APT and DFW International Airport Skylink APM.

The existing Las Colinas APT guideway was studied to determine the potential of a retrofit utilizing the existing structure with new vehicle technology and EV charging system. Potential modifications to the existing Las Colinas APT structure are suggested to accommodate rubber-tired ATS vehicle technology. For the DFW Skylink APM, a cursory review of the existing structure was also performed with a focus on analyzing the effect on fleet size given the reduced capacities of ATS vehicles compared to the existing APM.

6.1 POTENTIAL RETROFIT FOR LAS COLINAS APT

The Las Colinas Area Personal Transit system is a transit system located in the Las Colinas area of Irving, Texas, in the heart of the Dallas-Fort Worth metroplex. The Dallas County Utility and Reclamation District (DCURD) owns and operates the Las Colinas APT System, which was put in passenger service in 1989. The APT system ceased operations in recent years. Bidirectional guideway structure exists throughout the existing system. Proprietary APT system trackwork is provided on most of the guideway structure. During the most recent passenger operations, two separate routes were operated in lanes where trackwork is installed. One route operated between 600 E. Las Colinas Blvd. and Urban Towers, and the other route operated between 600 E. Las Colinas Blvd. and Tower 909. A portion of the guideway structure east of The Tower on Lake Carolyn was converted into a pedestrian walkway to provide an interface between the APT system and the Dallas Area Rapid Transit (DART) Orange Line.

The objective of this section of the report is to assess the structural capacity of the existing structures and determine how it can be modified to accommodate the composite ATS vehicle and wireless EV charging equipment. To accomplish this objective, the loading on the structure and the demolition/removal of existing trackwork and equipment was investigated. Also, operational considerations were given to the turnaround of vehicles at stations, adding safety rails, adding a roundabout to aid system operations, retaining the existing maintenance facility and keeping operations on the existing elevated dedicated right-of-way structure. Future consideration and accommodation for the ATS vehicles to operate in mixed traffic, while deemed possible, is not part of the scope of the study.

Figure 6.1-1 Las Colinas Vehicle, Guideway, and Proprietary Trackwork

6.1.1 Background

The Las Colinas APT guideway structure is a post-tensioned W-beam and U-beam system built mostly on 20 to 35-foot tall, cast-in-place columns supported by drilled shaft foundations. The W and U-beam superstructure is integral with the deck system supporting the guidebeams and other appurtenances. Most of the drilled shafts are straight shafts extended to a shale layer. A few of the drilled shafts are belled pier-types founded in clay soils.

The original design standards and drawings along with the subsequent design information were used in the following analysis of the guideway structure for the ATS (AV technology) application. It should be noted that the following analysis was for general planning and feasibility purposes and does not preclude the need for detailed engineering of specific applications for this guideway structure. Table 6.1.1-1 summarizes the design loads used for existing structure design.

Table 6.1.1-1 Guideway Lane Loading Criteria Based on AASHTO 1982

Load Type	Amount (lbs/ft)/lane
Total Dead Load i. Structure self-weight ii. Collateral load	2,500 i. 2,250 ii. 250
Live Load	1,500

6.1.2 Potential Retrofit

This system was designed specifically for the loads established by the original designers and some of the sections have required strengthening since the initial construction. The goal of the retrofit is to create a deck system that will accommodate a rubber-tired system that is not mechanically guided. Figure 6.1.2-1 shows the APT configuration for the guideway, trackwork, and guideway equipment. Additional potential retrofit details are given in Appendix J.

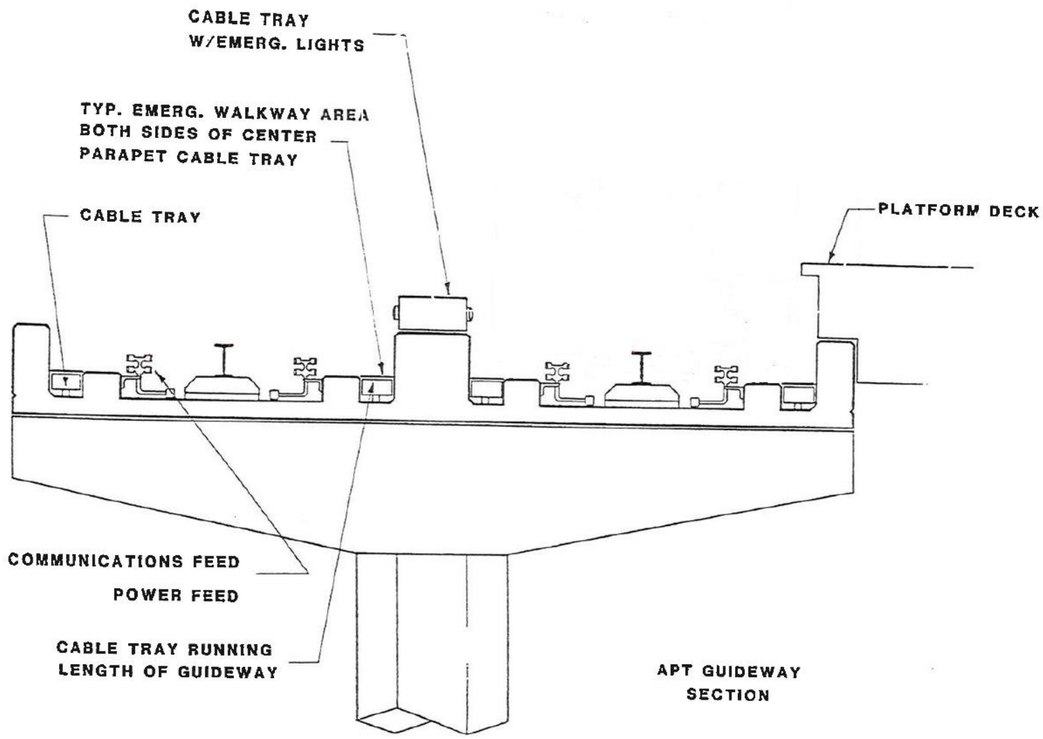


Figure 6.1.2-1 Las Colinas APT Configuration

The material for the deck system is a Durafiber FRP Decking which is available overseas and through at least one source domestically. Other domestic sources may be available at the time this retrofit occurs, but this material is currently available and is recommended to have a thickness of 4 ½" to 5" with a weight of 9 to 10 pounds per square foot (psf). It is thin, strong, and lightweight. Since it is more cost effective to layer a deck material over the existing concrete plinth running surfaces (trackwork) than to remove everything above the existing flat deck surface, the available depth given constraints for the FRP Decking is 6". Because it is lightweight and the thickness of the panel is within the available height limits, the Durafiber product would be a good fit, see Figures 6.1.2-2 and 6.1.2-3. Information on the Durafiber FRP product is included in Appendix D.

Figure 6.1.2-2 Expanded View of Polymer Deck Panel

Figure 6.1.2-3 Polymer Panel for Potential Retrofit Deck

While the existing APT was confined to a guideway track, a new ATS vehicle would no longer be confined. As an additional measure of safety for ATS vehicle passengers in this potential retrofit, new safety rails must be added to either side of the guideway, extending above the deck surface a minimum height that is established by the Manual for Assessing Safety Hardware (MASH). The lightest weight deck railing is the Type T631LS rail, which is also MASH compliant for TL-2. TL-2 is the rating for cars and trucks with speeds up to 44 mph. Because of the light weight of the potential ATS vehicles, the TL-2 designation for cars and trucks is adequate. A maximum speed of 44 mph is also adequate because of the speed constraints imposed through tight-radius curves in the system (there will be no superelevation due to the existing guideway deck configuration). The rail height is 2'-10" or 34" and is open below the W-beam longitudinal rail. The addition of decorative fencing will provide additional pedestrian protection. Fascia panels may also be added to improve the aesthetics, but the resulting additional wind load effects on the guideway system will have to be evaluated.

6.1.3 Final Configurations

The static width of the composite vehicle for Las Colinas APT is 6.9 feet. The overall width between safety railings for the one-way configuration is 9 feet. If a vehicle is disabled, there is approximately 2.1 feet for passenger emergency egress if the vehicle is against the opposite safety rail. A disabled vehicle will have to be pushed or towed to an area with additional width or to a maintenance area, see Figure 6.1.3-1.

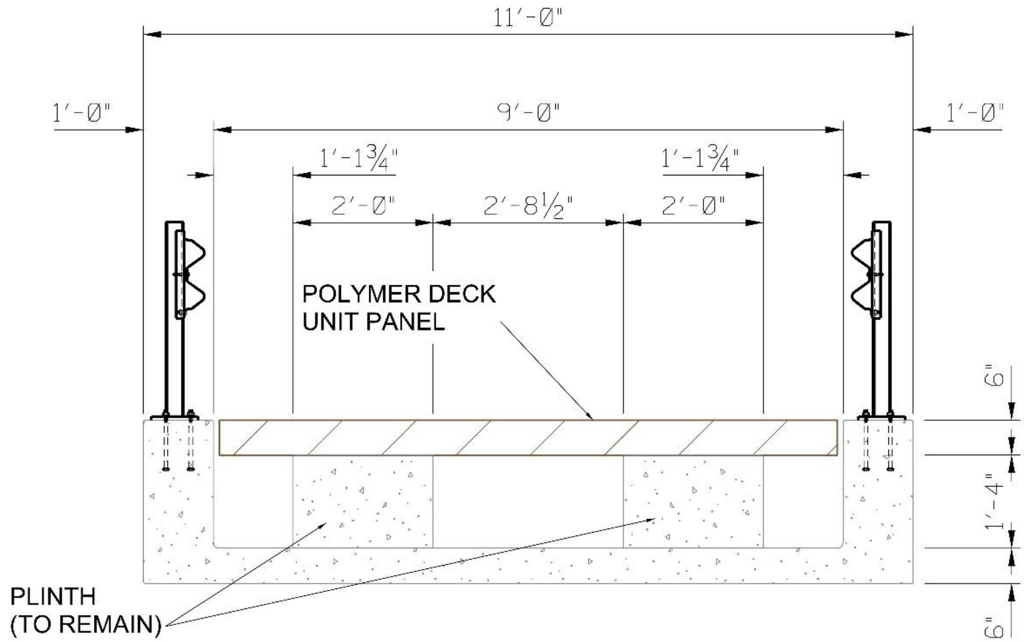


Figure 6.1.3-1 Single Direction Configuration

For the bidirectional configuration, the overall width between safety railings is 20 feet. If the outside vehicle abuts the rail with room for another vehicle beside it; this allows for 6.2 feet for passenger egress. With the dynamic envelope width of 8.7 feet (both vehicles in motion), there is 2.6 feet available for passenger egress. Safety procedures for disabled vehicles and passenger egress will have to be addressed for these configurations to be acceptable. See Figure 6.1.3-2 for bidirectional configuration.

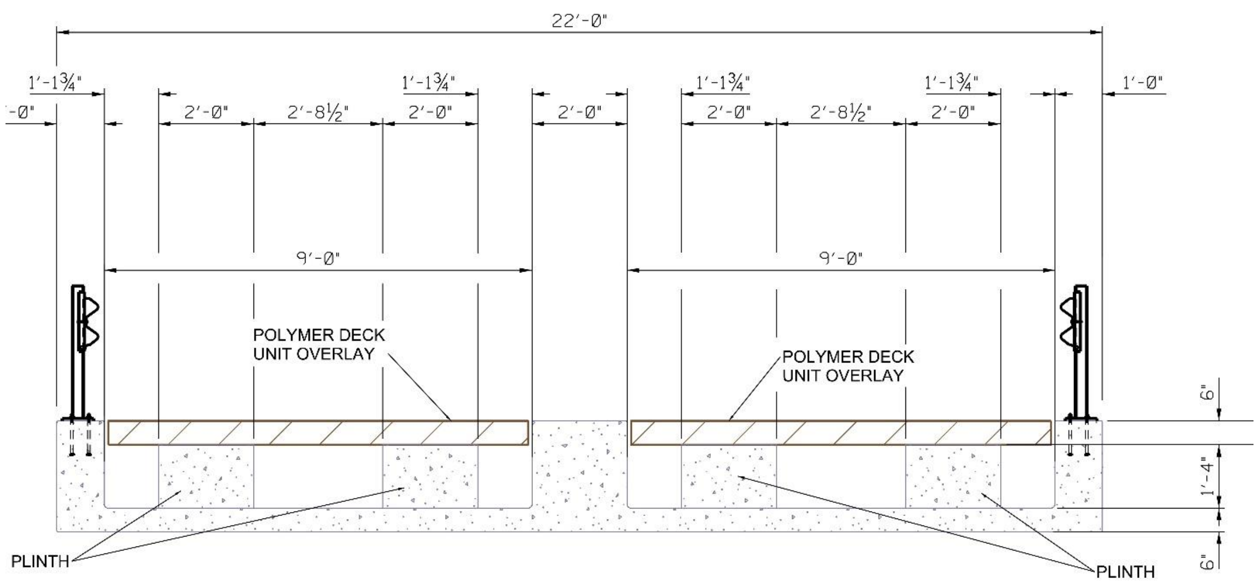


Figure 6.1.3-2 Bidirectional Configuration

6.1.4 Structural Analysis

To integrate a future ATS into the existing guideway structure, it is necessary to remove the existing steel guidebeams and use a lightweight Fiber Reinforced Polymer (FRP) deck system (as described in Sections 6.1.2 and 6.1.3) to elevate the deck surface to the top of the existing plinths. It is important to note that the business risk discussed in Section 4 is averted here given the concrete plinth and supports underneath shield the FRP from risk of fire below. The bidirectional supporting structure with existing configuration is shown in Figure 6.1.4-1 and single direction in Figure 6.1.4-2. Figure 6.1.4-3 shows a schematic of the retrofitted bidirectional deck system and Figure 6.1.4-4 shows the retrofitted single direction deck system. Looking at the deck sections (Figures 6.1.4-3 and 6.1.4-4), the new system would provide a smooth and leveled deck surface.

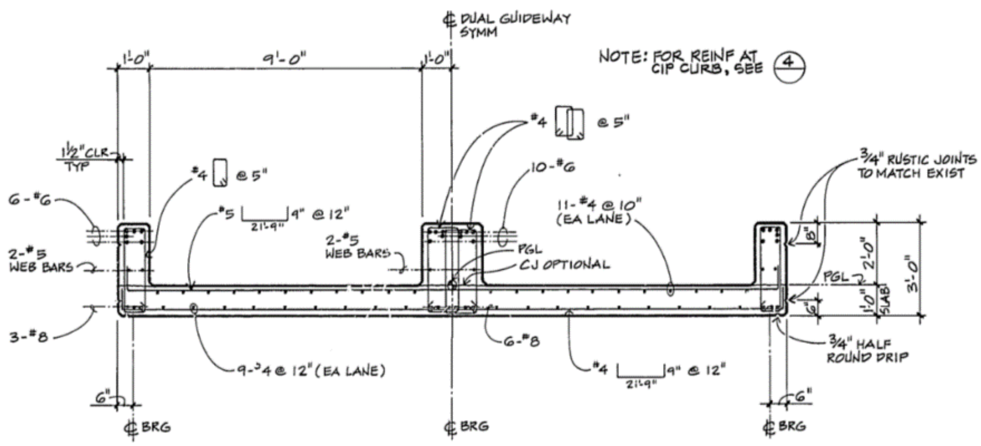


Figure 6.1.4-1 Typical Existing W-Beam Section (Guidance Attachments Not Shown)

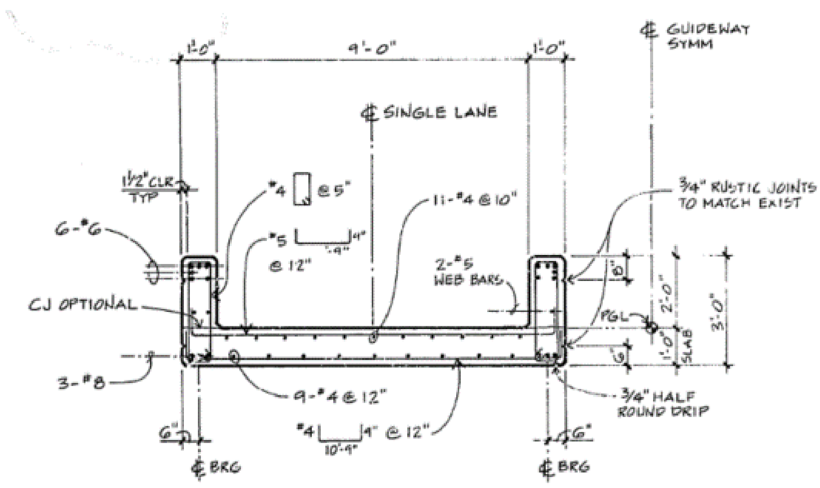


Figure 6.1.4-2 Typical Existing U-Beam Section (Guidance Attachments Not Shown)

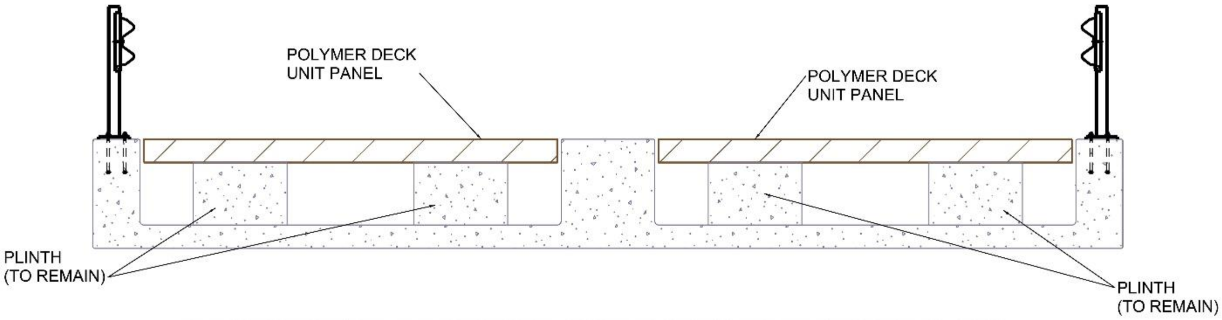


Figure 6.1.4-3 Potential Retrofit Bidirectional Deck System

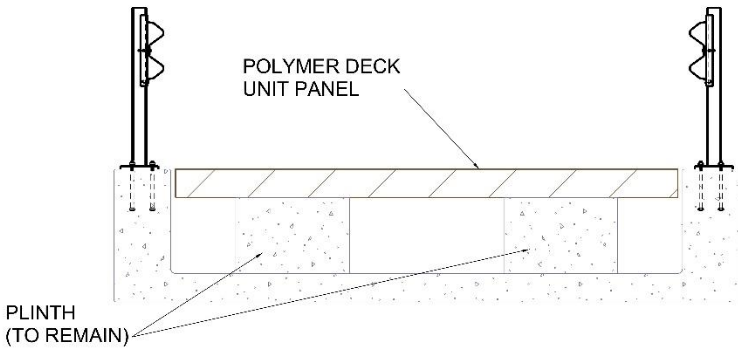


Figure 6.1.4-4 Potential Retrofit Single Direction Deck System

The AASHTO Load-and-Resistance Factor Design (LRFD) Bridge Design Specifications is used to calculate the design live load and determine the general capacity of the superstructure and substructure. The original design would have been Allowable Stress Design (ASD). According to AASHTO there is little difference in the final factors of safety between the two design codes. Every configuration of the existing structure was not analyzed for capacity because of the volume of the task. A structural and load assessment was performed as part of the feasibility study. Table 6.1.4-1 presents a comparison of the existing loads and the loads of the potential system.

Table 6.1.4-1 Load Comparison Between the Existing APT System and the Potential Retrofit ATS

Load Source	Existing APT System	Potential Retrofit ATS
Dead Load (Total Additional)	N/A	2,500 (lbs/ft)/lane
Polymer deck material	N/A	150 (lbs/ft)/lane
Deck safety rail system (T631)	N/A	2 × 20 (lbs/ft)
Existing guidebeams (to be removed)	2 x 45 (lbs/ft)	- 2 × 45 (lbs/ft)
Live Load Vehicle	30 (kips/vehicle)	18 (kips/vehicle)

With the potential retrofit, safety rails (T631 deck rails) were considered an essential component given the removal of guidance rails and elevation of the deck related to the edge of the guideway. For a single direction existing structure as shown in Figure 6.1.4-3 to the potential retrofit single direction structure shown in Figure 6.1.4-4, the total dead load of the structure is increased by the addition of the T631 rails (2x20 pounds per linear foot (plf)) and the polymer deck material (about 9 psf) and decreased by the removal of the 2 existing W10x45 guidebeams, resulting in 31 plf increase. The change to the factor of safety for the dead load is negligible. Conservatively, the new system utilizes an 18 thousand pounds (kip) live load for the composite vehicle while the existing APT system has a vehicle loading of 30 kips per vehicle. The existing live load factor of safety is 1.67 and the reduction in live load results in an additional increase of 1.67 for a total of 2.79 live load factor of safety. Because this system is a retrofit and was not originally designed for the considered vehicle types, a live load vehicle spacing of 150' was considered as minimum spacing resulting in 1 car per span for the single direction and 2 cars per span for the bidirectional structure. The bidirectional structure with existing configuration shown in Figure 6.1.4-1 and potential retrofit shown in Figure 6.1.4-3 were calculated with the same method and provide similar increased factors of safety based on the difference in live load. Two vehicles for a push-pull recovery of a failed vehicle were also included in the design checks, including an additional opposite direction vehicle for the bidirectional configuration. Translated, the potential retrofit of the guideway for an ATS vehicle will be supported by the existing structure, based on original designs. This analysis does not supersede the need for site inspections of the guideway to ensure it remains structurally sound.

6.1.5 EV Charging for Las Colinas APT

The existing power system for the APT vehicles will need to be updated for the new system since it is not compatible with the EV charging system. Selection of the vehicle and charging equipment has not been determined, but current consideration is for the use of opportunity EV charging at the stations. Since the specific system has not been selected and the size, weight and distance requirements are unknown, additional calculations may be required to determine structural capacity of the guideway at the stations. Removal of all existing power equipment should be considered before modifying the structure if the existing structural capacity is inadequate. The size and positioning of the power equipment at the stations must also be investigated. Ideally, the power supply would be located within the limits of the guideway so that it is not accessible to the public. However, it may also be possible to locate the equipment at a distance, such as below the structure or in a secured area on the station platform. Possible equipment configurations are shown in Figures 6.1.5-1 and 6.1.5-2.

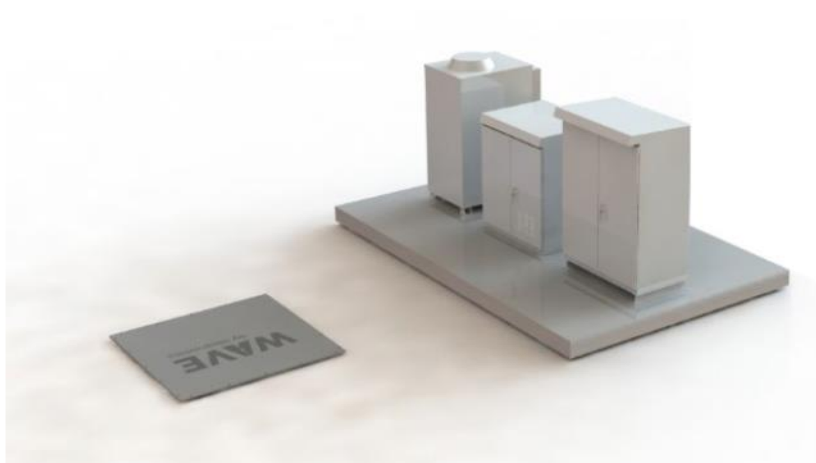


Figure 6.1.5-1 Single 250 kW Output Charging Pad and Equipment (One Direction Guideway)

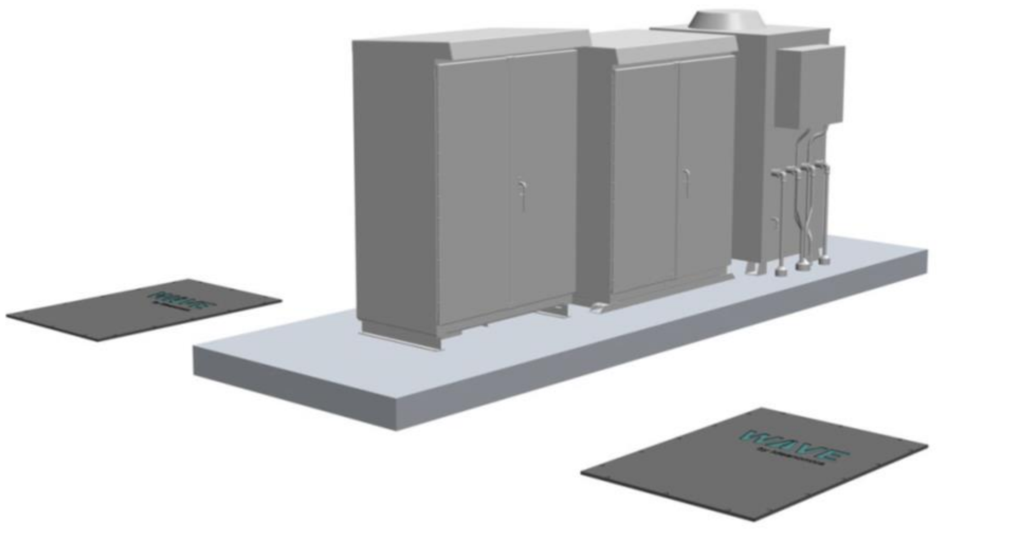


Figure 6.1.5-2 Dual 125 kW Output Charging Pads and Equipment (Bidirectional Guideway)

6.1.6 Visualization of the Potential Las Colinas APT Retrofit

The guideway analysis showed that the retrofit of existing Las Colinas APT infrastructure is possible. One option is to remove existing trackwork and add FRP decking with a safety rail. Limitations on guideway width may influence ATS vehicle selection and capabilities (e.g. bi-directional). Advancement of the retrofit should include engineering designs and analysis by others of the options provided in this report. Further project development activities at this location should consider which ATS vehicle technology best meets the needs and constraints of the site, operational feasibility (ridership, revenue generation), and future expansion opportunities.

Figures 6.1.6-1 and 6.1.6-2 below show a graphic visualization of the potential Las Colinas APT retrofit.

Figure 6.1.6-1 Las Colinas Potential ATS Over Lake Carolyn

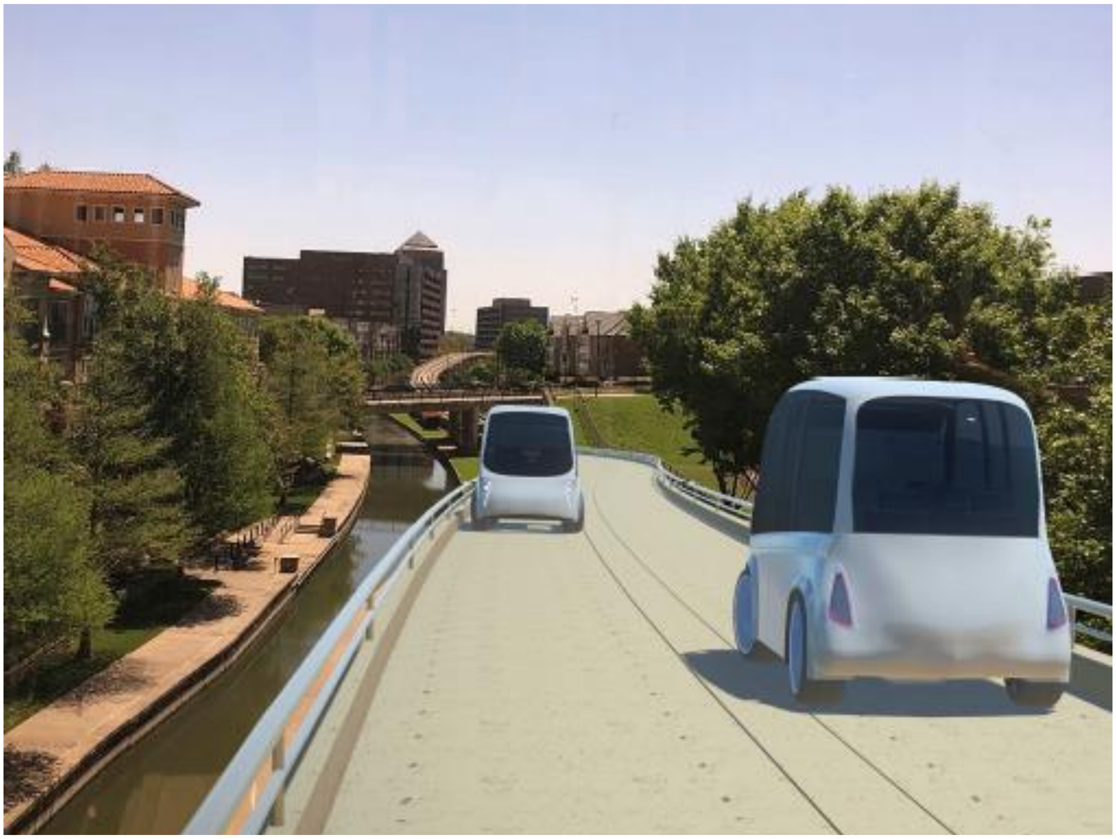


Figure 6.1.6-2 Las Colinas Potential Retrofit ATS

6.2 POTENTIAL RETROFIT FOR DFW INTERNATIONAL AIRPORT SKYLINK APM

The DFW International Airport Skylink APM system was also reviewed, at a conceptual level, for whether it could be retrofitted at some point in the future to support a rubber-tired ATS vehicle. Key challenges and areas that should be investigated further to determine the feasibility of the concept were also identified.

This review for a potential retrofit for DFW International Airport Skylink APM is different from the Las Colinas potential retrofit. The focus here is on how proper passenger service could be provided during and after the retrofit rather than a focus on the viability of a retrofit. This is a very high-level conceptual review that should be followed by future comprehensive studies.

As a first step to this conceptual review, an overview of the existing DFW Skylink APM and its operation is provided. This overview is followed by a discussion of three sample technologies and ideas for how the DFW Skylink APM could be retrofitted with each of these technologies.

6.2.1 Background/Description of Current Operation

Phase 1 System

The existing Phase 1 DFW Skylink APM opened in 2005. The technology implemented was the Bombardier (now Alstom) Innovia 200 Automated People Mover. It serves six terminal areas (A, B, C, D, E and F), and is operationally configured as two counter-rotating loops. There are currently no stations in the Terminal F area, but provisions were made to be able to accommodate two future stations in the Terminal F area. See Figure 6.2.1 -1 for a schematic diagram of the DFW Skylink alignment. A dual-track guideway extends along the full perimeter of the five terminal buildings, located at the airside face of each building. Each guideway lane has a secondary poured running surface that is 104 inches wide and sits on top of the primary deck. The primary deck is approximately 42 inches below the station platform finished floor height. Through the Terminal F area, the guideway is free-standing and configured to accommodate a future Terminal F. Between the terminal buildings, the dual-track guideway follows an alignment adjacent to the existing public and service roadway system. At the north and south ends of the System, dual-track guideway crosses the public/service roadways, to complete the six-terminal, dual-track layout.

At the north end of the System, guideway connections are provided for access and egress to the Maintenance & Storage Facility.

Each of the five terminal buildings feature two stations for APM service. Terminal F area alignment can accommodate two stations for a future Terminal F. The stations are constructed to permit passenger access to the APM from the secure concourse area of the terminals.

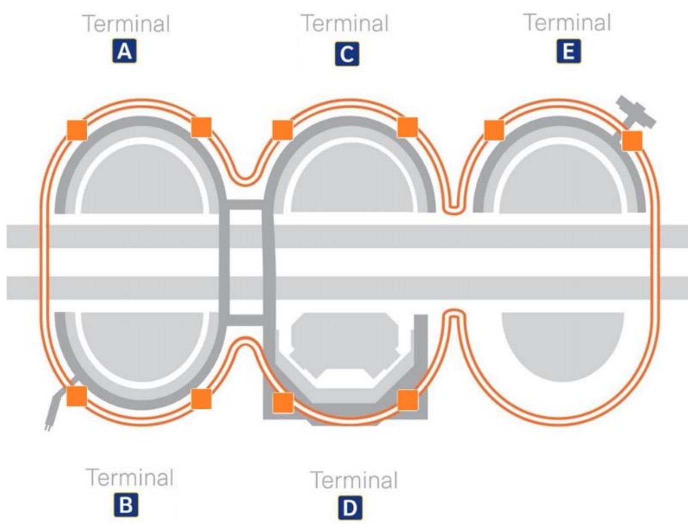


Figure 6.2.1-1: Schematic Diagram of DFW Skylink APM Alignment

Although the existing DFW Skylink APM vehicle technology can provide a fully bidirectional operation throughout the System, the Phase 1 System normally operates as two independent loops with trains on the two parallel guideway lanes circulating in opposing directions. Bidirectional capability is necessary for some failure management operational scenarios. Some failure management operations require passengers to deboard on the opposite side of the vehicle, hence the need for doors on both sides of the vehicles. The guideway lane closest to the terminal building is called the “Outer Route”. Although requirements are provided for reversed operation, normal service will be clockwise on the Inner Route and counterclockwise on the Outer Route. At each station, trains stop to allow passengers to deboard and board the System. Through the utilization of failure management switches, numerous failure management modes are possible.

Phase 2 System

The Phase 2 System is designed to serve the same six terminal areas. However, the Phase 2 System is intended to have a higher capacity level than the Phase 1 System. This additional capacity can be achieved through 1) the addition of vehicles and/or reduction of operating headways; 2) addition of new station platform doors; and 3) expansion of the Maintenance & Storage Facility.

6.2.2 AV Technologies Considered for Replacement

Consideration was given to the requirements of the existing DFW Skylink APM in terms of operational performance, including an extrapolated passenger demand, maximum round trip times, anticipated geometrical constraints, and other factors to identify potential autonomous technologies for preliminary consideration as to the potential viability of replacing DFW Skylink APM. For purposes of this conceptual review, the following technologies were considered, which are representative examples of autonomous technologies, but are not necessarily solutions:

- Group Rapid Transit
- Autonomous Bus

A GRT technology that is fully bidirectional and has doors on both sides of the vehicle is considered for this application.

In general, GRT vehicles and autonomous buses, such as the 2getthere GRT and the Irizar Autonomous Bus, have a significantly lower floor height, meaning that at each station, a topping slab running surface would have to be poured on top of the primary deck so that the vehicle floor level matches the finished floor level of the stations. This approach would require the construction of transitional ramps up in the approach area of each station and transitional ramps down departing each station. It is unknown at this time if the existing structural design can accommodate the extra weight of concrete that would be required at the stations and the extra weight of a topping slab spanning in between parapet walls throughout the guideway alignment to create a uniform flat running surface. Use of Styrofoam, along with concrete ribs down to the primary deck, would potentially lighten the extra weight of reinforced concrete required in the vicinity of the stations.

6.2.3 Capacity Considerations

In the Phase 1 System, the required line capacity during Peak Period Operations is 5,000 passengers per hour per direction (pphpd) for both the Inner Route and Outer Route.

In the Phase 2 System, the required line capacity during Peak Period Operations is 8,500 pphpd for both the Inner Route and Outer Route.

In 2015, DFW International Airport requested that Lea+Elliott, Inc. analyze the capacity provided by Skylink considering recent changes to the flight schedules. Specifically, DFW International Airport requested that L+E evaluate the AA “re-banked schedule” to determine its impact on Skylink ridership and operations under normal conditions and relative to the gate closures related to ongoing construction and to the fall major maintenance program (when individual loops are out of service for maintenance). The operational assessment was summarized in the report titled DFW Skylink Operational Assessment, September 18, 2015, prepared by L+E. The results of the DFW Skylink Operational Assessment report suggest that excess capacity is provided by operating 10 trains during the peak hours of the day and that sufficient capacity may be provided if the number of trains is reduced.

This study indicated that the normal capacity of each Skylink car is 69 passengers, based on 4.0 square feet per passenger, as specified in the original contract documents. However, a practical capacity more representative of the current level of service experienced by passengers, particularly in this post-COVID-19 era is 5.0 square feet per passenger is 57 passengers per car.

The results from the DFW Skylink Operational Assessment indicate that the peak link for the outer loop occurs between stations A North and B North and is 3,104 pphpd while the peak link for the inner loop occurs between stations C South and E North and is 2,843 pphpd. Extrapolating to the current year, a 3% increase in ridership per year from 2015 to 2022 was assumed. The assumed demand numbers are 4,000 pphpd for the inner loop and 3,500 pphpd for the outer loop. For capacity considerations for a replacement technology, these lower extrapolated peak links will be used for comparative purposes, and not the 5,000 pphpd (Phase 1) and 8,500 pphpd (Phase 2) required line capacity that the existing Skylink APM System is required to be able to meet. This entails some risk, as airport and/or airline operations might change in the future and require that a transportation system be able to transport those higher numbers.

Group Rapid Transit

A representative GRT vehicle is dimensionally smaller than the existing Skylink vehicles and typically carries a maximum of 22 passengers per vehicle. However, for airside passengers with carry-on baggage, the maximum capacity would be less. For the purposes of this report, a maximum capacity of 15 passengers was assumed to meet the 5 square feet per passenger criteria mentioned above. The representative GRT technology would not be able to meet 4,000 pphpd operating as individual vehicles with relatively short headways, due to the time it would take passengers to deboard and board vehicles. Instead, it would need to operate in a platoon operation, whereby vehicles would travel in a virtual train consist with relatively short physical separation between vehicles, but without being physically connected with couplers or drawbars. The representative GRT vehicles operating as a platoon with 5-car virtual trains running at 1-minute headways could, in theory, carry approximately 4,500 pphpd.

Although some GRT suppliers have previously indicated that their GRT has been tested in a platoon operation, it is unknown at this time if the GRT representative vehicles would be technically capable of 5-car virtual train platoon operations and do so with 1-minute platoon headways. With a car length of 19.7 feet and assuming a minimum of 5 feet physical separation in between each of the 5 vehicles, the resulting virtual train length would be approximately 120 feet. The existing station platforms could accommodate this length of virtual train, though it would require re-design and layout for the platform barrier wall and station platform doors. Figure 6.2.3-1 illustrates a generic center platform station with a potential GRT platoon interface.

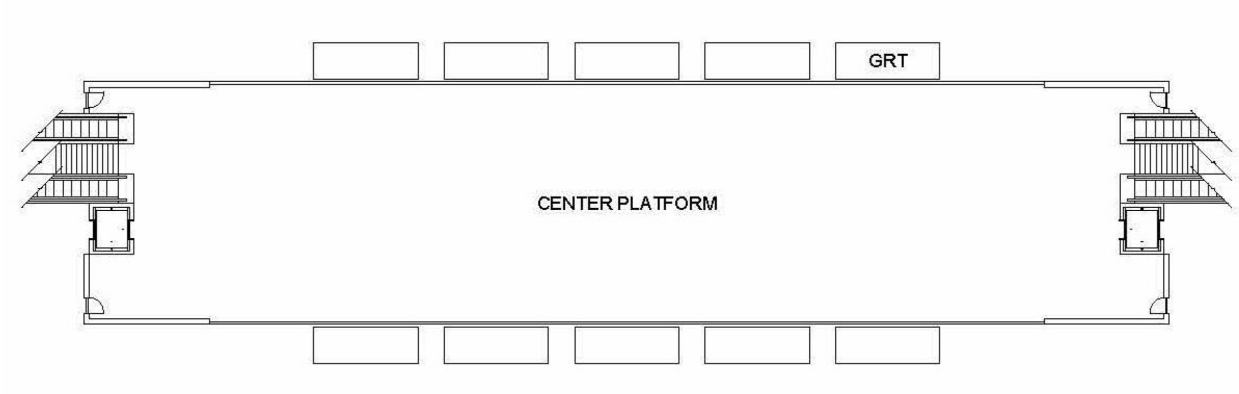


Figure 6.2.3-1 Generic Center Platform Station with Potential GRT Platoon Interface

Autonomous Bus

A representative autonomous bus can carry 40 seated and 42 standing passengers for a total of 82 passengers. However, for airside passengers with carry-on baggage, the maximum capacity would be less. For the purposes of this report, a maximum capacity of 50 passengers was assumed. However, because of the two narrow doors on one side of these buses, dwell times at stations for passenger deboarding and boarding would likely need to be significantly longer, thereby reducing the potential line capacity of these buses. Assuming 2-minute platoon headways, it appears that three (3) buses operating in a platoon configuration would be able to carry approximately 4,500 pphpd. The platooning capability of these buses is unknown at this time, including what separation would be required in between buses at the station platforms, but for purposes of this report, it was assumed that these buses either are capable or will be capable of platooning operations and that a minimum of ten feet is required. Figure 6.2.3-2 illustrates a generic center platform station with a potential autonomous bus platoon interface.

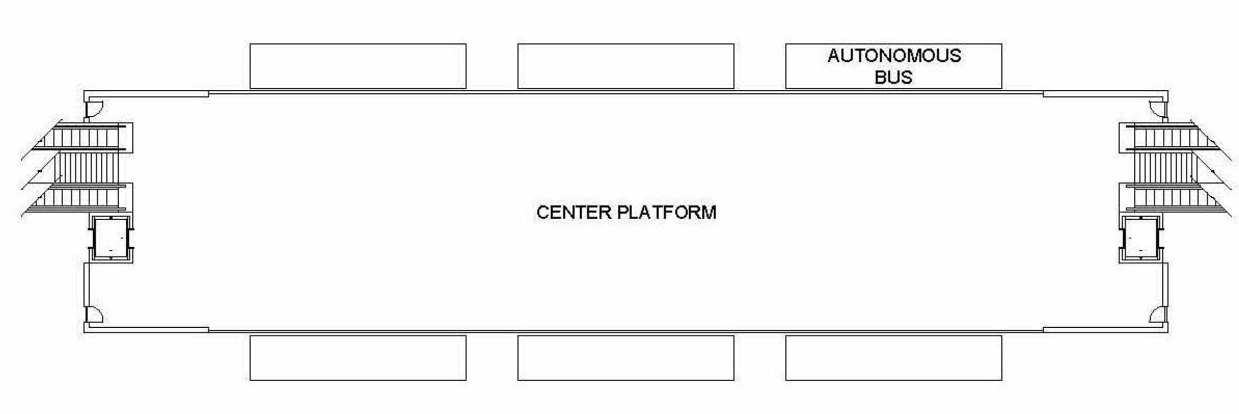


Figure 6.2.3-2 Generic Center Platform Station with Potential Autonomous Bus Platoon Interface

6.2.4 Review of Compatibility with Existing Infrastructure

The possible retrofit of the DFW International Airport Skylink APM System would not be without challenges. Consideration would have to be given to the operational challenges during construction and to the compatibility of the replacement system with the existing infrastructure.

There are a few challenges during construction to consider. To create a guideway suitable for an ATS, the existing Skylink APM System would have to cease operations to remove all the wayside guideway equipment along the guideway. Alternative means of transporting Skylink passengers would be required for an extended period. Because the stations are constructed to permit passenger access to the APM from the secure concourse area of the terminals, and the tight connections for passengers transferring in between stations and terminals, it would be very difficult to meet the tight connections by operating landside buses.

Passengers would have to leave the secure part of the terminals to walk to landside buses to take them to the nearest landside location to their departing gate, after which they would have to wait in line to clear security to enter back into to the secure part of the terminal and finally walk to their gate. Alternatively, large apron buses could, in theory, operate along the ramp to interconnect between pre-determined locations along the outer face of the terminals behind the gated aircraft. However, from experience at Houston George Bush Intercontinental Airport, a field test was conducted many years ago with a full-size 40-foot bus and driver to operate along the airside apron area back and forth in between set locations. These operations can be very inefficient and challenging, as aircraft movements and all other apron vehicles typically have priority for their movements, meaning that large buses must wait for these other higher priority movements, greatly increasing the travel time and decreasing the line capacity that large buses could practically carry.

Each guideway lane of the existing Skylink APM System has a secondary poured running surface (plinth) that is 104 inches wide and sits on top of the primary deck. For much of the alignment, both guideway lanes share a common primary deck, except at the stations, where the guideway lanes flare out to each side of center platform stations. Because much of the guideway alignment is curved, each guideway plinth is independently superelevated from each other. See Figures 6.2.4-1 and 6.2.4-2.

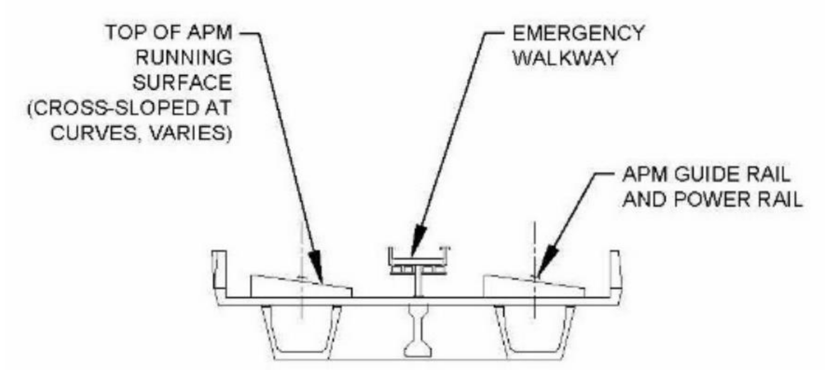


Figure 6.2.4-1 Existing Skylink Guideway Cross-Section at Curves (Typical)

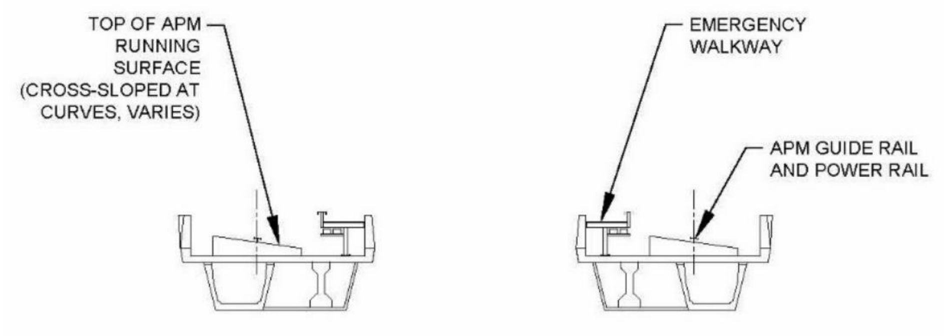


Figure 6.2.4-2 Existing Skylink Guideway Cross-Section at Curves (Approaching/Departing Stations)

This complicates the ability to design and construct a uniform flat surface suitable for autonomous vehicle technologies, particularly if superelevation is desired, which would enable higher speeds through curves. These 104-inch-wide plinths could be removed down to the level of the primary structural deck and then a topping slab could be poured to create a uniform flat running surface spanning in between the parapet walls. See Figures 6.2.4-3 and 6.2.4-4.

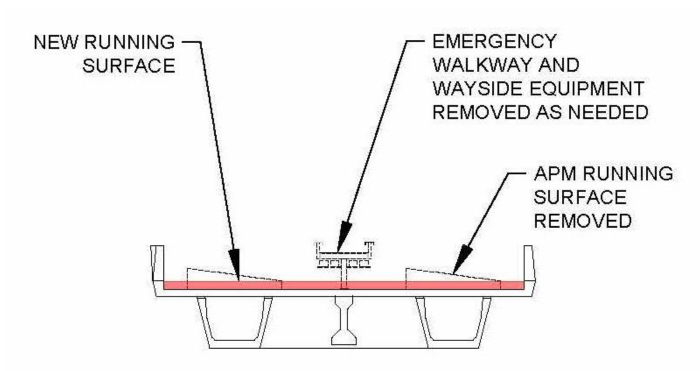


Figure 6.2.4-3 Potential Retrofit AV Guideway Cross-Section at Curves (Typical)

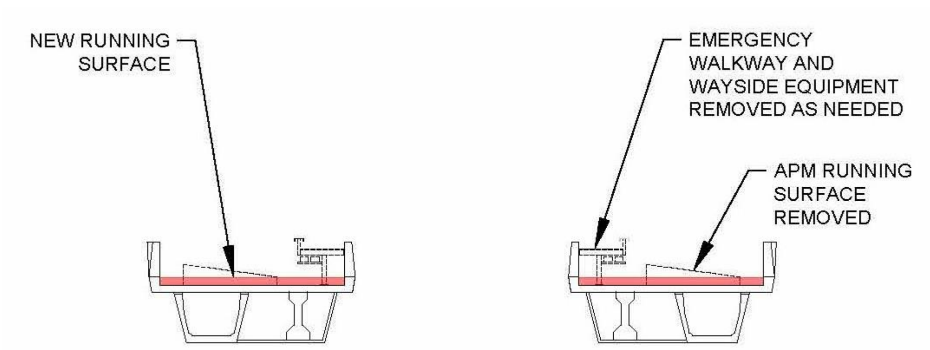


Figure 6.2.4-4 Potential Retrofit AV Guideway Cross-Section at Curves (Approaching/Departing Stations)

At the stations, depending upon the autonomous vehicle technology, it is likely that additional measures would be required because the existing station platforms are approximately 42 inches above the existing running surface on top of the existing plinths, see Figure 6.2.4-5.

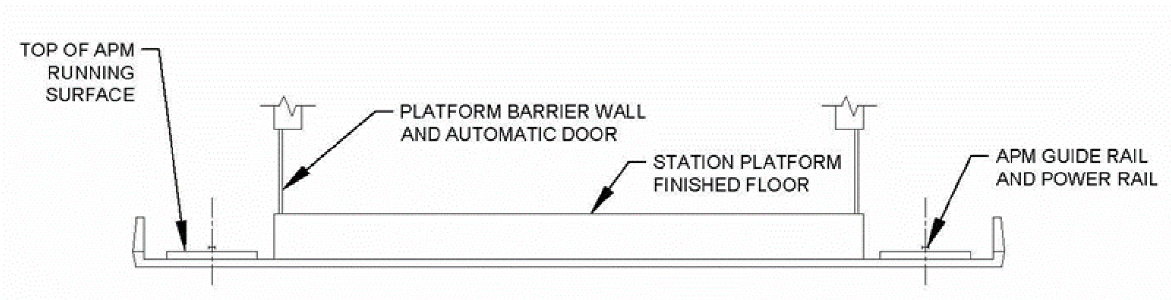


Figure 6.2.4-5 Existing Skylink Guideway Cross-Section at Stations

Vehicle floor heights above running surface vary widely among different autonomous vehicle technologies but are typically significantly less than 42 inches. One approach would be to construct transitional ramps up to the station in the approach area and transitional ramps down departing each station, see Figure 6.2.4-6.

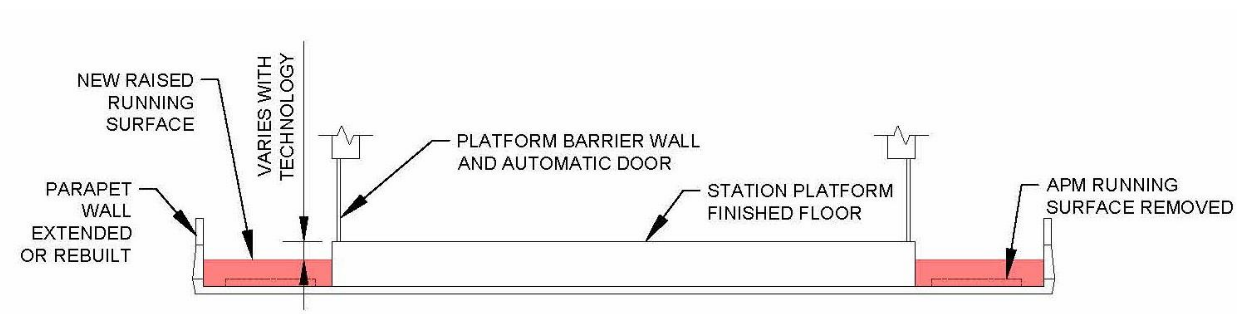


Figure 6.2.4-6 Potential AV Guideway Cross-Section at Stations

Additionally, the existing guideway parapet walls in the vicinity of the stations (and possibly throughout the guideway alignment) would need to be extended and structurally reinforced to be able to retain an autonomous vehicle (in the event of loss of vehicle control/guidance). If consideration were given to accommodating a larger autonomous technology, such as an autonomous bus, significant structural measures would be required to prevent any possibility of the vehicle from departing the guideway trough in the event of loss of vehicle control/guidance.

6.2.5 Customized Alternative

The scope of this study for the DFW Skylink APM Retrofit being limited to exploring the possibility of replacing the existing APM with an ATS technology only scratches the surface of possibilities that could be explored. For example, the potential DFW Skylink APM retrofit might require a customized autonomous vehicle solution, in lieu of off-the-shelf autonomous vehicle technologies that are currently available in the marketplace. A customized solution might be a fully bidirectional vehicle that is sized approximately the size of typical APM vehicles (nominally, 40 feet), with at least two sets of wide bi-parting doors on both sides of the vehicle, capable of higher speeds (somewhere in the range of 40 – 50 mph). This customized vehicle would be able to operate in platoon configuration, operate in a network configuration. leave the dedicated right-of-way, with the potential future capability (if they can achieve SAE Level 5), and operate in mixed-traffic with other conventional (non-autonomous) vehicles in any operational design domain.

If further consideration is to be given to determining the feasibility of replacing the DFW Skylink APM with an autonomous vehicle technology, a significant amount of additional in-depth study and analyses would be required beginning with an understanding of the DFW International Airport long-term development plans including definition of future goals for airport passenger connectivity. Once the priorities for the system retrofit are established, further studies could include, but would not be limited to, additional ridership studies to identify passenger demand, future service requirements, flexibility goals, potential phasing, operational analyses, guideway structural analyses, existing maintenance facility adequacy to meet AV maintenance requirements, architectural review of required modifications that would be required for the station platform barrier walls and platform doors, and contracting requirements. These additional studies could help clarify the possibilities that an ATS retrofit might offer.

7. NEXT STEPS

NCTCOG envisions the implementation of ATS as a state-of-the-art connectivity solution for passenger mobility and supply chain applications. As vehicle and wireless EV charging technologies advance, future ATS projects must retain flexibility to respond to the changing environment.

The tools, ideas and guidelines provided in this study support this vision by providing a framework to monitor and evaluate emerging technology innovations related to autonomous vehicle and wireless charging technologies. Furthermore, the guideway infrastructure design guidelines offer a streamlined and cost-effective approach to guideway construction using a standardized design that can be utilized across multiple projects, simplifying project development and creating a consistent brand identity for this mode.

It is intended that the database of ATS vehicle and wireless EV charging technologies be updated periodically to keep up with technological advancements. Moreover, as projects are advanced, the technologies will have to be assessed based on the needs of each project and the evolution of the technologies.

In addition to the ATS vehicle inventory, the wireless technology inventory, and the guideway design, this study assessed the concept applicability for two potential retrofit projects and two pilot projects. For the retrofit projects, this study identified the requirements for converting the systems into ATS installations. In the case of the Las Colinas APT, next steps must include the development of a long-range operational strategy, centered around a discussion of the system's objectives. This strategy should include a plan to identify sources of funding for the necessary capital improvements, acquisition of rolling stocks, and long-term operational needs. For the DFW Skylink APM, next steps involve a study of the "air-side" passenger movements to determine if the merits of an ATS-style operation, such as non-stop point-to-point service, offer a compelling case for converting from the current system.

The early-stage of development of the Dallas International District leaves a number of next steps to be considered before an ATS can be deployed. Not only—as in the case of Las Colinas—must a plan be laid for covering the necessary capital and operations costs, but a governance structure must be identified that will take the lead in implementing the system. In addition, further study is needed to identify the parking management and land use strategies that will directly affect the ATS and International District's overall success. While NCTCOG has developed in-house tools to identify locations where an ATS might be beneficial to implement, the development of processes to answer the outstanding questions on the International District ATS would provide a framework for the future development of ATS in other locations.

For the pilot project at the General Motors manufacturing facility and other projects where repeated movements can be supplanted by ATS technology, project development can utilize the findings of this study to determine compatibility of ATS vehicle technology with their particular objective as well as the appropriate operating structure to govern the ATS fleet. Implementation details must be coordinated among private and public entities on alignments which cross or utilize public right-of-way. The results of this study will support those discussions and enable opportunities for cohesive ATS implementations throughout the region.

Figure 7-1 Conceptual Image of ATS Manufacturing Operating Environment (OE-A)

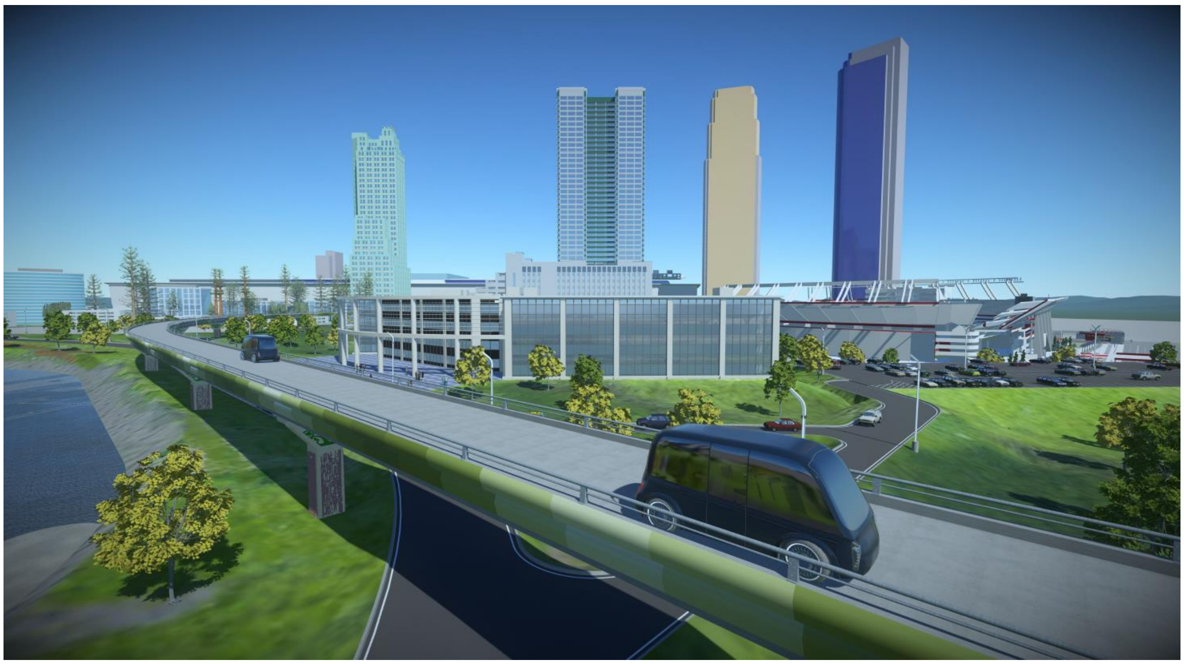


Figure 7-2 Conceptual image of ATS Passenger Operating Environment (OE-B)

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APPENDIX A
LIST OF VEHICLE TECHNOLOGIES

1. VEHICLE TECHNOLOGIES

These transit technologies are potentially compatible with the NCTCOG's goals for the region. While classifying transit technologies by categories can be challenging and subject to debate as there can be overlap between technology concepts, the listing below presents the technologies into these generally accepted categories:

- Group Rapid Transit (GRT)
- Automated Vehicle Shuttles / Autonomous Vehicles (AV)
- Next Generation Automated People Mover (APM)
- Automated Buses
- Other Autonomous Technologies

The following subsections identify representative technologies within these five technology categories.

1.1 GROUP RAPID TRANSIT (GRT)

A notable mention in this Group Rapid Transit (GRT) section is the West Virginia University Personal Rapid Transit System in Morgantown, WV. It is an automated people mover system that provides non-stop origin to destination travel between the separated campuses of West Virginia University and the Central Business District. The system consists of a fleet of seventy-one electrically powered, rubber-tired, passenger-carrying vehicles (8-seated and 13-standing), operating on a dedicated guideway network at close headways (minimum 15 seconds). Since 1975, the system continues to provide a safe, comfortable, low polluting, and reliable means of transportation. The system consists of 8.2 mi of guideway and five passenger stations. Although called a PRT, many feel that this system is better labeled Group Rapid Transit (GRT) because these vehicles can carry up to twenty-one passengers. This technology was originally supplied by Boeing and is not currently commercially available.

Figure 1.1-1 West Virginia University PRT Vehicle, Morgantown, WV, USA

Website: https://transportation.wvu.edu/prt

Several of the PRT suppliers have GRT vehicles in development including 2getthere (in partnership with Oceaneering) and Vectus. Examples of GRTs are shown below.

1.1.1 2getthere/Oceaneering GRT

Website: https://www.2getthere.eu/

2getthere has been operating its second generation ParkShuttle GRT system at the Rivium business park in Rotterdam, Netherlands since 1999 and has been working on its third generation ParkShuttle. It has announced projects in Dubai, Singapore, and Brussels. The Brussels system will be a phased implementation where it is planned to ultimately operate autonomously in mixed traffic on existing roadways.

Table 1.1.1-1 2getthere/Oceaneering GRT Vehicle Specifications

2getthere GRT Vehicle Specifications	Value
Vehicle length	19.7 ft
Vehicle width	6.9 ft
Vehicle height	9.2 ft
Vehicle weight (unloaded)	9,920 lbs
Vehicle capacity	22
Maximum speed	25 mph

Figure 1.1.1-1 2getthere GRT Vehicle, Brussels Airport

Figure 1.1.1-2 2getthere 3rd Generation ParkShuttle GRT

1.2 AUTONOMOUS VEHICLE (AV)

The following technologies are Autonomous Vehicles (AVs) included in this study:

- EasyMile
- Navya
- Applied EV and Oxbotica
- Schaeffler and Mobileye
- Aurrigo
- Einride
- Toyota
- Westfield
- e.GO MOOVE
- Continental
- IAV HEAT
- GM Cruise
- Zoox
- REE Automotive
- Baidu
- May Mobility

1.2.1 EasyMile EZ10

Website: http://www.easymile.com/

EasyMile provides software and complete solutions for driverless mobility and goods transportation.

They partner with blue-chip manufacturers to autonomize their vehicles with award-winning technology built on safety-by-design, ready for deployment today, with clear client benefits.

Their people mover solution, the EZ10 is the most deployed autonomous shuttle in the world, connecting transport and in many cases, providing a service where there otherwise wasn't one. For material handling, TractEasy is a tow-truck solution optimizing supply chains with cross/indoor-outdoor, 24/7 material handling at factories and industrial sites. It is also leading the way for specialized application of new autonomous solutions.

Since 2014, EasyMile has become known for quality delivery and real-world deployments. EasyMile's proven technology has driven autonomous vehicles in 400+ locations in more than 30 countries.

With several mass operations around the world EasyMile was the first to deploy fully driverless at Level 4 of autonomous driving in 2018. It is also the first autonomous vehicle solutions provider to be International Organization for Standardization (ISO) 9001:2015 certified.

Clients include leading transport operators such as Transdev, First Transit, MV, Keolis, RATP Dev, transit agencies such as Houston METRO and CapMetro, airports such as DFW, business parks, universities such as TSU, manufacturers, factories and logistics centers such as BWM and Daimler.

Table 1.2.1-1 EasyMile AV Vehicle Specifications

EasyMile EZ10 Vehicle Specifications	Value
Vehicle length	12.9 ft
Vehicle width	6.5 ft
Vehicle height	9 ft
Vehicle weight (unloaded)	4,696 lbs
Vehicle capacity	12 (6 seated)
Maximum speed	12 mph

Figure 1.2.1-1 EasyMile EZ10 Vehicle

1.2.2 NAVYA

NAVYA is a French company that specializes in the design and construction of autonomous and electric vehicles. NAVYA assists cities and private sites around the world in improving their transportation. The following are NAVYA vehicle technologies considered in this study.

1.2.2.1 AUTONOM Shuttle (ARMA)

Website: https://navya.tech/en/autonom-en/autonom-shuttle/

NAVYA developed the AUTONOM SHUTTLE as a driverless, electric shuttle service. In 2016, NAVYA delivered two pilot programs, and as of January 2018, NAVYA has sixty-five vehicles deployed worldwide in cities and on private sites in Europe, the United States, Asia, and the Pacific.

In 2017, NAVYA brought the first AUTONOM SHUTTLE to the United States at the University of Michigan's (Mcity) Mobility Transformation Center (MTC) in Ann Arbor, Michigan. Mcity will study how passengers react, track ridership and usage patterns, and survey users to gauge rider acceptance. This data will help improve the safety and operations of the vehicles. In November 2017, Las Vegas launched an autonomous bus route along a 0.6-mile route along Fremont Street using a NAVYA AV. While there is an on-board attendant who can stop or guide the shuttle in case of an emergency and an automobile that follows behind as a buffer to prevent rear ends, this makes Las Vegas the first to deploy AVs on public streets in mixed traffic.

Table 1.2.2.1-1 NAVYA AUTONOM SHUTTLE Vehicle Specifications

NAVYA AUTONOM SHUTTLE Vehicle Specifications	Value
Vehicle length	15.6 ft
Vehicle width	6.9 ft
Vehicle height	8.7 ft
Vehicle weight (unloaded)	5,291 lbs
Vehicle capacity	15
Maximum speed	28 mph

Figure 1.2.2.1-1 NAVYA AUTONOM SHUTTLE on Demo at APTA EXPO

Figure 1.2.2.1-2 NAVYA AUTONOM SHUTTLE Vehicle, Passenger Terminal EXPO, Cologne, Germany

1.2.2.2 AUTONOM CAB

Website: https://navya.tech/en/autonom-en/autonom-cab/

NAVYA launched AUTONOM CAB, the first autonomous taxi on the market, in Paris, France in November 2017. It was introduced to the United States at the Consumer Electronics Show (CES) in Las Vegas, Nevada in January 2018. Visitors tested the cab, which transported more than 1,500 people on the streets of Las Vegas. AUTONOM CAB is available as a private or shared service and is used for on-demand trips.

To use AUTONOM CAB includes an onboard touchscreen, allowing passengers to order tickets for a movie, select songs, and obtain tourist information.

Table 1.2.2.2-1 NAVYA AUTONOM CAB Vehicle Specifications

NAVYA AUTONOM CAB Vehicle Specifications	Value
Vehicle length	15.3 ft
Vehicle width	6.4 ft
Vehicle height	6.9 ft
Vehicle weight (unloaded)	4,409 lbs
Vehicle capacity	6
Maximum speed	55 mph

Figure 1.2.2.2-1 NAVYA AUTONOM CAB on the Streets of Paris

1.2.3 Applied EV and Oxbotica

Website: https://appliedev.com/

Applied EV and Oxbotica are collaborating on a fully autonomous, multi-purpose electric vehicle, using Applied EV's Blanc Robot EV-Skateboard combined with software from Oxbotica. They see this as being configurable for a variety of use cases. Applied EV is a Melbourne, Australia based company. They anticipate first deployments in the United Kingdom in the area of industrial logistics and automate goods delivery, with the potential, in the future, to scale the fleet across various industries and locations.

Table 1.2.3-1 Applied EV Vehicle Specifications

Applied EV Vehicle Specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

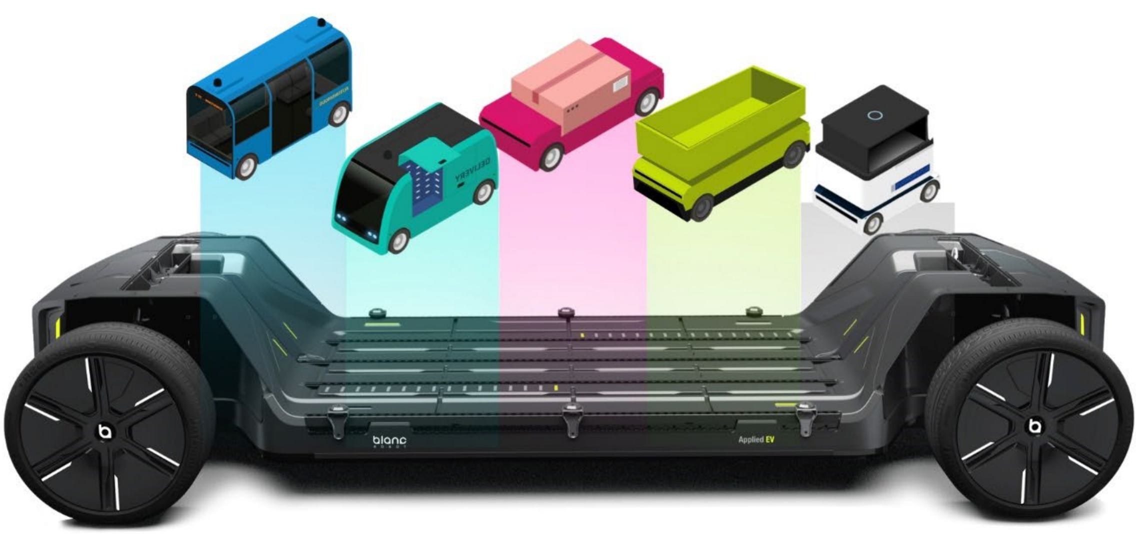

Figure 1.2.3-1 Applied EV's Blank Robot EV-Skateboard and Potential Applications

Figure 1.2.3-2 Applied EV's Blank Robot EV-Skateboard and Potential Delivery Application

Figure 1.2.3-3 Applied EV's Blank Robot EV-Skateboard and Potential Cargo Application

1.2.4 Schaeffler and Mobileye

Website: https://www.schaeffler.com/content.schaeffler.com/en/news_media/dates_events/iaa/iaa.jsp

Schaeffler and Mobileye have agreed to a long-term cooperation agreement to advance for autonomous vehicle platform for moving people or logistics movers. Schaeffler's rolling chassis is a flexible, scalable platform developed for autonomous solutions, such as the transportation of people or goods, along with special applications such as mobile charging solutions.

Table 1.2.4-1 Schaeffler Rolling Chassis Vehicle Specifications

Schaeffler Vehicle Specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

Figure 1.2.4-1 Schaeffler Rolling Chassis

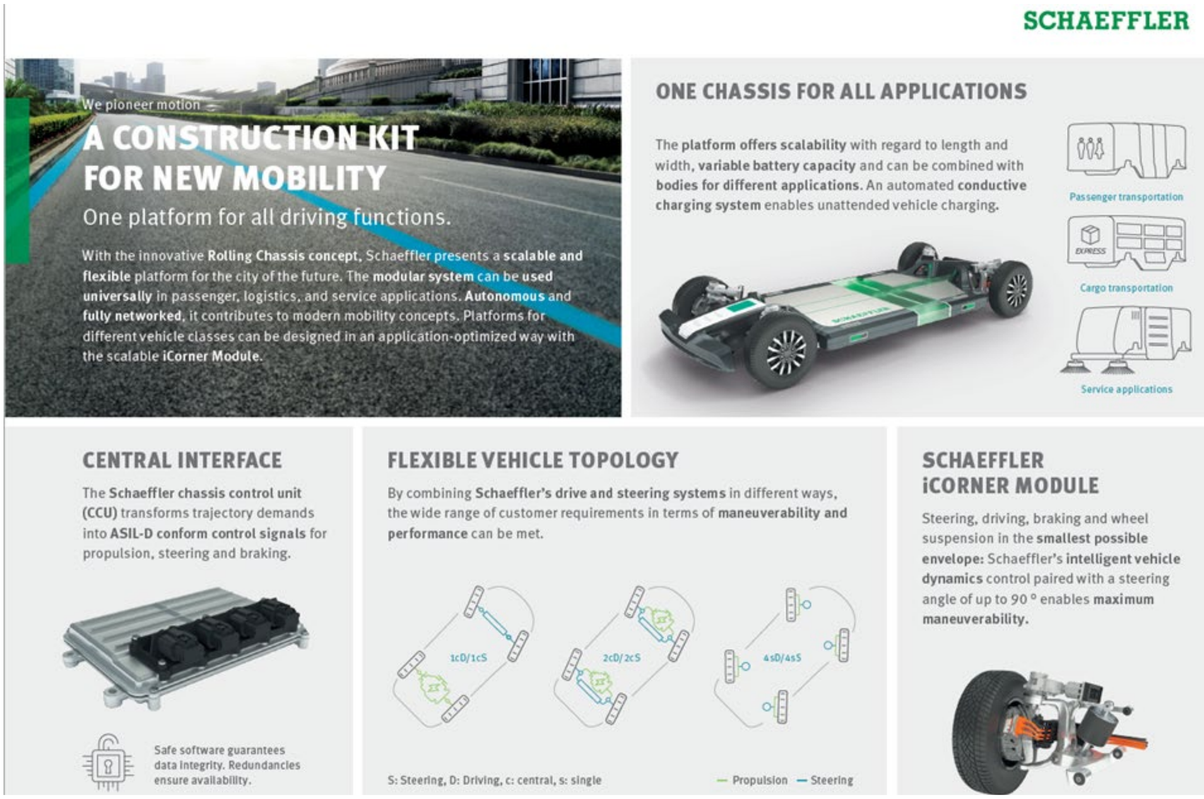

Figure 1.2.4-2 Schaeffler Rolling Chassis

1.2.5 Aurrigo

1.2.5.1 AURRIGO AUTO-SHUTTLE

Website: https://aurrigo.com/products/

The AUTO-SHUTTLE® has been designed for the first and last mile transportation. The vehicle can accommodate ten seated passengers and is equipped with a wheelchair ramp. The 22kW electric motor and 47kWh battery gives it a range of 124 miles.

Table 1.2.5.1-1 Aurrigo Auto Shuttle Vehicle Specifications

Aurrigo Auto Shuttle Specifications	Value
Vehicle length	19.0 ft
Vehicle width	7.5 ft
Vehicle height	8.3 ft
Vehicle weight (loaded)	Information requested
Vehicle capacity	10 seated
Maximum speed	Information requested

Figure 1.2.5.1-1 Aurrigo Auto Shuttle

1.2.5.2 AURRIGO AUTO-DOLLY

Website: https://aurrigo.com/products/

The Aurrigo Auto-Dolly is an autonomous electric transport platform for on-airport work. It is available as either a baggage dolly or a cargo dolly and can move pallets or unit load devices (ULDs). A new battery pack is available that offers up to 120 miles of operation on a single charge.

Table 1.2.5.2-1 Aurrigo Auto-Dolly Vehicle Specifications

Aurrigo Auto-Dolly Vehicle Specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

Figure 1.2.5.2-1 Aurrigo Auto-Dolly

1.2.6 Einride

Website: https://www.einride.tech/

Einride is a Swedish company that has a cargo/goods movement AV that is capable of operating [at least on an airport runway/taxiway Operational Design Domain (ODD)] at relatively fast speeds (compared to most other AV shuttles). It can be configured in a "closed" cargo/goods cabin configuration or an "open" cargo/goods movement configuration.

Table 1.2.6-1 Einride Vehicle Specifications

Einride Vehicle Specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

Figure 1.2.6-1 Einride "Closed" Cabin Configuration

Figure 1.2.6-2 Einride "Open" Cabin Configuration

1.2.7 Toyota e-Palette

Website: https://global.toyota/en/newsroom/corporate/34527341.html

https://toyotatimes.jp/en/insidetoyota/115.html?padid=ag478_from_pickup

The Toyota e-Paletttte is an electric vehicle with an intended use for autonomous mobility as a service. Some of the characteristics of the e-Palette include having a large open interior and a wide door opening, smooth acceleration and deceleration profiles, and precise stopping position.

Table 1.2.7-1 Toyota e-Palette Vehicle Specifications

Toyota e-Palette Vehicle Specifications	Value
Vehicle length	17.2 ft
Vehicle width	6.8 ft
Vehicle height	9.0 ft
Vehicle weight (loaded)	Information requested
Vehicle capacity	20 passengers
Maximum speed	Information requested

Figure 1.2.7-1 Toyota e-Palette People Mover Configuration

Figure 1.2.7-2 Toyota e-Palette Logistics Configuration Example

1.2.8 Westfield POD

Website: https://westfieldavs.com/westfield-pod/

Westfield POD (now EVIE Autonomous) is the new incarnation of the Ultra vehicle that is currently operating at Heathrow Terminal 5. Aim Technologies Group acquired the assets of Westfield POD in October 2022 which will be developed under EVIE Autonomous. Westfield POD has autonomous guidance, navigation and control unit using a combination of sensors for navigation. PODs can be adapted both externally and internally to suit a variety of applications and environments.

Table 1.2.8-1 Westfield POD Vehicle Specifications

Westfield POD Vehicle Specifications	Value
Vehicle length	12.1 ft
Vehicle width	5.4 ft
Vehicle height	6.9 ft
Vehicle weight (loaded)	2,385 lbs
Vehicle capacity	992 lbs
Maximum speed	25 mph

Figure 1.2.8-1 Westfield POD

1.2.9 e.GO MOOVE (previously ZF e.GO Mover)

Website: https://www.electrive.com/2021/01/24/e-go-moove-gets-street-approval/

In December 2020, the e.GO MOOVE People Mover received initial road approval for public road operations. In 2019, e.GO MOOVE introduced the e.GO Cargo Mover, which is specially designed for delivery services and craftsmen.

Table 1.2.9-1 e.GO MOOVE People Mover Vehicle Specifications

e.GO MOOVE Vehicle Specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

Figure 1.2.9-1 e.GO MOOVE People Mover

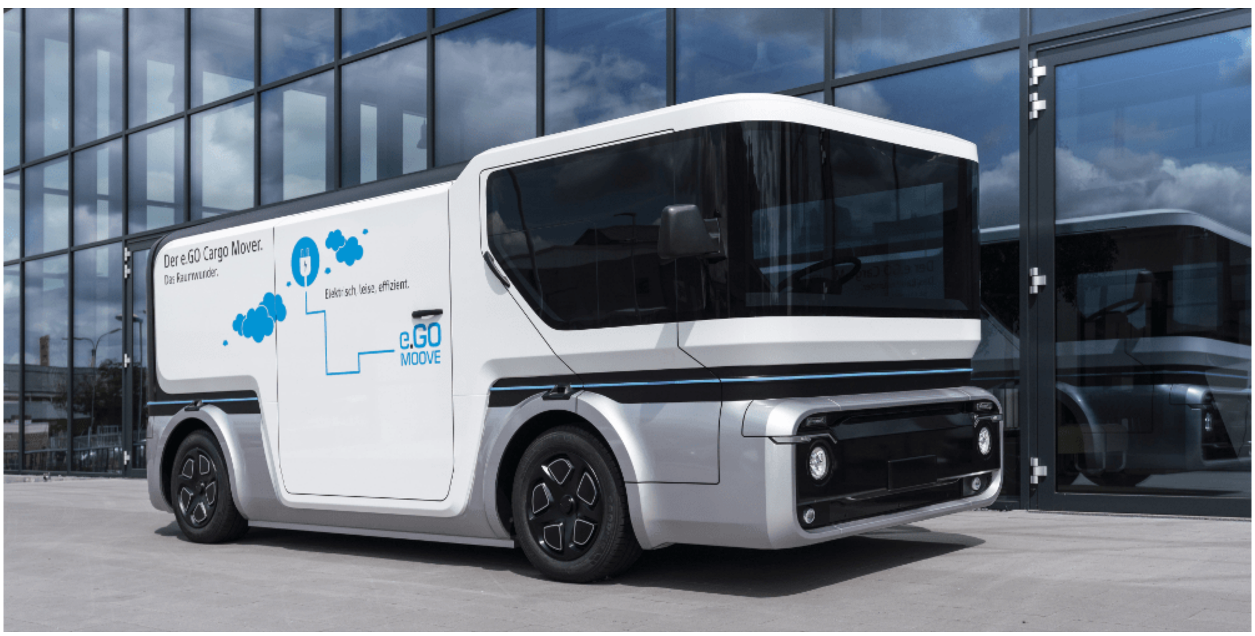

Figure 1.2.9-2 e.GO MOOVE Cargo Mover

1.2.10 Continental CUbE

Website: https://www.continental-automotive.com/en-gl/Passenger-Cars/Autonomous-Mobility/Stories

https://www.continental-automotive.com/Passenger-Cars/Autonomous-Mobility/Functions/Driverless-Mobility

Continental has built a demonstration vehicle named CUbE (Continental Urban mobility Experience) to serve as a platform for development of autonomous vehicle-related technologies and also to provide means for autonomous mobility. Continental uses the EasyMile EZ10 vehicle and does not intend to market their version for commercial purposes.

Table 1.2.10-1 Continental CUbE Vehicle Specifications

Continental CUbE Vehicle Specifications	Value
Vehicle length	12.9 ft
Vehicle width	6.5 ft
Vehicle height	9 ft
Vehicle weight (loaded)	4,696 lbs
Vehicle capacity	12 (6 seated)
Maximum speed	25 mph

Figure 1.2.10-1 Continental CUbE

1.2.11 IAV HEAT

Website: https://www.iav.com/en/news/heat-takes-you-autonomously-through-hafencity/

https://www.iav.com/en/news/first-autonomous-shuttle-bus/

Debuting in Hamburg in 2019, this new shuttle for HEAT (Hamburg Electric Autonomous Transportation) is part of a research and development project to integrate an autonomous shuttle bus into regular street traffic.

Table 1.2.11-1 IAV HEAT Vehicle Specifications

IAV HEAT Vehicle Specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

Figure 1.2.11-1 IAV HEAT

1.2.12 Cruise Origin

Website: https://www.getcruise.com/

Cruise is a majority-owned subsidiary of General Motors (GM). The Cruise Origin has a new, all-electric platform built by General Motors. The Cruise Origin does not have manual controls that would enable it to be manually-driven.

Table 1.2.12-1 Cruise Origin Vehicle Specifications

Cruise Origin Vehicle Specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

Figure 1.2.12-1 Cruise Origin

1.2.13 Zoox

Website: https://zoox.com/

Zoox is a subsidiary of Amazon since 2020. The Zoox vehicle has four-wheel steering and comes equipped with a 133-kWh battery. Zoox uses cameras, radars and lidars as part of their sensor package.

Table 2.2.13-1 Zoox Vehicle Specifications

Zoox Vehicle Specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

Figure 1.2.13-1 Zoox

1.2.14 REE Automotive

Website: https://ree.auto/

REE has developed an electric vehicle platform that allows flexibility to create a wide range of different types of autonomous vehicles. REEcorner, integrates major vehicle components (control, powertrain, suspension, braking and steering) into the arch of the wheel. REE is supported by a network of strategic partners, including Navya, Mitsubishi Corporation, Mahindra, and Magna.

Table 1.2.14-1 REE e-Shuttle Vehicle Specifications (Variable – Large Size Example in Table)

REE Automotive e-Shuttle Specifications	Value
Vehicle length	23.6 ft
Vehicle width	7.9 ft
Vehicle height	10.0 ft
Vehicle weight (loaded)	Information requested
Vehicle capacity	22 pax
Maximum speed	(Depends on AV technology integration)

Figure 1.2.14-1 REE E-Shuttle

Table 1.2.14-2 REE Leopard Vehicle Specifications

REE Leopard Specifications	Value
Vehicle length	9.5 – 11.5 ft
Vehicle width	3.9 – 5.9 ft
Vehicle height	4.6 – 7.2 ft
Vehicle weight (GVWR)	Up to 2 Tons
Vehicle capacity	Information requested
Maximum speed	Up to 100 mph

Figure 1.2.14-2 REE Leopard

1.2.15 Baidu Apolong II

Website: https://www.prnewswire.com/news-releases/baidu-launches-apolong-ii-multi-purpose-autonomous-minibus-in-guangzhou-301350119.html

The Baidu Apolong II autonomous minibus uses cameras, LiDARs and radars to enable it to operate on open roads. The vehicle incorporates vehicle-to-everything (V2X) capability, as well as 5G cloud-based remote driving services.

Table 1.2.15-1 Apolong II Vehicle Specifications

Apolong II Vehicle Specifications	Value
Vehicle length	14.2 ft
Vehicle width	7.0 ft
Vehicle height	8.9 ft
Vehicle weight (loaded)	Empty weight = 5,291 lbs; Gross weight = 7,716 lbs
Vehicle capacity	14 total (8 seated + 6 standing)
Maximum speed	Operating Speed = 12.5 mph; Max Speed = 25 mph

Figure 1.2.15-1 Apolong

1.2.16 May Mobility

Website: https://maymobility.com/

While this report does not generally address technologies that add autonomous controls to conventional vehicles, it is important to include May Mobility, which introduced service in Arlington, Texas on March 15, 2021. This service integrates on-demand ride sharing, public transportation, and accessibility. This service, known as Arlington RAPID (Rideshare, Automation, and Payment Integration Demonstration) is a partnership between the City of Arlington, The University of Texas at Arlington, Via, and May Mobility. The service uses 4 Lexus RX 450h SUVs and one wheelchair-accessible Toyota Sienna Autono-Maa.

Table 1.2.16-1 May Mobility Sienna Autono-Maa Specifications

May Mobility Vehicle Specifications	Value
Vehicle length	17.2 ft
Vehicle width	7.6 ft
Vehicle height	6.6 ft
Vehicle weight (loaded)	Empty weight: 4,600 lbs, Max weight: 6,000 lbs
Vehicle capacity	5 seated passengers, or 1 wheelchair and 1 service animal with room for 2 additional passengers
Maximum speed	25 mph in AV mode, projected to reach 30 mph with new development

Figure 1.2.16-1 May Mobility

1.3 NEXT GENERATION AUTOMATED PEOPLE MOVER (APM)

APMs are distinguished by their ability to be operated fully automatically without drivers. Automatic operation requires an exclusive right of way. Guidance may be provided by horizontally mounted guide wheels that track side-mounted guide rails, a guideway-mounted center guidebeam, the guidebeam itself, guideway-mounted center guide rail or traditional rails. The guideway of the APM system refers to the track or other running surface (including supporting structure) that supports, powers, contains, and physically guides APM vehicles designed to travel exclusively on it. APMs require a separate and exclusive guideway that can be elevated, at-grade (fenced or otherwise protected) or in tunnels. Electric power is supplied via a “third rail” on the guideway at 480 or 600 VAC; or 600, 750, or 1500 VDC. Headways can be as low as 90 seconds but are typically between two and five minutes.

APM suppliers are keenly aware of the rapid development of AVs, which do not require mechanical guidance or guideway-supplied electrical power. This awareness and understanding that the future is changing, and the desire to remain relevant in a world that is embracing Autonomous Vehicles, is driving APM suppliers to consider how to adapt their technologies to become Autonomous Vehicles. Non-mechanical guidance is in development by many of the APM suppliers. With the rapid advance in battery technology, some suppliers are also considering how batteries might be used to power APMs since this is still under development and the details of the technological advances are not known. APM technology suppliers include Alstom and Mitsubishi.

1.4 AUTONOMOUS BUSES

The following technologies are Autonomous Buses included in this study:

- New Flyer
- Irizar
- Volvo
- Iveco

1.4.1 New Flyer

Website: https://www.newflyer.com/bus/xcelsior-av/

New Flyer, a manufacturer of transit buses, has released the Xcelsior AV, a self-driving transit bus. They claim that this is the first heavy-duty automated transit bus in North America. The bus was developed with Robotic Research, a Maryland-based research and technology company. Federal regulations have not yet been developed for the deployment of Level 4 autonomous vehicles in public transit on shared roadways. Therefore, deployment of this Autonomous Bus is limited to specific Operational Design Domain (ODD) applications.

Table 1.4.1-1 New Flyer Autonomous Bus Specifications

New Flyer Autonomous Bus specifications	Value
Vehicle length	41 ft
Vehicle width	Information requested
Vehicle height	11’-1”
Vehicle weight (loaded)	Information requested
Vehicle capacity	40 seated passengers; 42 standees
Maximum speed	Information requested

Figure 1.4.1-1 New Flyer

1.4.2 Irizar

Website: https://www.irizar.com/en/se-presenta-el-primer-autobus-autonomo-del-grupo-irizar-en-malaga/

In January 2020, the first Irizar Group autonomous bus was delivered to the city of Malaga (Spain). The bus that was used for this pilot project is the Irizar i.e. bus model. This bus is capable of operating autonomously or manually. The bus will be operating on a route transferring cruise passengers arriving to Malaga, and will utilize a precise positioning and guidance system that is linked to a central control center.

Table 1.4.2-1 Irizar Autonomous Bus Specifications

Irizar Autonomous Bus Specifications	Value
Vehicle length	Approx. 40 ft
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	60 passengers
Maximum speed	Information requested

Figure 1.4.2-1 Irizar Autonomous Bus

1.4.3 Volvo

Website: https://www.volvobuses.com/en/city-and-intercity/innovation/automation.html

Volvo's approach for autonomous buses is to focus first on automated functionality with technologies that would decrease distractions or enable the bus driver to stay alert, and driver assistance systems such as collision warning with automatic braking, lane departure warnings, etc. Although Volvo has been conducting full-scale, testing with autonomous buses driven in controlled environments. Field testing has included one in Singapore in partnership with Nanyang Technological University.

Table 1.4.3-1 Volvo Autonomous Bus Specifications

Volvo Autonomous Bus Specifications	Value
Vehicle length	Approx. 40 ft
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	60 passengers
Maximum speed	Information requested

Figure 1.4.3-1 Volvo Autonomous Bus

1.4.4 Iveco

Website: https://www.sustainable-bus.com/smart-mobility/iveco-autonomous-bus-under-development-with-easymile/

Iveco, in partnership between Iveco Bus and a group of other companies and laboratories, have been developing an autonomous bus. Their principal partner is EasyMile, the company that has already developed an autonomous shuttle (EasyMile EZ10). On September 23, 2021, EasyMile reported that Iveco Bus, EasyMile and other partners completed testing of a fully autonomous standard bus prototype.

Table 1.4.4-1 Iveco Autonomous Bus Specifications

Applied EV vehicle specifications	Value
Vehicle length	Approx. 40 ft
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	100 passengers (total seated and standing)
Maximum speed	Information requested

Figure 1.4.4-1 Iveco Autonomous Bus

1.5 OTHER AUTONOMOUS TECHNOLOGIES

Other autonomous technologies include:

- Stanley Robotics
- Oceaneering
- Citroen Skate
- Outrider
- Kodiak Robotics
- Honda Autonomous Work Vehicle

1.5.1 Stanley Robotics

Website: https://stanley-robotics.com/automotive-industry/

Stanley Robotics has developed a technology for the automotive industry that allows their robots to locate a specific car, lift it up off the ground, move the car and park it to another location, using a fleet management system. This technology could have usefulness for automotive manufacturers for moving new vehicles around within their facility after they are manufactured. Their autonomous robots allow for 24/7 operations. This might be a potential solution for the specific case described in OE-A.

Table 1.5.1-1 Stanley Robotics Vehicle Specifications

Applied EV vehicle specifications	Value
Vehicle length	Information Requested
Vehicle width	Information Requested
Vehicle height	Information Requested
Vehicle weight (loaded)	Max total weight of transportable car = 6,000 lbs
Vehicle capacity	Information Requested
Maximum speed	6.2 mph

Figure 1.5.1-1 Stanley Robotics

1.5.2 Oceaneering

Website:

Oceaneering Mobile Robotics (OMR) | Oceaneering

Oceaneering's UniMover™ D 100 is a small, last-mile personal delivery vehicle. It has the same floor height as the 2getthere GRT. Potential applications envisioned include using this vehicle to deliver packages at high speed and then transitioning them to smaller vehicles and directly to the final destination.

Oceaneering also offers the Concept Cargo vehicle shown below.

Table 1.5.2-1 Oceaneering Concept Cargo Vehicle Specifications

Oceaneering vehicle specifications	Value
Vehicle length	approx. 20 ft
Vehicle width	approx. 7 ft
Vehicle height	approx. 9 ft
Vehicle weight (loaded)	approx. 14,000 – 14,500 lbs
Vehicle capacity	approx. 5,500 – 6,000 lbs
Maximum speed	25 mph

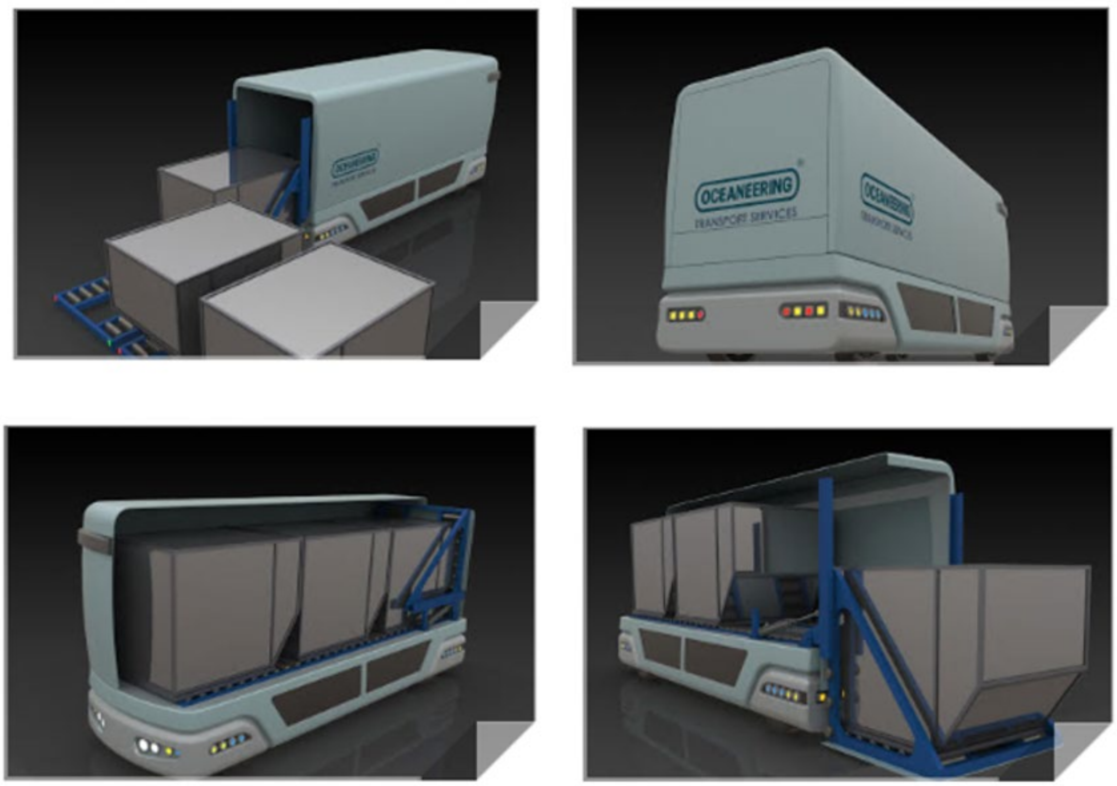

Figure 1.5.2-1 Oceaneering Concept Cargo

1.5.3 Citroen Skate

Website: https://newatlas.com/automotive/citroen-skate-autonomous-interchangeable-pods/

Citroen has developed an autonomous vehicle platform that is multi-directional, thanks to an unusual spherical concept tire developed by Goodyear. A range of types of operations could theoretically be achieved by interchanging pods that would fit on top of the skate platform. Citroen claims that pods can be interchanged in as little as 10 seconds.

Table 1.5.3-1 Citroen Skate Vehicle Specifications

Oceaneering vehicle specifications	Value
Vehicle length	5.2 ft
Vehicle width	8.5 ft
Vehicle height	1.6 ft
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	16 mph

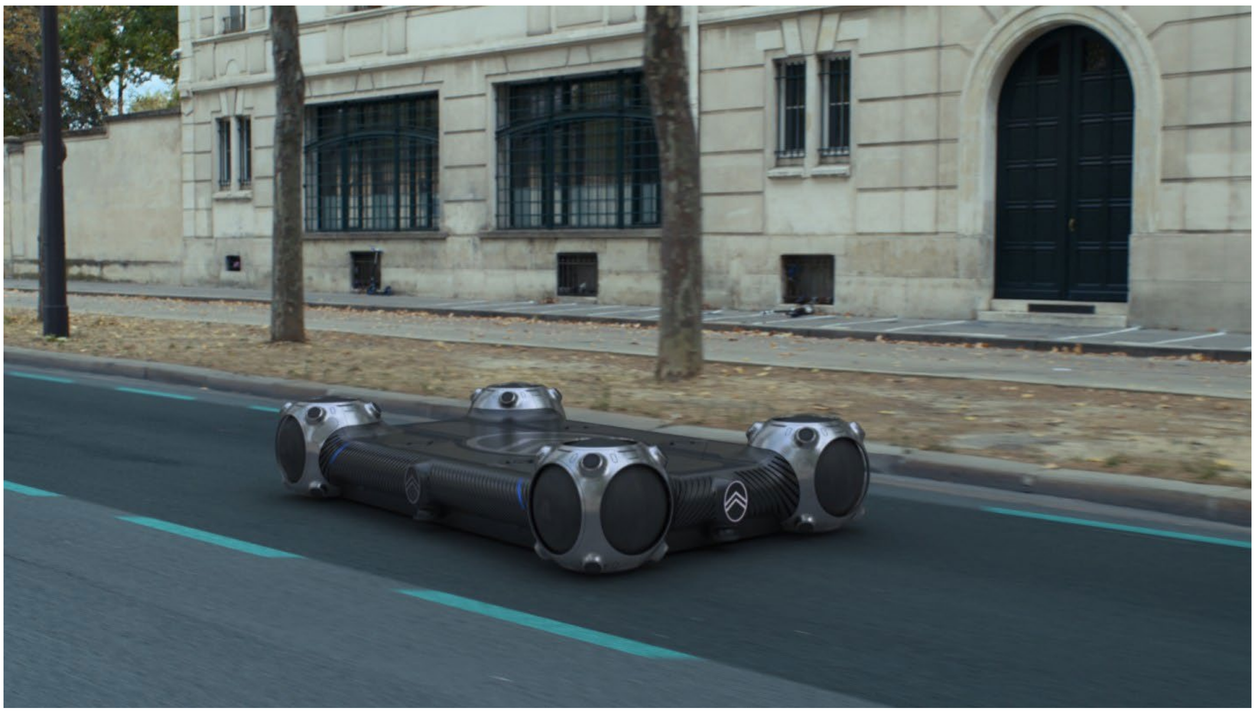

Figure 1.5.3-1 Citroen Skate

1.5.4 Outrider

Website: https://www.outrider.ai/

Outrider offers a fully integrated system for autonomous yard operations. Outrider focuses only on automating yard operations with a 3-part integrated system consisting of management software, autonomous vehicles, and site infrastructure. Their technology is tested at their testing facility, which is a 4.5 acre distribution yard that is operational daily in order to simulate real-world yard operations.

Table 1.5.4-1 Outrider Vehicle Specifications

Oceaneering vehicle specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

Figure 1.5.4-1 Outrider

1.5.5 Kodiak Robotics

Website: https://kodiak.ai/

The Kodiak Driver is a purpose-built technology system tailored for long-haul trucks, including a sensor system and mapping solution to accommodate highway driving. The company claims it can operate in construction zones. They also claim to be able to operate in heavy traffic, merging onto and off highways, operate day and night, operate in harsh weather, and handle changing lanes.

Table 1.5.5-1 Kodiak Vehicle Specifications

Oceaneering vehicle specifications	Value
Vehicle length	Information requested
Vehicle width	Information requested
Vehicle height	Information requested
Vehicle weight (loaded)	Information requested
Vehicle capacity	Information requested
Maximum speed	Information requested

Figure 1.5.5-1 Kodiak Robotics

1.5.6 Honda Autonomous Work Vehicle

The Honda Autonomous Work Vehicle (3rd generation) has the capability of autonomous operation using various sensors, including a GPS for location, lidar, radar and stereoscopic 3D cameras. It can operate via remote control. This is an off-road vehicle that can be used for construction sites, as well as for other industries that need autonomous operation.

The second-generation prototype of a Honda Autonomous Work Vehicle (AWV) had a successful field test at a large-scale solar energy construction site in New Mexico.

Table 1.5.6-1 Honda Autonomous Work Vehicle Specifications

Oceaneering vehicle specifications	Value
Vehicle length	9.5 ft
Vehicle width	4.9 ft
Vehicle height	4.9 ft
Vehicle weight (unloaded)	1,590 lbs
Maximum load capacity	880 lbs
Maximum speed	Information requested

Figure 1.5.6-1 Honda Autonomous Work Vehicle

APPENDIX B

LIST OF WIRELESS ELECTRICAL VEHICLE CHARGING TECHNOLOGIES

Note: Most of the information on this appendix was obtained from the manufacturer's websites.

1. WIRELESS ELECTRIC VEHICLE CHARGING TECHNOLOGIES

The following is a compilation list of EV charging technologies and descriptive information regarding these technologies that is intended to supplement the information provided in Section 3.4 of the report. The compilation is divided into two primary categories. Stationary wireless electric vehicle charging technologies require the electric vehicle to remain stationary over some sort of charging plate embedded below the roadway surface and/or guideway surface. Dynamic wireless electric vehicle charging technologies permit vehicles to charge while the vehicles are in motion over some sort of charging plate embedded below the roadway surface and/or guideway surface.

1.1 STATIONARY WIRELESS ELECTRIC VEHICLE CHARGING TECHNOLOGIES

Stationary wireless EV charging technologies include:

- WiTricity
- InductEV
- Continental AG
- Plugless Power
- HEVO
- WAVE
- Electreon

1.1.1 WiTricity

Additional information on the WiTricity wireless charging technology can be found on the following website.

https://witricity.com/

In addition the information provided in Section 3.5.1.1 of the report, the following are diagrams of the WiTricity concept.

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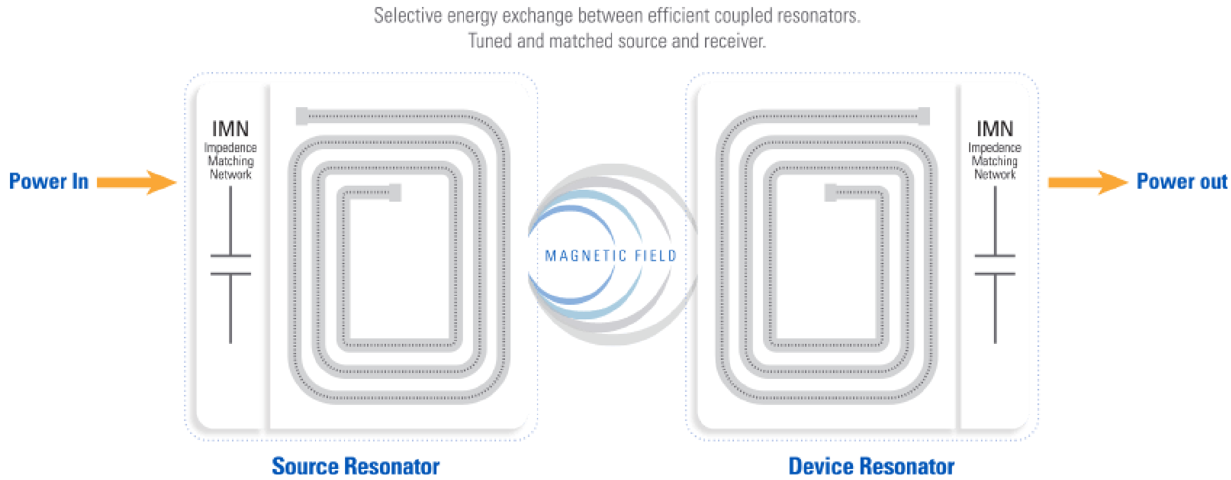

Figure 1.1.1-1 Conceptual Diagram for Selective Energy Exchange Between Coupled Resonators

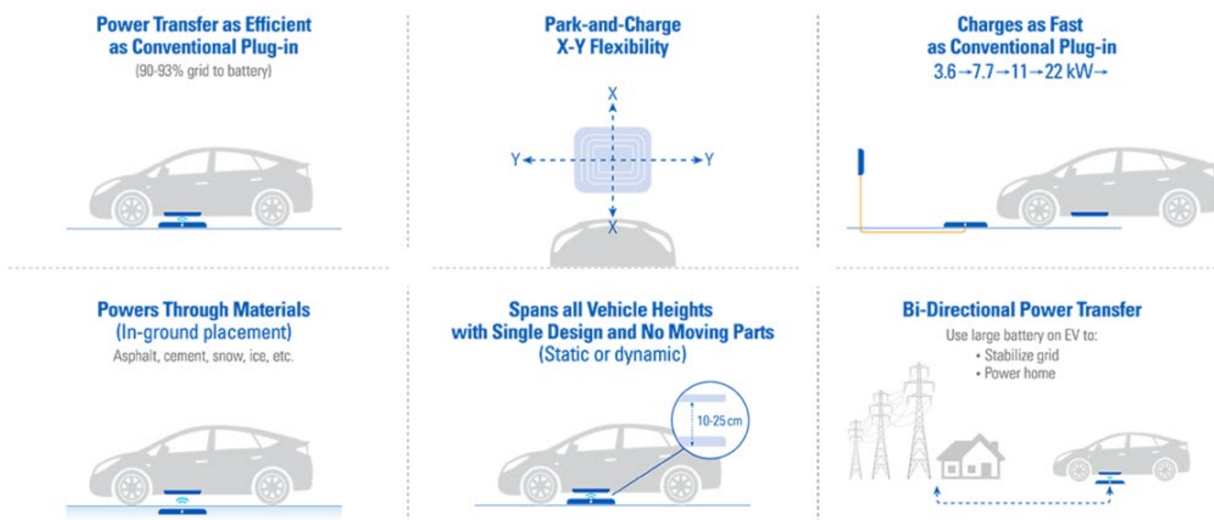

Figure 1.1.1-2 Conceptual Diagram Illustrating Key Characteristics

1.1.2 InductEV

Additional information on the InductEV wireless charging technology can be found on the following website.

https://www.inductev.com/

InductEV (formerly Momentum Dynamics) is a developer and provider of fast, efficient autonomous high-power wireless charging systems for the automotive and transportation industries. Their technology works by feeding an AC current into a resonant transmitting coil, thereby creating a magnetic field. A resonant receiving coil captures this magnetic field, creating an AC current in that coil.

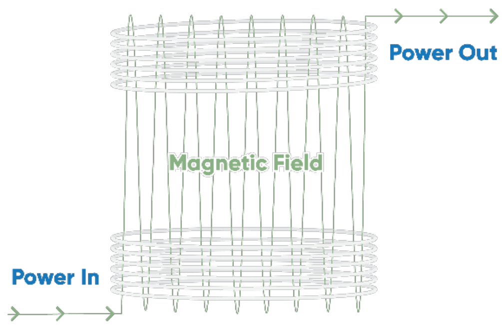

Figure 1.1.2-1 Conceptual Diagram for Resonant Magnetic Induction

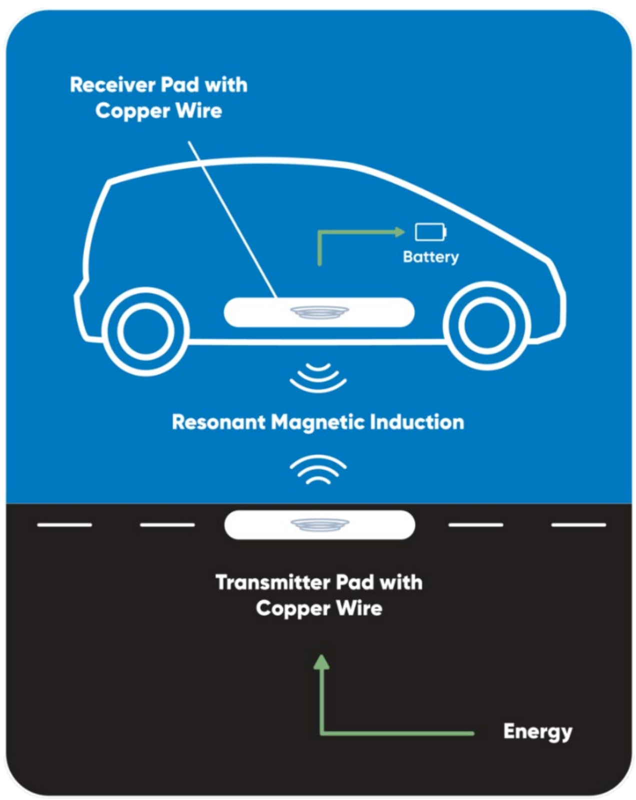

Figure 1.1.2-2 Conceptual Diagram Illustrating Components in Roadway and Vehicle

1.1.3 Continental AG

Additional information on the Continental AG wireless charging technology can be found on the following website.

https://www.continental.com/en/press/press-releases/2017-05-31-inductive-charging/

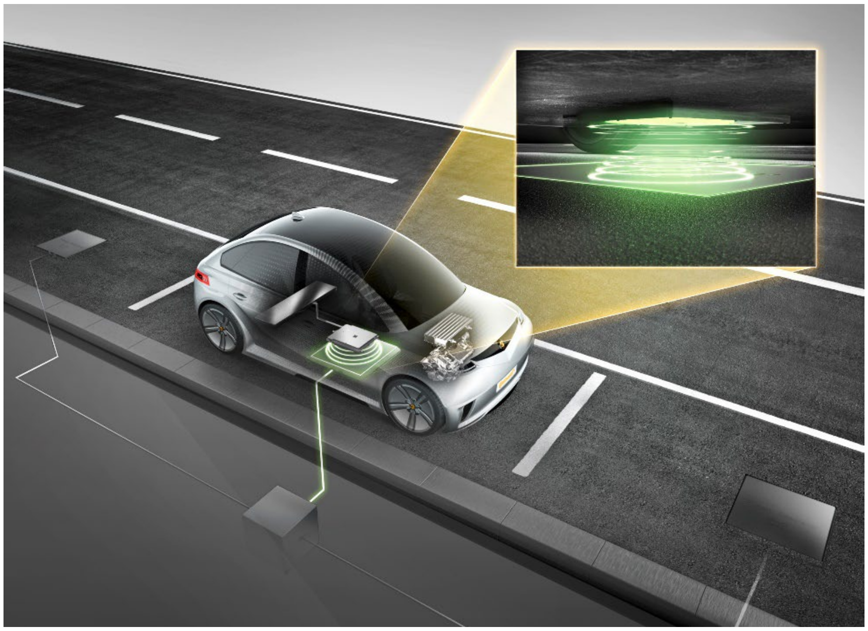

Figure 1.1.3-1 Continental Automated Wireless Charging Technology

1.1.4 Plugless Power

Additional information on the Plugless Power wireless charging technology can be found on the following website.

https://www.pluglesspower.com/

Plugless Power utilizes inductive charging technology to eliminate the need to plug in an Electric Vehicle using two aligned magnetic coils sending power to the Electric Vehicle over an air gap between the vehicle and the Wireless Charging Station.

Figure 1.1.4-1 Plugless Power Wireless Charging in Parking Space

Figure 1.1.4-2 Plugless Power Wireless Charging

1.1.5 HEVO

Additional information on the HEVO wireless charging technology can be found on the following website.

https://hevo.com/

HEVO was founded in 2011 with the goal of accelerating adoption of electric vehicles. It was deemed that easier vehicle charging will be essential to pave the way for mass adoption of electric vehicles. The U.S. Department of Energy's Oak Ridge National Laboratory has licensed its wireless charging technology for electric vehicles to HEVO. HEVO is focused on Level 2 (L2) Stationary Wireless Charging. HEVO technology has only been applied to passenger vehicles. The HEVO charging pad can be installed flush with the floor or attached directly on top of the floor.

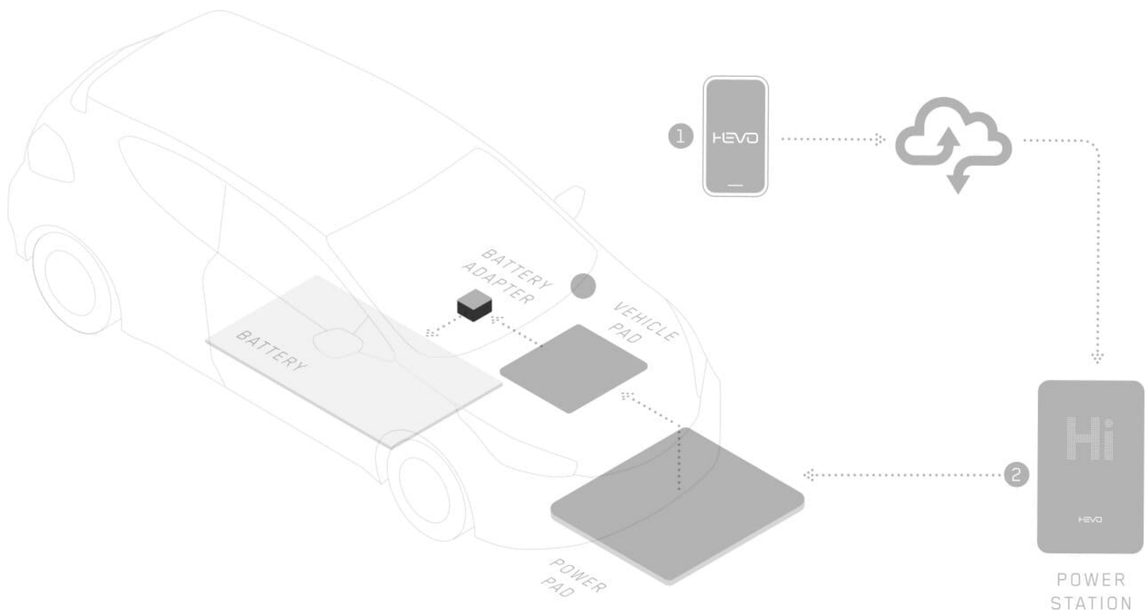

Figure 1.1.5-1 HEVO Wireless Charging Concept Diagram

1.1.6 WAVE

Additional information on the WAVE wireless charging technology can be found on the following website.

https://waveipt.com/

1.1.7 Electreon

Electreon has been at the forefront of implementing wireless electric vehicle charging for both dynamic and stationary applications. This company will be discussed more in depth in Section 1.2.2 herein.

Electreon offers hardware and software solutions as well as Charging as a Service (CaaS) options. CaaS is a subscription-based EV charging package that provides turnkey EV charging solutions with minimal upfront purchasing costs. Subscribers pay a monthly fee over a fixed term instead of all upfront costs at once. The service includes project management and installation efforts, operation and maintenance with guaranteed uptime.

1.2 DYNAMIC WIRELESS ELECTRIC VEHICLE CHARGING TECHNOLOGIES

Dynamic wireless EV charging technologies include:

- Magment GmbH
- Electreon
- IPT Technology
- Integrated Roadways

1.2.1 Magment GmbH

Additional information on the Magment wireless charging technology can be found on the following website.

https://www.magment.co/

Magment is a German-headquartered company founded in 2015 with operations in the United States. Magment offers an innovative magnetizable concrete product consisting of cement and recycled magnetic particles called ferrite

Current projects in development that include the use of Magment technology include a collaboration with the Indiana DOT and Purdue University, as a part of ASPIRE, to develop the world's first contactless wireless charging concrete pavement highway segment.

Figure 1.2.1-1 Wireless Charging Concept for Roadways

Figure 1.2.1-2 MagPad

Figure 1.2.1-3 Magnetizable Concrete Product

1.2.2 Electreon

Additional information on the Electron wireless charging technology can be found on the following website.

https://www.electreon.com/

Figure 1.2.2-1 Wireless Charging Concept for Roadways

Figure 1.2.2-2 Wireless Charging Concept for Roadways

1.2.3 IPT Technology

Additional information on the IPT Technology wireless charging technology can be found on the following websites.

https://ipt-technology.com/

https://ipt-technology.com/e-mobility-wireless-dynamic-charging/

https://www.electrichybridvehicletechnology.com/news/charging-technology/ipt-group-acquires-wireless-charging-technology-from-bombardier.html

IPT PRIMOVE technology works through magnetic inductive power transfer, with current flowing from pre-assembled ground wiring coils to a receiver pad under the vehicle through electromagnetic induction.

IPT Group, a global manufacturer of wireless charging and electrification solutions with applications in industrial and e-mobility applications, has acquired wireless charging technology company PRIMOVE from Bombardier.

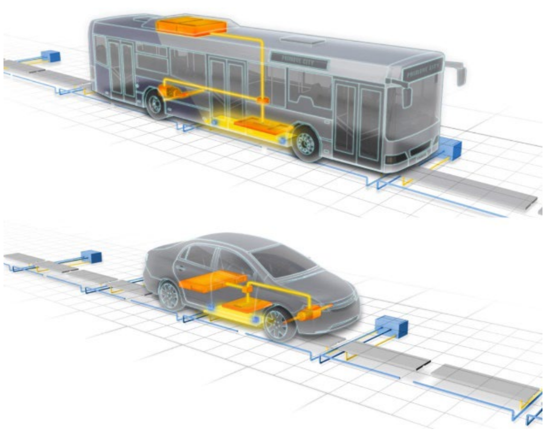

Figure 1.2.3-1 IPT PRIMOVE Dynamic Charging

Figure 1.2.3-2 IPT PRIMOVE Dynamic Charging Installation in Mannheim, Germany

1.2.4 Integrated Roadways

Additional information on the Integrated Roadways wireless charging technology can be found on the following website.

https://integratedroadways.com/

Integrated Roadways is developing durable precast concrete sections called Smart Pavement. The wireless charging system is designed to work efficiently up to and beyond standard highway speeds, which means Integrated Roadways wireless charging can work in a parking space, a bus stop, in a city street, or even on the interstate.

In parking applications, the wireless charging system can operate continuously as the system charges, providing equivalent performance as a comparable plug-charge system. Charging capacity is possible up to 250kW.

APPENDIX C

STRUCTURAL INFORMATION NORMAL WEIGHT AND LIGHTWEIGHT CONCRETE DESIGN VALUES

Note: Engineering review and final design under a Professional Engineer's (PE) seal must be completed for final structure. The following guidelines are provided for support and not to replace/take the place of sealed engineering design.

Design Values for Normal Weight Concrete vs Lightweight Concrete 8000 psi Beam *		
	Normal Weight Concrete	**Lightweight Concrete**
Tensile Strength		
Compressive Strength	8000 psi	8000 psi
Splitting Tensile	0.090 f'c	0.080 f'c
Beam Rupture	0.085 f'c	0.075 f'c
Tensile Field	0.060 f'c	0.055 f'c
Modulus of Elasticity		
At Transfer	4200-5600 ksi	3100-3300 ksi
In Service	5000-6500 ksi	3300-3500 ksi
Dried at 50% RH	5400 ksi	3100 ksi
Creep Coefficient for P/S and Self Weight		
Interval		
Transfer to day 7-60	0.25-1.2	0.25-1.2
Autogenous Shrinkage Strain during Accelerated Cure		
Microstrain	About 250	Lower
Total Shrinkage Strain		
Microstrain	About 350	About 350-450
Typical Beam Concrete Constituents		
Portland Cement	450 pcy	480 pcy
Slag	300 pcy	320 pcy
Water	232 pcy	248 pcy
Water to cement ratio	0.31	0.31
Fine Aggregate	1050 pcy	1150 pcy
Coarse Aggregate	2100 pcy	1050 pcy
Working Stress for Vertical Beam End Reinforcement		
Non-aggressive environment	22 ksi	19 ksi
Aggressive environment	16 ksi	16 ksi

psi = pounds per square inch
ksi = 1000 pounds per square inch
pcy = pounds per cubic yard
f'c = compressive stress

*Information consolidated from "Precast Prestressed Concrete Beams and Girders for Virginia Highway Bridges", Rodney T. Davis, PhD, PE, Virginia Transportation Research Council.

APPENDIX D

RESEARCH

1. CONTACTS

The following companies/individuals were instrumental in the development of this document:

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2. MATERIAL INFORMATION

2.1 RECYCLED STRUCTURAL PLASTIC LUMBER

The properties of Recycled Structural Plastic Composite (RSPC) are described in a document World's First Thermoplastic Bridges, written by Vijay Chandra, P.E., Director of Structures, Parsons Brinkerhoff Inc., John S. Kim, Ph.D., P.E., Supervising Bridge Engineer, Parsons Brinkerhoff Inc., Dr. Thomas J. Nosker, Ph.D., Professor, Rutgers University, and George J. Nagle, P.E., Manager of Engineering, Axion International, Inc. This publication discusses the need for replacement of our bridge infrastructure, existing project applications, the properties of RSPC, the financial and environmental advantages of RSPC, and future project applications. The following information is a summary of the publication.

At the time the article was written, one third of the 600,000 U.S. highway bridges were structurally deficient or functionally obsolete. The old bridges were constructed of steel, concrete and wood and have been replaced using the same conventional materials. In an effort to establish methods in accordance with Accelerated Bridge Construction (ABC) and the "Going Green" initiative, new materials are being developed. Scientists at Rutgers University and Axion International, Inc., developed a structural thermoplastic consisting of almost 100% recycled material. Thermoplastic bridge elements are fabricated off site and can be assembled quickly on site. Time considerations are essential for bridge replacements because of the impact of traffic at every bridge.

The first bridge built using thermoplastic materials was at Fort Leonard Wood, Missouri in 1998. The deck was thermoplastic, and the girders were steel. Although the initial costs were high, the additional cost was recouped in eight years. The bridge capacity was 12.5 tons. Another vehicle bridge was constructed of thermoplastics in New Baltimore, New York, a bowstring truss (arched). A vehicular bridge with thermoplastic beams, deck and rails was constructed in 2002 in the Wharton State Forest, New Jersey. The innovation was that it used thermoplastic molded I-beams. The initial cost was close to the cost of a treated wood bridge and has a 36-ton capacity. In 2009, a bridge constructed entirely of RSPC was built at Fort Bragg, North Carolina for M-1 Abrams tank loads, 71 tons. Railroad bridges have also been constructed of RSPC.

The following tables and figures from the publication show the material properties of RSPC:

Table 2.1-1 Common Construction Material Weights

Material Weight Comparison	
Wood (Oak)	45 lbs/ft^3
RSPC	50 lbs/ft^3
Concrete	150 lbs/ft^3
Steel	489 lbs/ft^3

lbs/ft^3 = pounds/cubic foot

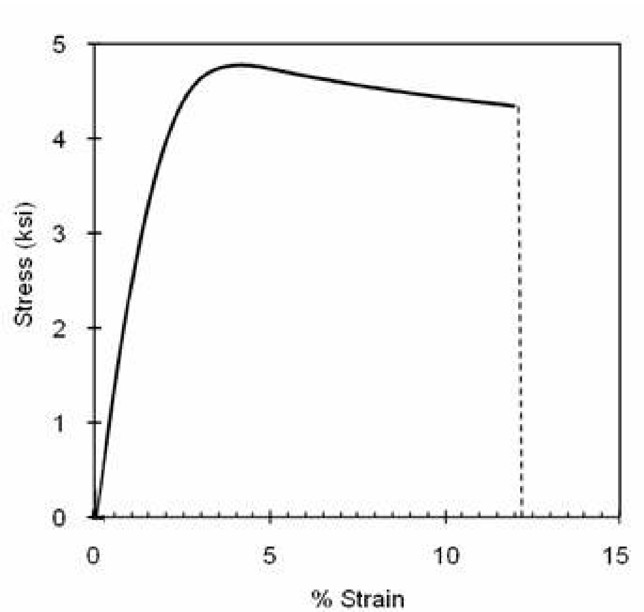

Figure 2.1-1 Stress-Strain Curve

Table 2.1-2 Material Properties of RSPC

Thermoplastic Properties	
Specific Gravity	0.85-0.90
Eleatic Modulus	250,000 lbs/in^2
Allowable Flexural Stress	600 lbs/in^2 (Ultimate = 3000 lbs/in^2)
Allowable Compressive Stress	600 lbs/in^2 (Ultimate 2,500 -4,300 lbs/in^2)
Allowable Shear Stress	350 lbs/in^2 (Ultimate = 1500 lbs/in^2)
Coefficient of Thermal Expansion	0.0000282 in/in/deg F
Cyclic Loading Railroad Tie Wear (2 million Cycle Test, 20 kilopounds Vertical Load, 3.75-7.5 kilopounds Lateral Load	No tie plate cutting damage or cracks

The financial advantages of RSPC are not seen in the initial cost but is very significant in the lifetime cost. Maintenance costs over the life of a bridge structure are significant. Timber bridges are damaged by moisture and inspects, concrete bridges crack and lose strength as the steel reinforcement corrodes from moisture intrusion in the cracks, and steel corrodes and loses section so it must be painted on a regular cycle.

The fact that RSPC elements are constructed of consumer and industrial waste is sustainable and very beneficial for the environment because most plastic, including recyclable plastic, ends up in landfills. One bridge at Fort Bragg used 86,000 pounds of recycled plastic. Additional advantages include:

- Ultraviolet Degradation: less than 0.003 inches per year.
- Fire Resistance: the RSPC ignition point is higher than wood.
- Moisture Absorption: virtually impervious.
- Thermal Resistance: 125 degrees C to -125 degrees C, well beyond current temperature ranges.
- Environmental Resistance: resistant to marine borers, corrosion, insects, and rot.
- Abrasion: highly resistant to abrasion.
- Creep: designed for a 600 lbs/in^2 allowable tensile, compressive, and flexural stress.
- Skid Resistance: can be modified by use of surface texturing.
- Acid Resistance: RSPC is resistant to most acids and salts.
- Abutment Backfill: needs a lightweight backfill such as expanded polystyrene or similar.
- Surface Texturing: surface texturing may be embossed on the deck boards.
- Color: basic color is graphite, but colors such as gray, beige, etc., may be produced.

Because of the current mechanical properties of the RSPC, span lengths are limited to about 30 feet, simple span bridges. With advanced research, longer spans may be possible.

Note: All figures and tables are from the referenced document.

3. FRP COMPOSITE BRIDGE TECHNOLOGY

The properties of Fiber Reinforced Polymers (FRP) are described in marketing documents provided by Orenco Composites. FRP has been used for sporting goods, boats, wind turbines, and satellite antennae for decades, but its use here in the US for bridges has been limited. FRP composite bridges began with the establishment of a company called FiberCore® Europe by Jan Peeters and Simon de Jong in Rotterdam, The Netherlands. There are over 1,400 FRP bridges in the Netherlands, Europe and worldwide. InfraCore® in the US was developed from FiberCore®. FRP consists of high-strength fibers and a polymer matrix. The fibers are generally fiberglass or carbon fiber mats. Material property comparisons are shown in the following figures from the Orenco documents:

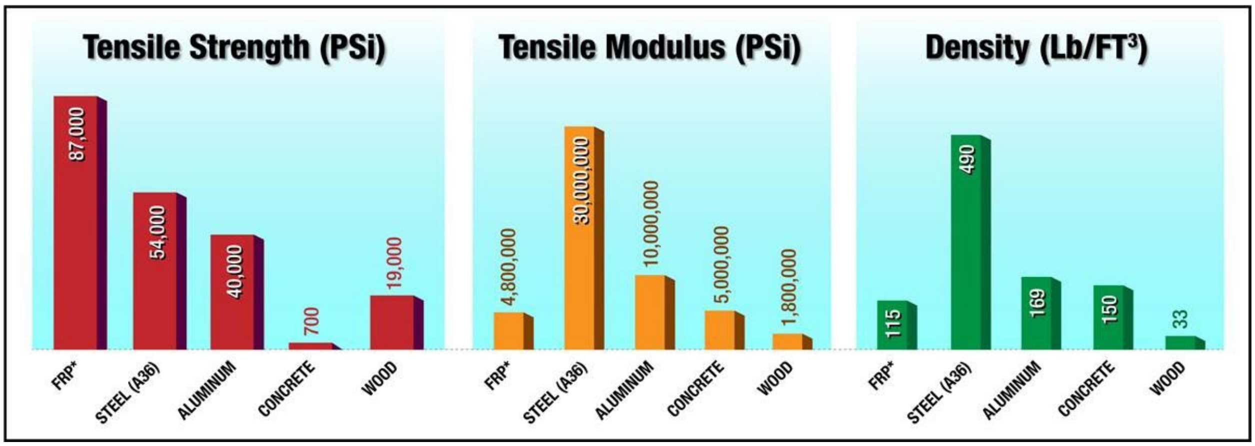

Figure 3-1 Property Comparison

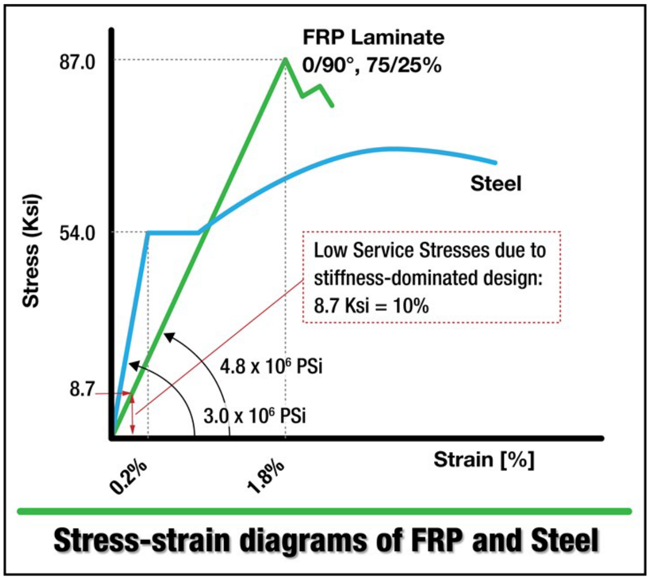

Figure 3-2 Stress-Strain Diagram

According to Orenco, FRP has 61% greater tensile strength than steel, 84% tensile modulus lower than steel (like concrete) and has properties that allow higher strain to failure than steel, allowing for resilient bridges that tolerate deflection and fatigue.

The FiberCore® system uses reverse Z shaped units to duplicate the performance of a steel I-Beam.

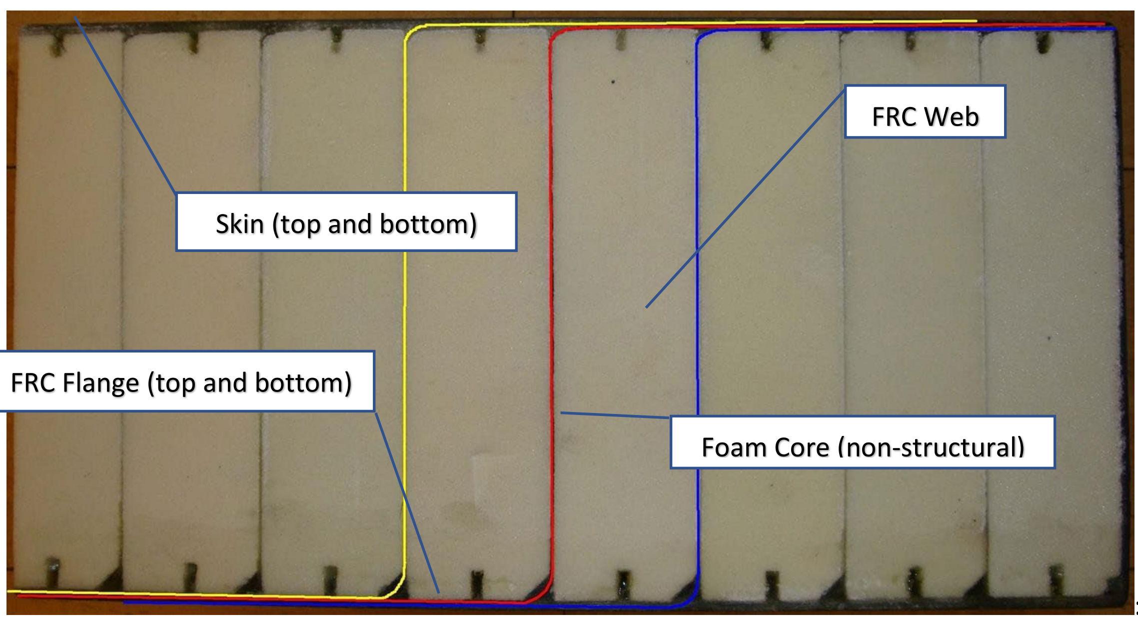

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Figure 3-3 Typical Cross Section of Deck

The capacity of the section is determined by web spacing/density, web thickness, fiber angle architecture and skin thickness. Properties and characteristics of InfraCore®:

- Non-magnetic
- Energy-absorbing: resistant to shells, bullets and crashes
- Shock-resistant
- Resistant to impact
- Resistant to fatigue
- Lightweight: floats, transportable, can be temporary, low inertia
- Insulating: thermal, electrical and acoustically insulating
- Chemically inert: Corrosion-resistant, resistant to acids and bases
- Liquid-tight
- Large dimensions possible

FRP is sustainable based on carbon emissions.

Table 3-1 Environmental Data

Embodied Energy and Carbon Comparison											
	Material Weight		Embodied Energy Coefficients		Embodied Energy		Embodied Carbon Coefficients		Embodied Carbon	
Materials	(Kg)	(lb)	(MJ/Kg)	(KiloWatt hour/lb)	(MJ)	(KiloWatt Hour)	(Kg CO_2/ Kg)	(lb CO_2/ lb)	(Kg CO_2)	(lb CO_2)
Timber	3000	6,614	10	1.26	30,000	8,300	0.31	0.31	930	2,050
Steel Section	3000	6,614	28.1	3.54	84,300	23,419	2.12	2.12	6360	14,021
Hybrid Steel Beams/ Timber Deck	Timber 1250 Steel 1250	Timber 2756 Steel 2756	Timber 10 Steel 28.1	Timber1.26 Steel 3.54	47,625	13,229	Timber 0.31 Steel 2.12	Timber 0.31 Steel 2.12	3037	6,695
FRP Composite Deck and Handrails	750	1,653	26	3.28	19,500	5,417	1.23	1.23	922	2,033

1. The coefficients for general timber are based on sustainable source from managed forests using only fossil fuel derived carbon. Source inventory of Carbon & Energy (ICE) Version 2.0
2. The coefficients for steel are for steel section using 35.5% recycled. Source ICE Version 2.0

3. The coefficients for FRP are from a 2009 University of New South Wales Report – "Composites: Calculating Their Embodied Energy", chapter 6.

4. Conversions from metric to US units calculated by webconversiononline.com

Traffic bridges in Europe rated to 60 tons:

Figure 3-4 Vehicular Bridge

Figure 3-5 Vehicular Bridge

Figure 3-6 Vehicular Bridge

FRP has been used for the addition of cantilevered sidewalks on vehicular bridges and for deck replacements of vehicular drawbridges, swing-bridges and conventional steel bridges.

Note: All figures and tables are from the referenced document.

4. DESIGN OF FRP BRIDGES – USDA FOREST SERVICE

This document can be found at https://www.fs.usda.gov/t-d/pubs/pdfpubs/pdf06232824/pdf06232824dpi72pt05.pdf

The referenced publication includes commentary on design specifications for FRP pedestrian bridges, design concerns and other concerns in the Design of FRP Bridges. The section for Inspecting and Maintaining FRP Bridges includes commentary on testing procedures, inspection methods, qualifications of inspectors, visual signs of damage and defects, and a section on Repair and Maintenance. It also includes data on selected existing FRP bridges in the US Forest Service system.

The following include references to publications on FRP listed on the FHWA website:

- Composite Bridge Decking - Final Project Report, FHWA-HIF-13-029
- Laminate Specification and Characterization - Composite Bridge Decking, FHWA-HIF-12-020
- Jim Williams, (2008) "The Ongoing Evolution of FRP Bridges", 'Public Roads, Vol. 72 No. 2, FHWA-HRT-08-006, Sept/Oct 2008.
- Behavior of Fiber-Reinforced Polymer Composite Piles Under Vertical Loads, FHWA-HRT-04-107
- A Laboratory and Field Study of Composite Piles for Bridge Substructures, FHWA-HRT-04-043
- NCHRP Project 20-68A, Scan 13-03 - Advances in Fiber-Reinforced Polymer (FRP) Composites in Transportation Infrastructure
- Field evaluation of hybrid-composite girder bridges in Missouri, 2014
- Guide Specifications for Design of FRP Pedestrian Bridges, First Edition 2008

APPENDIX E
LRFD LOAD TABLE WITH APM MODIFICATIONS

Note: Engineering review and final design under a Professional Engineer's (PE) seal must be completed for final structure. The following guidelines are provided for support and not to replace/take the place of sealed engineering design.

Table E-1 - LRFD Load Table with APM Modifications

Load Combination Limit State	DL, EP, CL	PS, C, S	LL, IM,PL, BR	CF	LF	SF, B	WA	WS	WL	T	TG	DS	EQ (not used, TxDOT)	CT	IL
Strength I	0.9/1.25	0.9/1.00	1.35	1.35	-	1.00	1.00			0.5/1.20		1.00			
Strength II	0.9/1.25	0.9/1.00	1.35		1.35	1.00	1.00			0.5/1.20		1.00			
Strength III	0.9/1.25	0.9/1.00				1.00	1.00	1.00		0.5/1.20		1.00			
Strength IV	0.9/1.25	0.9/1.00				1.00	1.00			0.5/1.20					
Strength V	0.9/1.25	0.9/1.00	1.35		1.35	1.00	1.00	1.00	1.00	0.5/1.20		1.00			
Extreme Event I	1.00	0.9/1.00	g_{EQ}			1.00	1.00						1.00		
Extreme Event IIa	1.00	0.9/1.00	1.00			1.00	1.00							1.00	
Extreme Event IIb	1.00	0.9/1.00	1.00			1.00	1.00								
Extreme Event IIc	1.00	0.9/1.00	1.00			1.00	1.00								
Extreme Event IId	1.00	0.9/1.00	1.00			1.00	1.00								1.00
Service Ia[a]	1.00	0.9/1.00	1.00	1.00		1.00	1.00			0.0/1.00	0.50	0.0/1.00			
Service Ib[a]	1.00	0.9/1.00				1.00	1.00	1.00		0.0/1.00	1.00	0.0/1.00			
Service Ic[a]	1.00	0.9/1.00	1.00	1.00	1.00	1.00	1.00	0.5	1.00	0.0/1.00	0.50	0.0/1.00			
Service II[b]	1.00	0.9/1.00	1.30	1.3		1.00	1.00			1.00/1.20					
Service III	1.00	0.9/1.00	g_{LL}	g_{LL}	g_{LL}	1.00	1.00			1.00/1.20	0.50	1.00			
Service IV	1.00	0.9/1.00				1.00	1.00	1.00		1.00/1.20		1.00			
Fatigue I - LL, IV and CF only *(infinite life)*[c]			1.35												
Fatigue I - LL, IV and CF only *(finite life)*[c]			1.00												

Notes:

X.XX Items in gray are modified from AASHTO to reflect APM charasteristics.

g_{LL} 1.0 for prestressed components desinged using the refined estimates of time-dependent losses as specified in AASHTO Article 5.9.5.4 in conjunction with taking advantage of the elastic gain.
0.8 for all other prestressed concrete components

g_{EQ} Check for both No train and for One train per structure:
For dual guideway structures, a train on either the left or right track,whichever is worse.
For single guideway structures, a single train.

Service III = crack control

Service IV = column crack control

[a] When vehicles are in operation, vehicle speed and wind speed are determined by system requirements.

[b] Steel slip critical connections only.

[c] Fatigue load combination to be chosen based on the number of cycles and the design life of the complete system or individual components. Factors may be modified based on available test data.

LRFD/ASCE LOADING ABBREVIATIONS

Table E-2 - LRFD Table Abbreviations

ABBREVIATIONS		
Load Case		
B	Buoyancy	AASHTO/ASCE
BR	Braking Force	AASHTO
C	Creep (CR)	AASHTO/ASCE
CF	Centrifugal force (CE)	AASHTO/ASCE
CL	Construction loads (includes EL)	ASCE
CT	Vehicle collision	AASHTO/ASCE
DL	Dead load (Includes DC, DW)	AASHTO/ASCE
DS	Differential Settlement	AASHTO/ASCE
EP	Earth pressure (Includes EH, EV, ES and DD)	AASHTO/ASCE
EQ	Seismic forces	AASHTO/ASCE
IL	Snow and ice loads	AASHTO/ASCE
IM	Impact forces	AASHTO/ASCE
LL	Live load	AASHTO/ASCE
LF	Longitudinal force	AASHTO/ASCE
PL	Pedestrian or walkway load	ASCE
PS	Prestressing	AASHTO/ASCE
S	Shrinkage (SH)	AASHTO/ASCE
SF	Stream flow	AASHTO/ASCE
T	Thermal force	AASHTO/ASCE
TG	Temperature gradient	AASHTO
WA	Water loads except Buoyancy and Stream Flow	AASHTO
WL	Wind loads on live load	AASHTO/ASCE
WS	Wind loads on structure	AASHTO/ASCE
TxDOT		
Braking Forces =	5% of design truck plus lane load	
No EQ		
No Vehicle Collision		
LLDF	Lever Rule, except no girder shall be less than #lanes/number of girders	

APPENDIX F

MISCELLANEOUS TABULAR DATA

Note: Engineering review and final design under a Professional Engineer's (PE) seal must be completed for final structure. The following guidelines are provided for support and not to replace/take the place of sealed engineering design.

1. Minimum Radius for Chorded Spans

Beam Spacing, S= 7.0 ft			
Minimum Radius for Chorded Spans			
Span Length (ft)	60	90	120
Minimum radius (ft)	1100	2200	4100
S/2 (ft)	3.4084	3.4385	3.44
	OK	OK	OK

2. Girder Lengths with Radial Piers, Beam spacing = 6.9 (See Figure F-1)

		Girder Lengths with Radial piers					
Radius	Max Span	G1	G2	G3	G4	G5	G6
ft	ft	ft	ft	ft	ft	ft	ft
500	45	42.93	43.56	44.19	44.81	45.44	46.07
900	60	58.34	58.8	59.27	59.73	60.2	60.66
1000	63	61.4	61.84	62.28	62.72	63.16	63.6
1500	80	78.57	78.94	79.31	76.69	80.06	80.43
2000	87	85.74	86.05	86.35	86.65	86.95	87.26
2200	90	88.78	89.07	89.36	89.64	89.93	90.21
2500	95	93.85	94.11	94.38	94.64	94.91	95.17
3000	105	103.89	104.03	104.38	104.62	104.87	105.11
3500	115	113.93	114.16	114.39	114.61	114.84	115.07
3800	120	118.95	119.17	119.39	119.61	119.83	120.05
4000	125	123.96	124.17	124.39	124.61	124.83	125.04

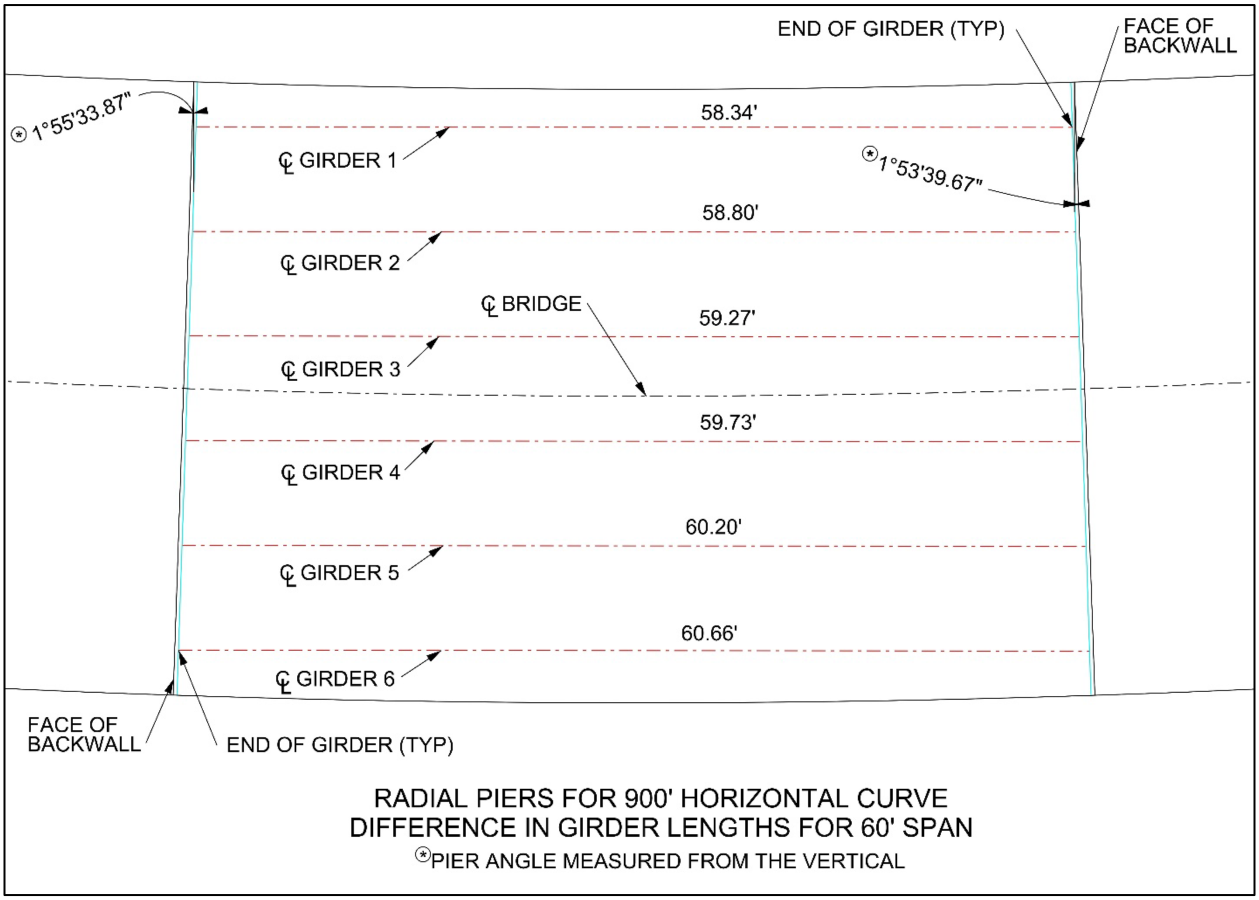


Figure F-1 – Girder Lengths with Radial Piers

3. TxDOT Concrete I-Girder prices from the most recent Average Low Bid Unit Prices to determine the most cost-effective girder length (Updated from August 2022 data).

		12 MONTH AVERAGE		
Item Description	Unit	Statewide	Fort Worth	Dallas
PRESTR CONC GIRDER (TX28)	LF	$159.28	$223.73	$210.35
PRESTR CONC GIRDER (TX34)	LF	$205.89	$290.00	$186.84
PRESTR CONC GIRDER (TX40)	LF	$117.99		
PRESTR CONC GIRDER (TX46)	LF	$206.84		$177.74
PRESTR CONC GIRDER (TX54)	LF	$182.80		$153.78
PRESTR CONC GIRDER (TX62)	LF	$191.96		$185.84
PRESTR CONC GIRDER (TX70)	LF	$232.05		$230.00

4. Superelevation Data (See Figure F-2)

Max Superelevation = 6%

Lt = (CS)(W)/G Where:		
	L_t =	Length of Transition
	CS =	Change in Cross Slope
	W =	Distance between axis of rotation and edge of traveled way
	G =	Maximum Relative Gradient

Begin Cross Slope at -2% = -0.02

G = 0.5% for > 50 mph = 0.005

W One Way = 10.167 — Distance between ext girders = 16.67 ft

W Two Way = 19.25 — Distance between ext girders = 34.83 ft

MPH =	55	Transition Length (ft)		Height Difference between exterior girders at max e (in)	
R	e	Lt - One Way	Lt - Two Way	Lt - One Way	Lt - Two Way
1060	0.060	163	308	12.0	25.1
1320	0.058	159	300	11.6	24.2
1470	0.056	155	293	11.2	23.4
1610	0.054	150	285	10.8	22.6
1750	0.052	146	277	10.4	21.7
1890	0.050	142	270	10.0	20.9
2050	0.048	138	262	9.6	20.1
2210	0.046	134	254	9.2	19.2
2400	0.044	130	246	8.8	18.4
2590	0.042	126	239	8.4	17.6
2810	0.040	122	231	8.0	16.7
3040	0.038	118	223	7.6	15.9
3290	0.036	114	216	7.2	15.0
3580	0.034	110	208	6.8	14.2
4200	0.032	106	200	6.4	13.4
4580	0.030	102	193	6.0	12.5
5020	0.028	98	185	5.6	11.7
5520	0.026	94	177	5.2	10.9
6110	0.024	89	169	4.8	10.0
6820	0.020	81	154	4.0	8.4
9410	-0.020	0	0	0	0

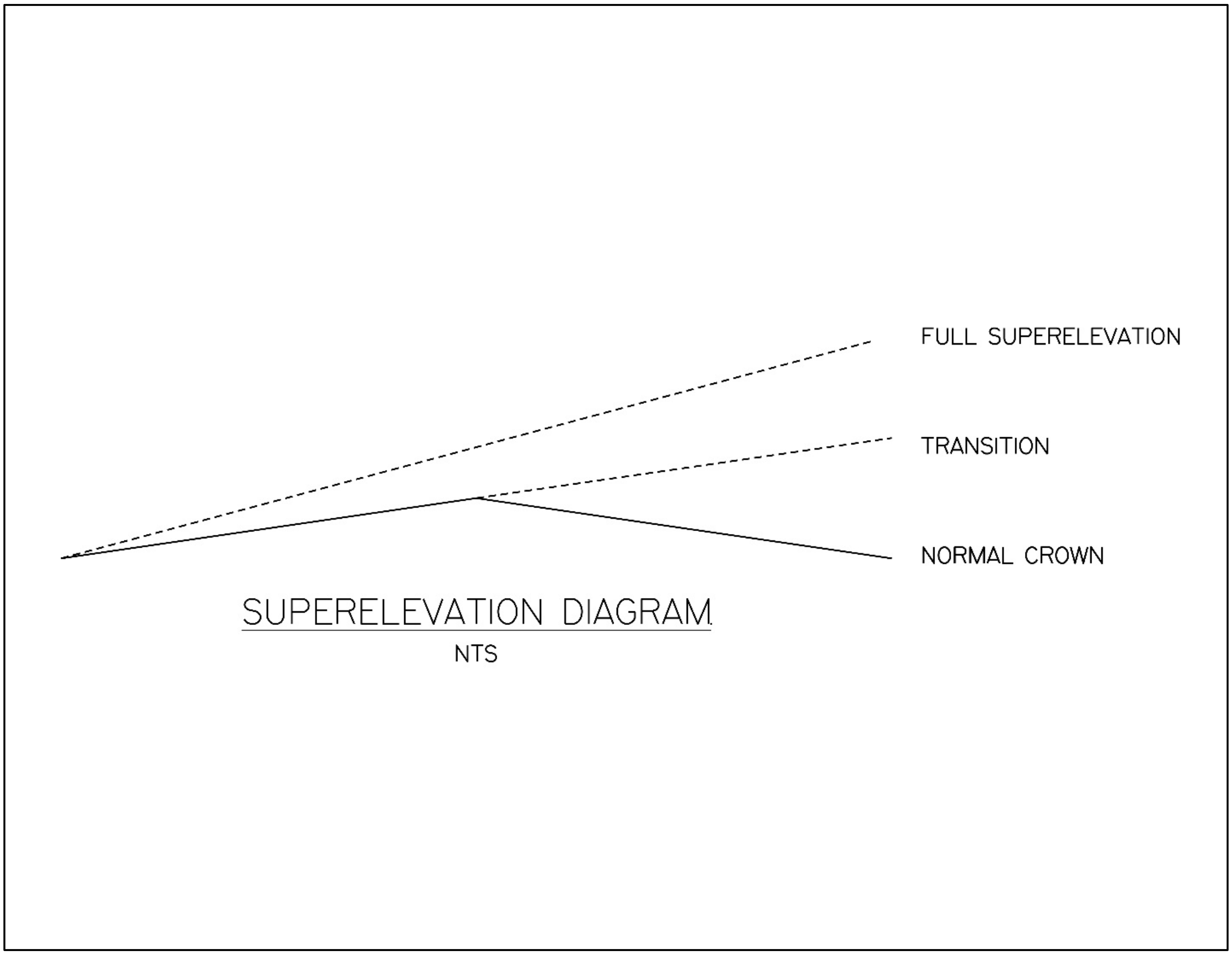


Figure F-2 – Superelevation Diagram

APPENDIX G

STRUCTURAL INFORMATION FOR MODULAR UNITS

Note: Engineering review and final design under a Professional Engineer's (PE) seal must be completed for final structure. The following guidelines are provided for support and not to replace/take the place of sealed engineering design.

Superstructure

The superstructures are modular and are designed for single direction and bi-directional traffic. The single direction configuration will only be used when the guideway lanes must be separated. The single direction superstructure will consist of 2 slabs and TX54 prestressed concrete (PC) I-girder units and a center TX54 PS I-girder, which will be referred to as TX54. The total width is 22'-8" out-to-out with a 20'-4" guideway. This allows enough guideway width for passenger emergency egress. If a vehicle is disabled, there is enough clearance for a maintenance vehicle to pass to tow the disabled vehicle.

The bi-directional configuration consists of two exterior units of TX54 PC I-girder units with attached slabs, four additional TX54's and three slab sections. The out-to-out width is 40'-10" and the guideway width is 38'-6". This width allows for two ATS lanes and a center lane for passing or crossover. There are also two 4'-0" wide emergency egress walkways.

The superstructures may be modified with full thickness precast overhangs, based on the concept shown in TxDOT Standard PCP(0), Precast Concrete Panels for Overhangs, but must be designed specifically for this project. The single direction superstructure would then consist of two precast overhangs, two precast slab sections and three TX54's. The bi-directional structure would consist of two precast overhangs, five precast slab sections and six TX54's. The precast slab section lengths are one third the span length and can be stockpiled if desired. Figures G-1 through G-6 show the basic slab/girder concept.

The TX54 I-girder was selected for this project because it can be used for span lengths from 40' through 120'. See Appendix F, Section 3 for TxDOT cost data.

Substructure

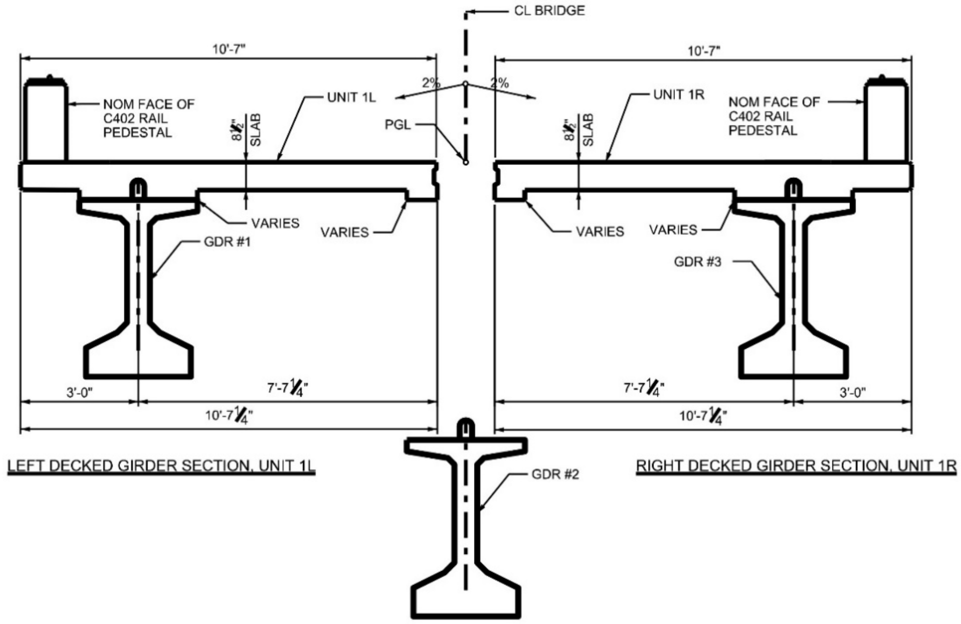
The substructures consist of a column design for both the single and bi-directional structures and hammerhead caps for both single direction and bi-directional structures.

Bent Caps

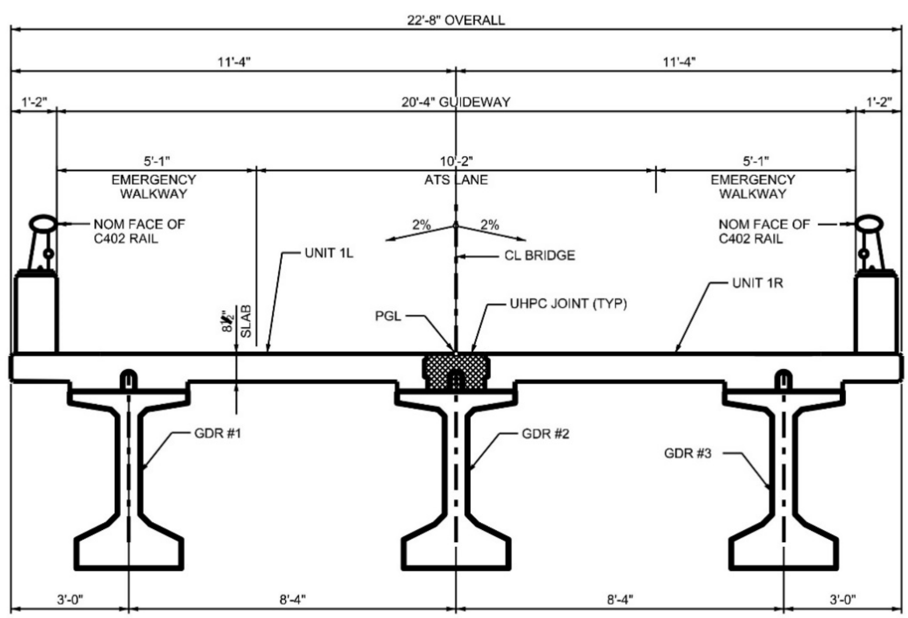
The precast single direction bent cap is 20'-8" long by 3'-6" deep tapering to 5'-6" deep at the column by 4'-6" wide and the bi-directional precast bent cap is 38'-10" long by 3'-6" deep tapering to 7'-0" deep at the column by 4'-6" wide. Both bent cap types can be precast and stockpiled if desired.

Columns

The column segments are 6'-0" by 4'-0" rectangular sections and can be cast full height in 5' increments. For example, 10-0", 15'-0", 20'-0" column segments may be precast and stockpiled if desired. For a 15'-0" section used at a location requiring an 11'-6" column height, 3'-6" of the column can be buried below the ground line. The column increments need to be coordinated with the foundation designer to ensure the top of foundation is constructed at the appropriate elevation.

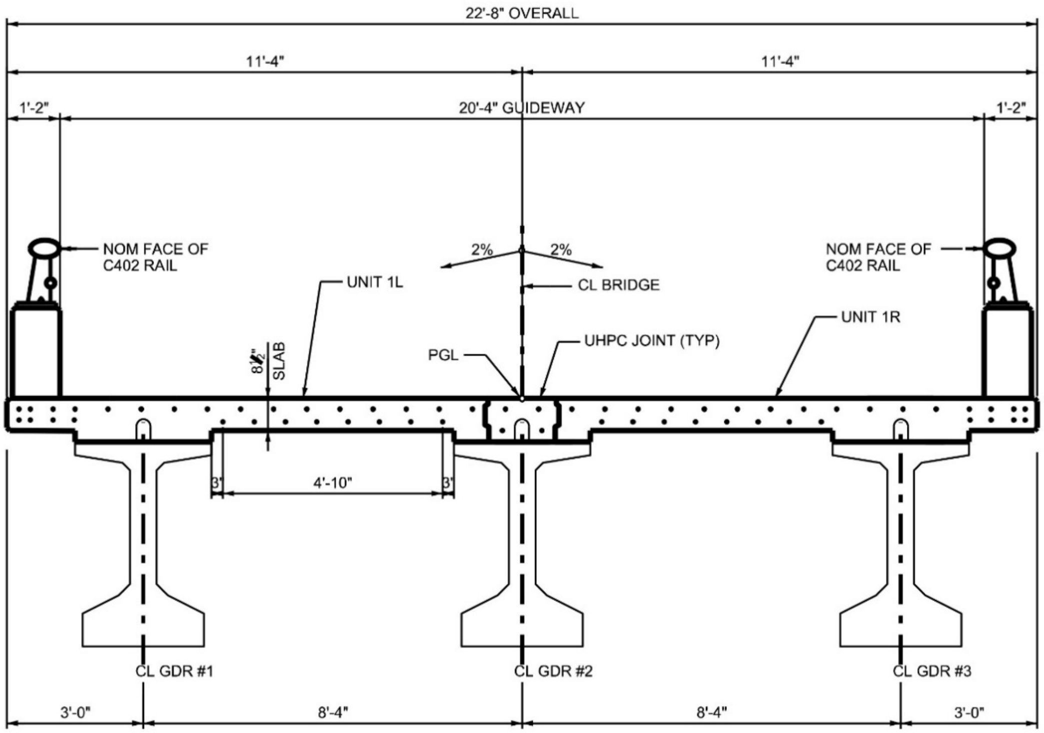


TYPICAL SECTION WITH PRECAST CONNECTION

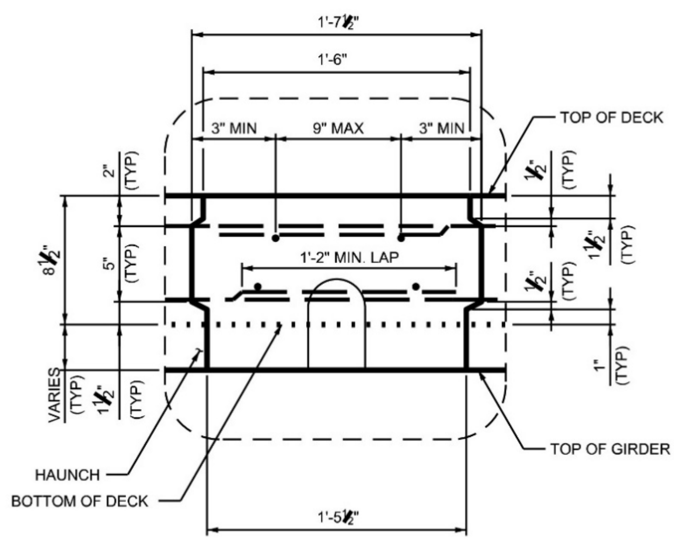


TYPICAL SECTION WITH PRECAST CONNECTION

Figure G-1 – Single Direction Configuration



TYPICAL SECTION WITH PRECAST CONNECTION



UHPC CONNECTION DETAIL

Figure G-2 – Single Direction Slab Design

SLAB CONSTRUCTION SEQUENCE:

1. CONSTRUCT I-GIRDERS AND PRECAST SECTIONS. EXTERIOR DECK SECTIONS SHALL BE PRECAST WITH C402 PEDESTAL.

2. HAUNCHES MAY BE CALCULATED AND CAST INTO THE DECK PANEL SECTIONS OR PANELS MAY BE CAST FLAT AND LEVELED WITH WELDED ANGLES OR LEVELING BOLTS.

3. PLACE DECKED GIRDER SECTIONS AND SLAB SECTIONS WITH EDGE SEALING STRIPS AND POUR UHPC CLOSURES.

4. DIAMOND GRIND DECK TO REMOVE DISCONTINUITIES. ATTACH C402 RAIL STEEL SECTIONS.

5. CONTRACTOR SHALL SUBMIT ACCELERATED BRIDGE CONSTRUCTION (ABC) ASSEMBLY PLAN FOR APPROVAL PRIOR TO COMMENCING WORK. AT A MINIMUM, ASSEMBLY PLAN SHALL INCLUDE METHOD FOR CREATING, LIFTING AND TRANSPORTING PRECAST UNITS AND ASSEMBLY OF THE STRUCTURE INCLUDING ERECTION AND BRACING REQUIREMENTS. LIFTING, BRACING AND ERECTION PLANS AND CALCULATIONS SHALL BE SEALED AND SIGNED BY A LICENSED TEXAS PROFESSIONAL ENGINEER."

6. CONTRACTOR SHALL ACCOUNT FOR VERTICAL ALIGNMENT WHEN CASTING SUPERSTRUCTURE UNITS.

Figure G-3 –Sheet Notes

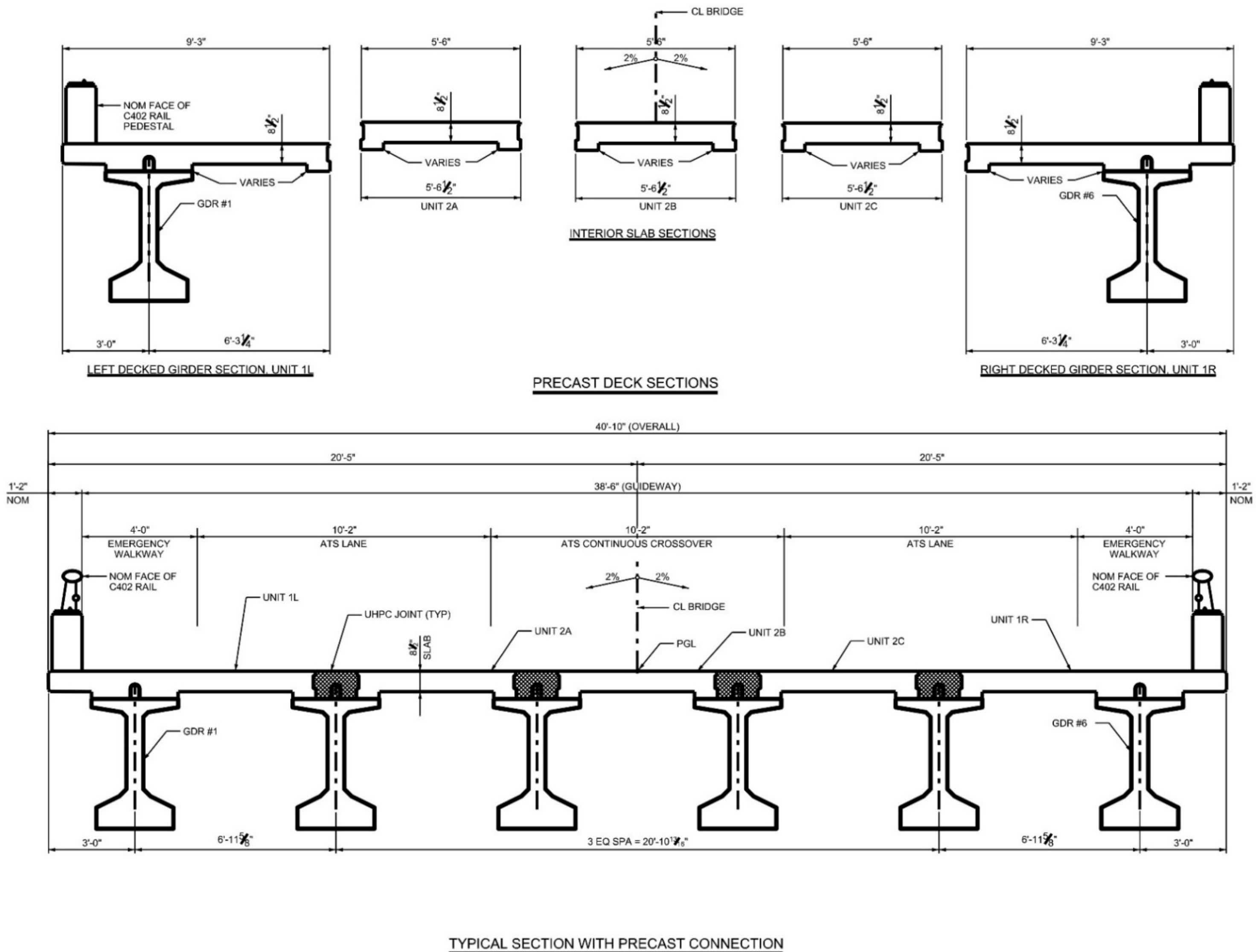
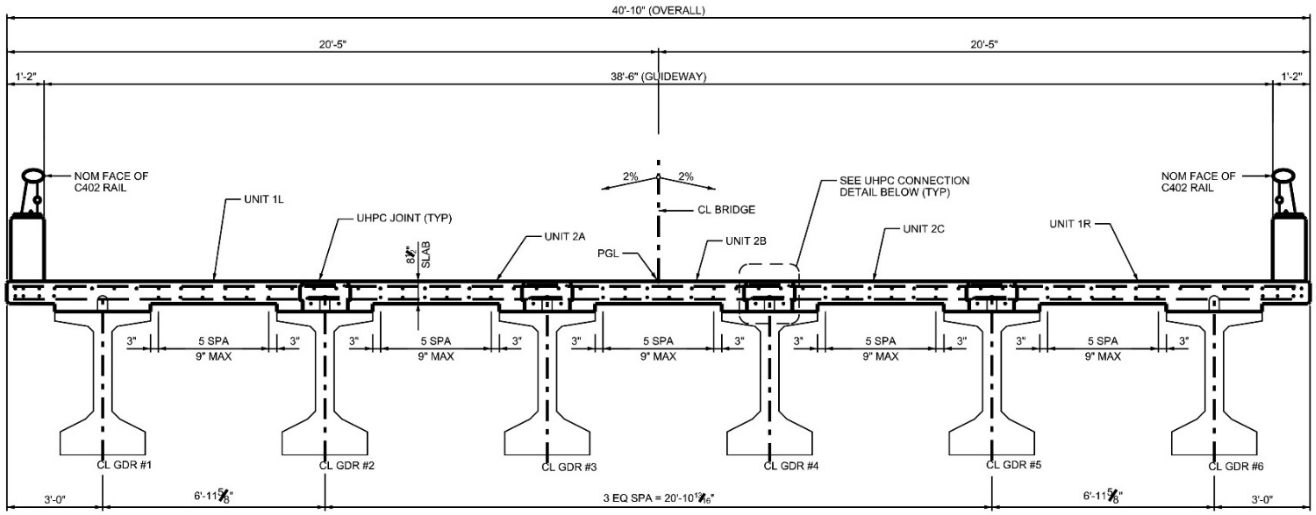


Figure G-4 – Bi-Directional Superstructure Configuration



TYPICAL SECTION WITH PRECAST CONNECTION

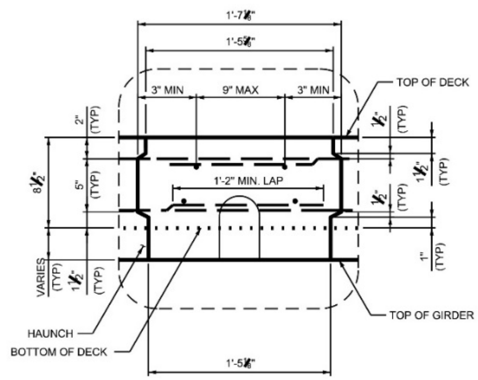


Figure G-5 – Bi-Directional Slab Design

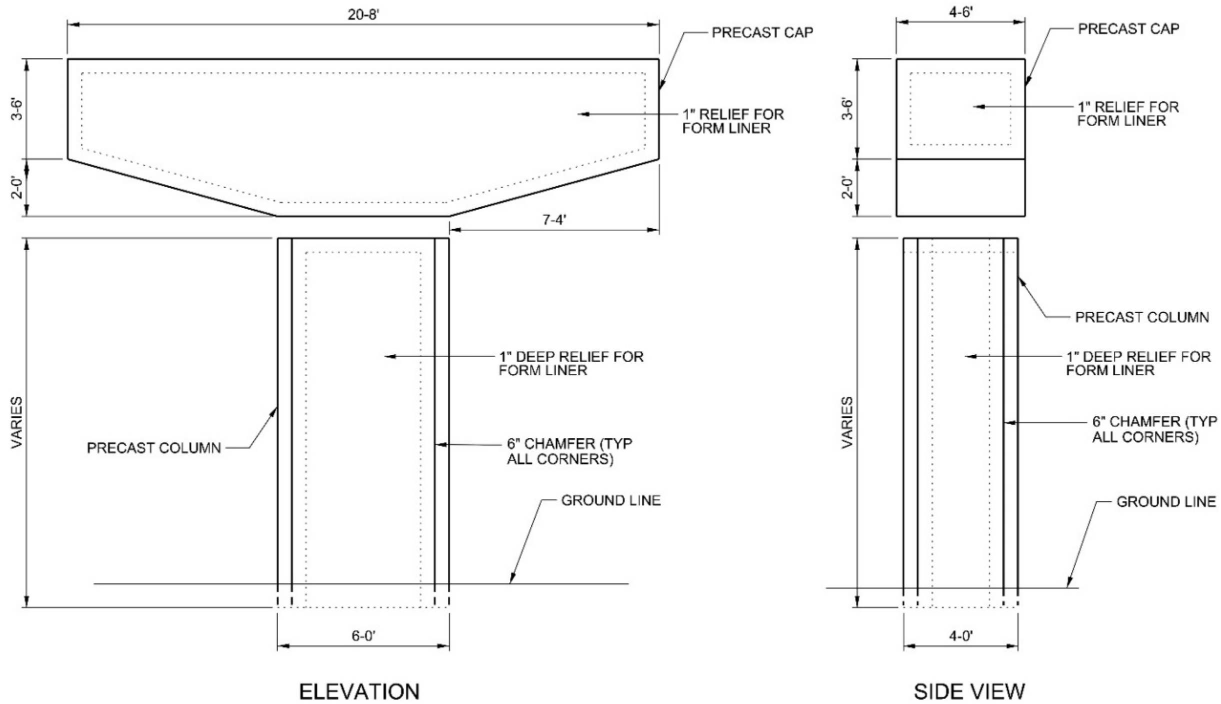


Figure G-6 – Single Direction Substructure Geometry

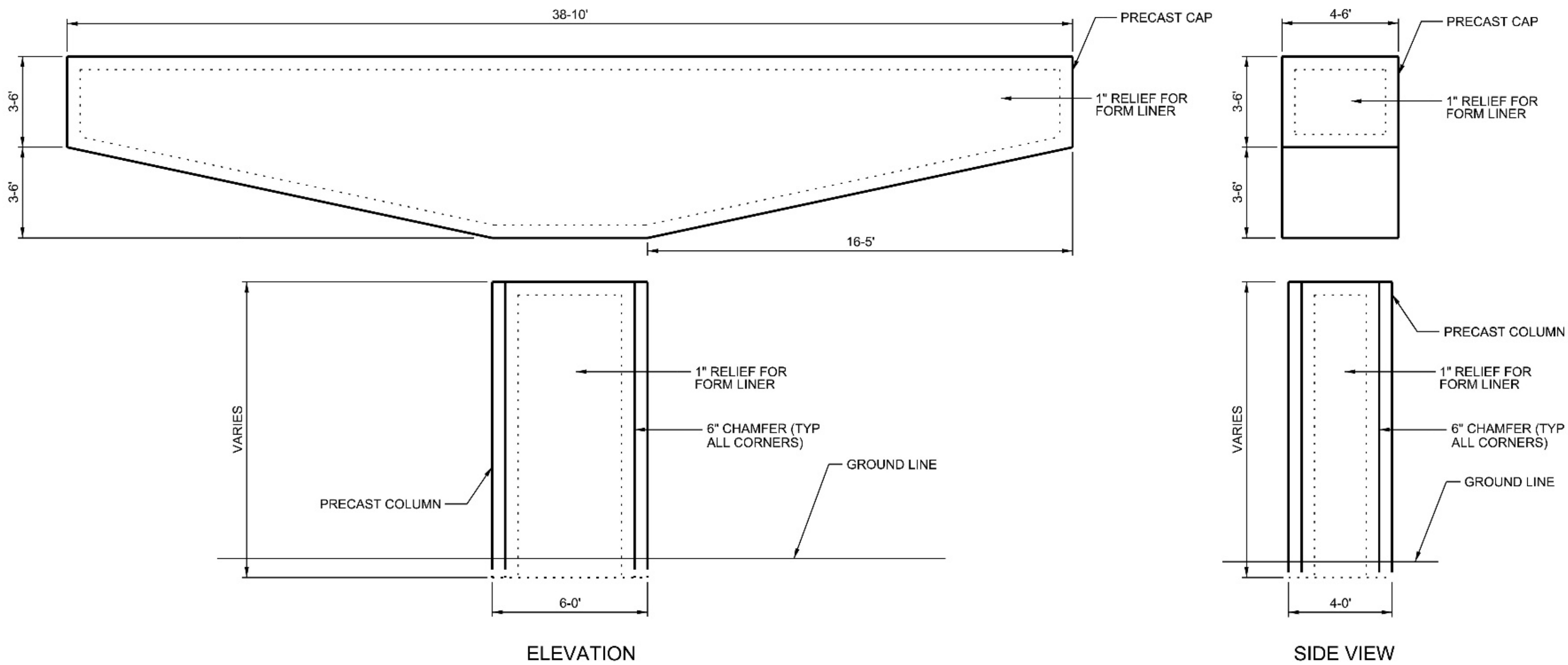
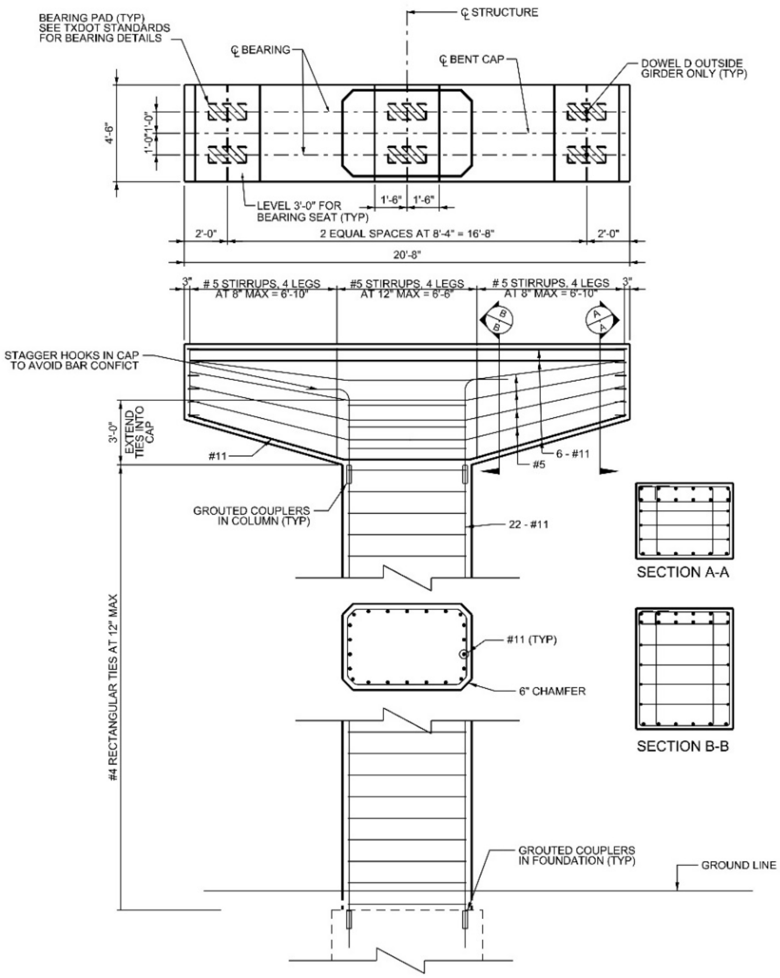


Figure G-7 –Bi-Directional Substructure Geometry



SUBSTRUCTURE NOTES:

1. DRAWINGS ARE NOT COMPLETE AND ARE BASED ONLY ON PRELIMINARY DESIGN. PROVIDE BAR DETAILS IN FINAL DESIGN.

2. DESIGN IS BASED ON MAXIMUM 120-0" SPAN LENGTH AND MAXIMUM COLUMN HEIGHT OF 25'-0".

3. DESIGN AND CONSTRUCT FOUNDATION AND COORDINATE CONNECTION TYPE FOR PRECAST COLUMNS.

4. PRELIMINARY DESIGN WAS PERFORMED WITH CLASS C, 3.6 KSI CONCRETE. ALL LOADS ARE BASED ON NORMAL WEIGHT CONCRETE. FINAL DESIGN WITH LIGHTWEIGHT CONCRETE MAY REDUCE THE REINFORCEMENT REQUIREMENTS.

5. THERE ARE MULTIPLE METHODS OF CONNECTING PRECAST COLUMNS TO FOUNDATIONS AND PRECAST CAPS TO PRECAST COLUMNS. GROUTED COUPLERS TO SPLICE THE REINFORCEMENT IS SHOWN HERE. REFERENCE TO OTHER METHODS ARE SHOWN IN THIS APPENDIX AND CAN BE FOUND IN PUBLICATION NO. FHWA-IF-09-010, CONNECTION DETAILS FOR PREFAB -RICATED BRIDGE ELEMENTS AND SYSTEMS.

6. SET PRECAST COLUMN ON FOUNDATION IN ACCORDANCE WITH REQUIREMENTS FOR CONNECTIONS. SHIM AS REQUIRED TO ENSURE COLUMN IS LEVEL.

7. SET PRECAST CAP ON COLUMN IN ACCORDANCE WITH REQUIREMENTS FOR CONNECTIONS. SHIM AS REQUIRED TO ENSURE CAP IS LEVEL.

8. CONTRACTOR SHALL SUBMIT ACCELERATED BRIDGE CONSTRUCTIO (ABC) ASSEMBLY PLAN FOR APPROVAL PRIOR TO COMMENCING WOI AT A MINIMUM, ASSEMBLY PLAN SHALL INCLUDE METHOD FOR CREATING, LIFTING AND TRANSPORTING PRECAST UNITS AND ASSEMBLY OF THE STRUCTURE INCLUDING ERECTION AND BRACINC REQUIREMENTS. LIFTING, BRACING AND ERECTION PLANS AND CALCULATIONS SHALL BE SEALED AND SIGNED BY A LICENSED TEXAS PROFESSIONAL ENGINEER."

9. CONTRACTOR SHALL ACCOUNT FOR SUPERELEVATION AND BEARING SEAT ELEVATION REQUIREMENTS WHEN CASTING PRECAST CAP UNITS.

10. UNLESS NOTED OTHERWISE, CHAMFER ALL CORNERS 3/4".

PRELIMINARY DESIGN

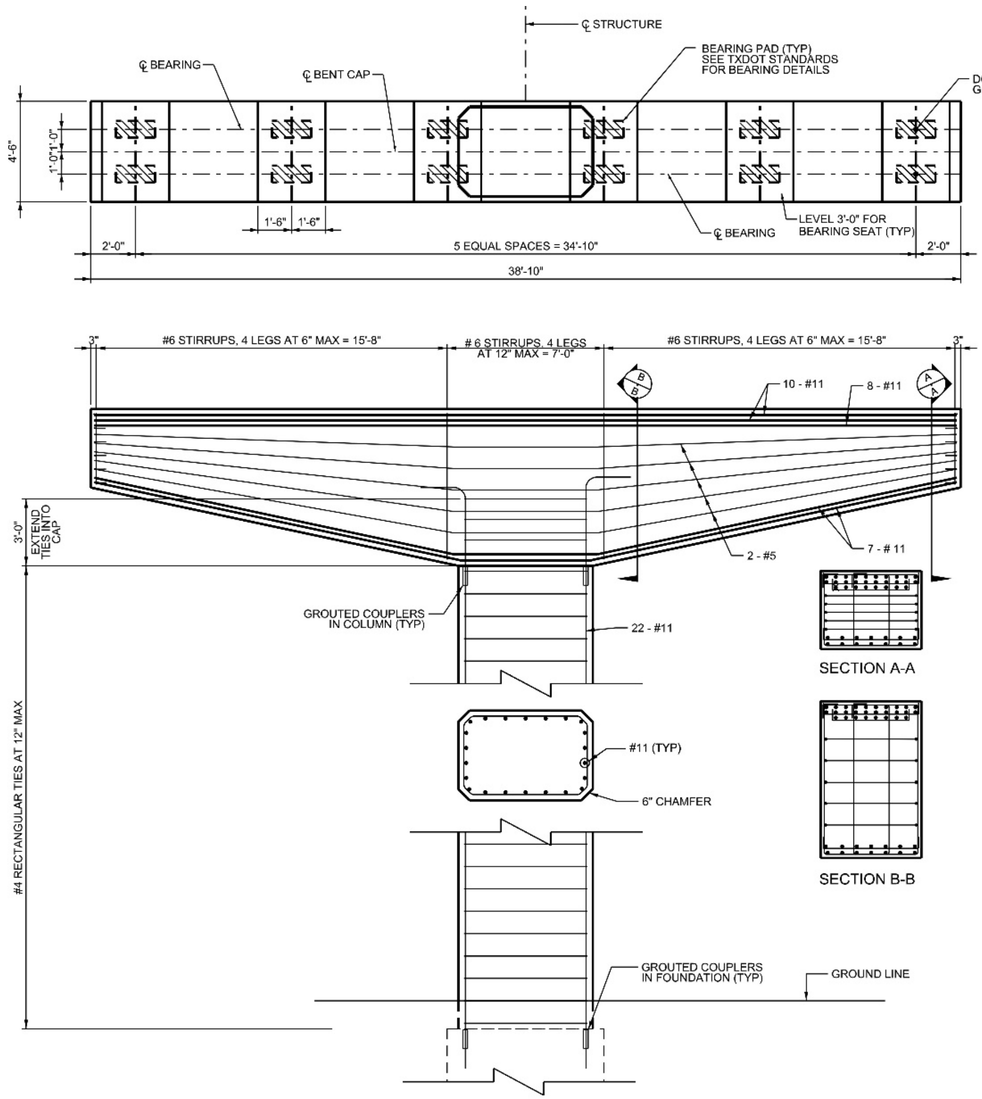
HAMMERHEAD CAP	
CAP WIDTH	4'-6"
CAP DEPTH	3'-6"/5'-6"
CAP LENGTH	20'-8"
CONCRETE TYPE	CLASS C
CONCRETE STRENGTH	3.6 KSI

REINFORCEMENT	BAR SIZE	# BARS
TOP BARS	#11	28
BOTTOM BARS	#11	6
STIRRUPS	#6	4 LEGS AT 6" SPACING

COLUMN	
COLUMN WIDTH	6'-0"
COLUMN DEPTH	4'-0"
COLUMN HEIGHT	VARIES
CONCRETE TYPE	CLASS C
CONCRETE STRENGTH	3.6 KSI

REINFORCEMENT	BAR SIZE	# BARS
VERTICAL	#11	22
TIES	#4	12" SPACING

Figure G-8 – Single Direction Preliminary Design



SUBSTRUCTURE NOTES:

1. DRAWINGS ARE NOT COMPLETE AND ARE BASED ONLY ON PRELIMINARY DESIGN. PROVIDE BAR DETAILS IN FINAL DESIGN.

2. DESIGN IS BASED ON MAXIMUM 120-0" SPAN LENGTH AND MAXIMUM COLUMN HEIGHT OF 25'-0".

3. DESIGN AND CONSTRUCT FOUNDATION AND COORDINATE CONNECTION TYPE FOR PRECAST COLUMNS.

4. PRELIMINARY DESIGN WAS PERFORMED WITH CLASS C, 3.6 KSI CONCRETE. ALL LOADS ARE BASED ON NORMAL WEIGHT CONCRETE. FINAL DESIGN WITH LIGHTWEIGHT CONCRETE MAY REDUCE THE REINFORCEMENT REQUIREMENTS.

5. THERE ARE MULTIPLE METHODS OF CONNECTING PRECAST COLUMNS TO FOUNDATIONS AND PRECAST CAPS TO PRECAST COLUMNS. GROUTED COUPLERS TO SPLICE THE REINFORCEMENT IS SHOWN HERE. REFERENCE TO OTHER METHODS ARE SHOWN IN THIS APPENDIX AND CAN BE FOUND IN PUBLICATION NO. FHWA-IF-09-010, CONNECTION DETAILS FOR PREFAB -RICATED BRIDGE ELEMENTS AND SYSTEMS.

6. SET PRECAST COLUMN ON FOUNDATION IN ACCORDANCE WITH REQUIREMENTS FOR CONNECTIONS. SHIM AS REQUIRED TO ENSURE COLUMN IS LEVEL.

7. SET PRECAST CAP ON COLUMN IN ACCORDANCE WITH REQUIREMENTS FOR CONNECTIONS. SHIM AS REQUIRED TO ENSURE CAP IS LEVEL.

8. CONTRACTOR SHALL SUBMIT ACCELERATED BRIDGE CONSTRUCTION (ABC) ASSEMBLY PLAN FOR APPROVAL PRIOR TO COMMENCING WORK. AT A MINIMUM, ASSEMBLY PLAN SHALL INCLUDE METHOD FOR CREATING, LIFTING AND TRANSPORTING PRECAST UNITS AND ASSEMBLY OF THE STRUCTURE INCLUDING ERECTION AND BRACING REQUIREMENTS. LIFTING, BRACING AND ERECTION PLANS AND CALCULATIONS SHALL BE SEALED AND SIGNED BY A LICENSED TEXAS PROFESSIONAL ENGINEER."

9. CONTRACTOR SHALL ACCOUNT FOR SUPERELEVATION AND BEARING SEAT ELEVATION REQUIREMENTS WHEN CASTING PRECAST CAP UNITS.

10. UNLESS NOTED OTHERWISE, CHAMFER ALL CORNERS 3/4".

PRELIMINARY DESIGN

HAMMERHEAD CAP	
CAP WIDTH	4'-6"
CAP DEPTH	3'-6"/7'-0"
CAP LENGTH	38'-10"
CONCRETE TYPE	CLASS C
CONCRETE STRENGTH	3.6 KSI

REINFORCEMENT	BAR SIZE	# BARS
TOP BARS	#11	28
BOTTOM BARS	#11	14
STIRRUPS	#6	4 LEGS AT 6" SPACING

COLUMN	
COLUMN WIDTH	6'-0"
COLUMN DEPTH	4'-0"
COLUMN HEIGHT	VARIES
CONCRETE TYPE	CLASS C
CONCRETE STRENGTH	3.6 KSI

REINFORCEMENT	BAR SIZE	# BARS
VERTICAL	#11	22
TIES	#4	12" SPACING

Figure G-9 – Bi-Directional Preliminary Design

PHOTOS OF PRECAST UNIT INSTALLATION

Figure G-10 - Transverse Slab Units with Attached Bridge Railing

Figure G-11 - Installation of Precast Bridge Cap

APPENDIX H

GIRDER DESIGN TABLES

Note: Engineering review and final design under a Professional Engineer's (PE) seal must be completed for final structure. The following guidelines are provided for support and not to replace/take the place of sealed engineering design.

GIRDER DESIGN TABLES

Table H-1 – SINGLE DIRECTION TX54 GIRDER DESIGN

Designed TX54 Girders, Single Direction Configuration, 8.5" Slab										
Span Length	Girder No.	Prestressing Strands					Depressed Strand Pattern		Concrete	
		Total No.	Size (in)	Strength fpu (ksi)	"e" CL (in)	"e" End (in)	No.	To End (in)	Release f'ci (ksi)	28 Day f'c (ksi)
40	All	8	0.6	270	21.01	21.01			4.000	5.000
45	All	10	0.6	270	21.01	21.01			4.000	5.000
50	All	12	0.6	270	21.01	21.01			4.000	5.000
55	All	12	0.6	270	21.01	21.01			4.000	5.000
60	All	12	0.6	270	21.01	21.01			4.000	5.000
65	All	14	0.6	270	21.01	21.01			4.000	5.000
70	All	14	0.6	270	21.01	21.01			4.000	5.000
75	All	16	0.6	270	20.76	20.26	4	6.5	4.000	5.000
80	All	16	0.6	270	20.76	20.76			4.000	5.000
85	All	18	0.6	270	20.56	19.67	4	8.5	4.000	5.000
90	All	20	0.6	270	20.41	19.21	4	10.5	4.000	5.000
95	All	22	0.6	270	20.28	18.46	4	14.5	4.000	5.000
100	All	26	0.6	270	20.08	16.39	4	28.5	4.000	5.000
105	All	30	0.6	270	19.81	12.21	6	44.5	4.000	5.000
110	All	32	0.6	270	19.63	11.38	6	50.5	4.100	5.000
115	All	36	0.6	270	19.34	12.01	6	50.5	4.700	5.500
120	All	38	0.6	270	19.22	13.22	6	44.5	5.200	6.100
125	All	42	0.6	270	19.01	12.72	6	50.5	5.600	6.600

Table H-2 – BI-DIRECTIONAL TX54 GIRDER DESIGN

Designed TX54 Girders, Bi-Directional Configuration, 8.5" Slab										
Span Length	Girder No.	Prestressing Strands					Depressed Strand Pattern		Concrete	
		Total No.	Size (in)	Strength fpu (ksi)	"e" CL (in)	"e" End (in)	No.	To End (in)	Release f'ci (ksi)	28 Day f'c (ksi)
40	All	10	0.6	270	21.01	21.01			4.000	5.000
45	All	12	0.6	270	21.01	21.01			4.000	5.000
50	All	14	0.6	270	21.01	21.01			4.000	5.000
55	All	14	0.6	270	21.01	21.01			4.000	5.000
60	All	16	0.6	270	20.76	20.26	4	6.5	4.000	5.000
65	All	16	0.6	270	20.76	20.26	4	6.5	4.000	5.000
70	All	18	0.6	270	20.56	19.23	4	10.5	4.000	5.000
75	All	18	0.6	270	20.56	19.67	4	8.5	4.000	5.000
80	All	20	0.6	270	20.41	18.81	4	12.5	4.000	5.000
85	All	20	0.6	270	20.41	18.81	4	12.5	4.000	5.000
90	All	24	0.6	270	20.17	17.84	4	18.5	4.000	5.000
95	All	28	0.6	270	20.01	14.29	4	44.5	4.000	5.000
100	All	32	0.6	270	19.63	11.38	6	50.5	4.100	5.000
105	All	34	0.6	270	19.48	13.48	6	40.5	4.700	5.400
110	All	38	0.6	270	19.22	12.27	6	50.5	5.000	5.700
115	All	42	0.6	270	19.01	12.72	6	50.5	5.600	6.400
120	All	46	0.6	270	18.66	11.36	8	50.5	5.800	6.800

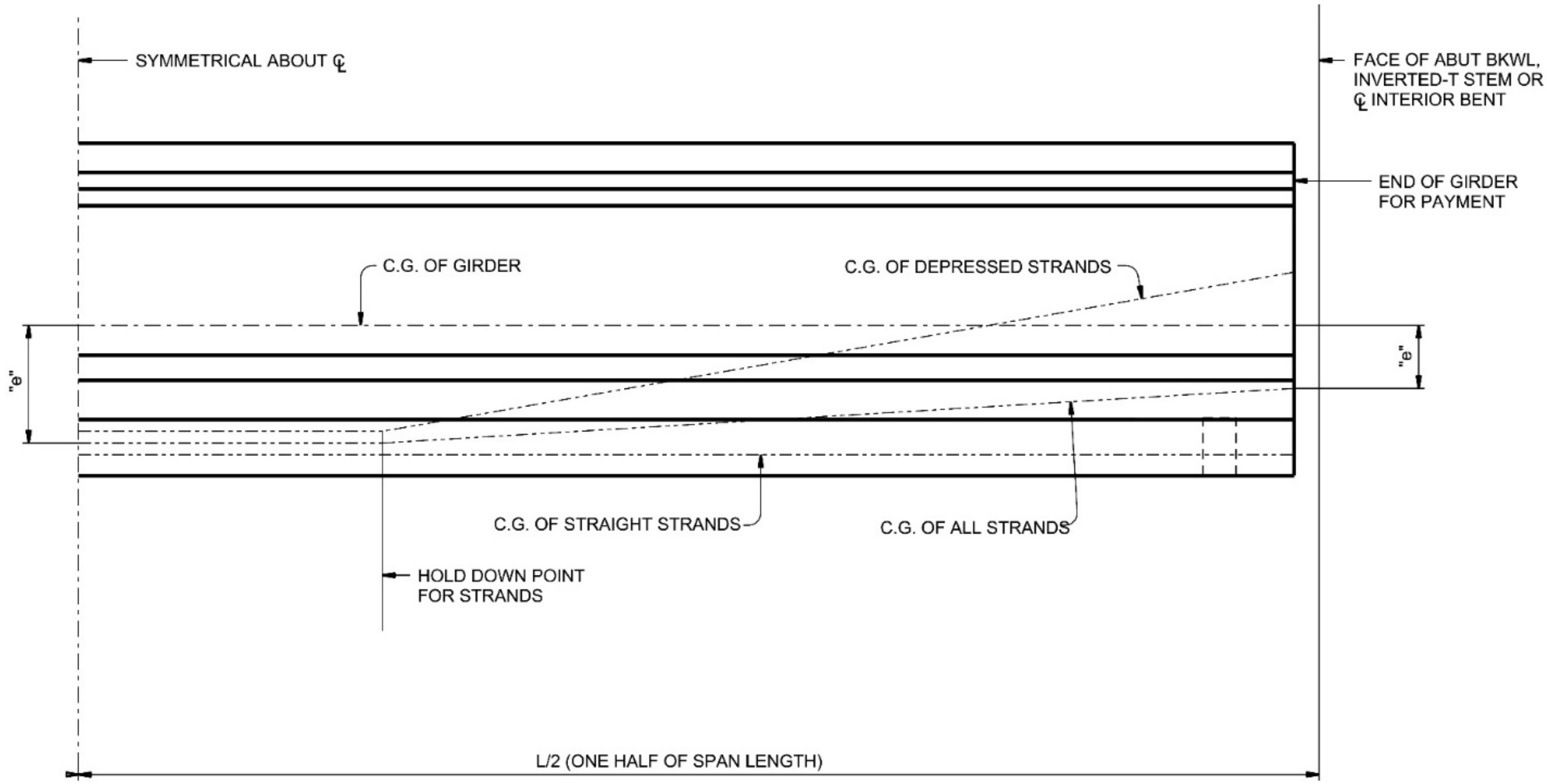


Figure H-1 – STRAND DIAGRAM

APPENDIX I

GM MANUFACTURING PLANT PROPOSED ROUTE AND FLEET ANALYSIS

To support study development and ensure the vehicles inventoried provided a range of potential solutions in a goods movement environment, three operational configurations reviewing various AV technologies were developed for a high-level analysis of the GM Manufacturing Plant.

The ATS requirements include being able to handle palletized freight and unitized freight and to be able to provide additional capacity to accommodate production increases in the future, if necessary.

Three operational considerations and fleet analyses were developed as follows:

Operational Configuration One

Technology A was considered for Operational Configuration One. The use of this technology would mimic the current trucking operation by being able to pick up the freight right at the entrance of the facility and transport it along the newly constructed bridge directly to the rail facility without having to use any additional labor or technology.

Operational Configuration Two

Technologies B, C, and D were considered for Operational Configuration Two. Technologies B and C were grouped in the analysis since they can carry similar freight weight and dimensions. In Operational Configuration Two, the cargo would have to be moved by other means from the originating facility to a designated point in the manufacturing facility, and the vehicles would need a larger space to turn around than the vehicles used for Operational Configuration One. This option delivers the cargo to approximately the same area as Operational Configuration One.

Operational Configuration Three

Technologies B, C, and D were also considered for Operational Configuration Three. Operational Configuration Three is a shorter route for the autonomous technologies between origin and destination; it is assumed that the cargo will be moved by other means to a designated point in the manufacturing facility and again after it is transported to a designated point at the railhead. This option delivers the cargo to a different staging area at the railhead. While this option may not be realistic given operations and staging requirements at the railhead, the comparison of Operational Configuration Three with Operation Configuration Two illustrates the impact of delivery distance on fleet requirements for various technologies.

APPENDIX J

LAS COLINAS POTENTIAL RETROFIT GENERAL INFORMATION

1. GENERAL INFORMATION FOR POTENTIAL SYSTEM RETROFIT

The existing Area Personal Transit (APT) System at Las Colinas in Irving, Texas was constructed for a system of fully automated, mechanically guided vehicles. The retrofit identifies issues that will create limitations for a new autonomous vehicle system which does not need physical guides.

The existing guideway system was not designed for unguided wheeled vehicle impact or for personal safety in the event of emergency passenger egress from transit vehicles and does not meet highway standards. It includes upturned concrete edge beams that rise 1'-10" above the guideway deck. To retrofit for the new system, the deck elevation would need to be raised to the level of the existing edge beams and center median section, with new guardrails attaching to the top of the existing edge beams and extending to meet the required height for vehicles. The narrow guideway limits the angles of impact for the future ATS vehicles and may allow for a reduction in requirements, but since there is no crash test data, a reduction cannot be assumed. Manual for Assessing Safety Hardware (MASH) criteria must be met.

The lightest weight guardrail in consideration for this Las Colinas retrofit is a 2'-10" high rail, Type T631LS, which meets MASH requirements and is adequate for speeds up to 44 mph, but not adequate for pedestrian comfort and safety, so the rail must be modified to provide additional height. In addition, the rail has openings which do not meet pedestrian criteria. The easiest and safest guardrail improvement is to add 3'-6" high sections of chain link fencing, or similar, to protect the pedestrians from a fall hazard. Although not an attractive solution, the addition of architectural panels will hide the safety features. The rail mounting details may need to be very specific to avoid the locations of the draped prestressing strands within the post-tensioned edge beams.

There are many details to be considered to retrofit the guideway for a completely new system, and the post-tensioned edge and center beams create some design challenges because they cannot be readily modified.

The new guardrail section will need to be mounted to the existing edge beams and the post tensioning strands in the beam are draped and parabolic. Whether the base plate of the new rails section is mounted with standard base plates and vertical fasteners or with a steel saddle and side fasteners, extra precautions will be required to avoid damaging existing reinforcing steel and post-tensioning strands shown schematically in Figure 1-1.

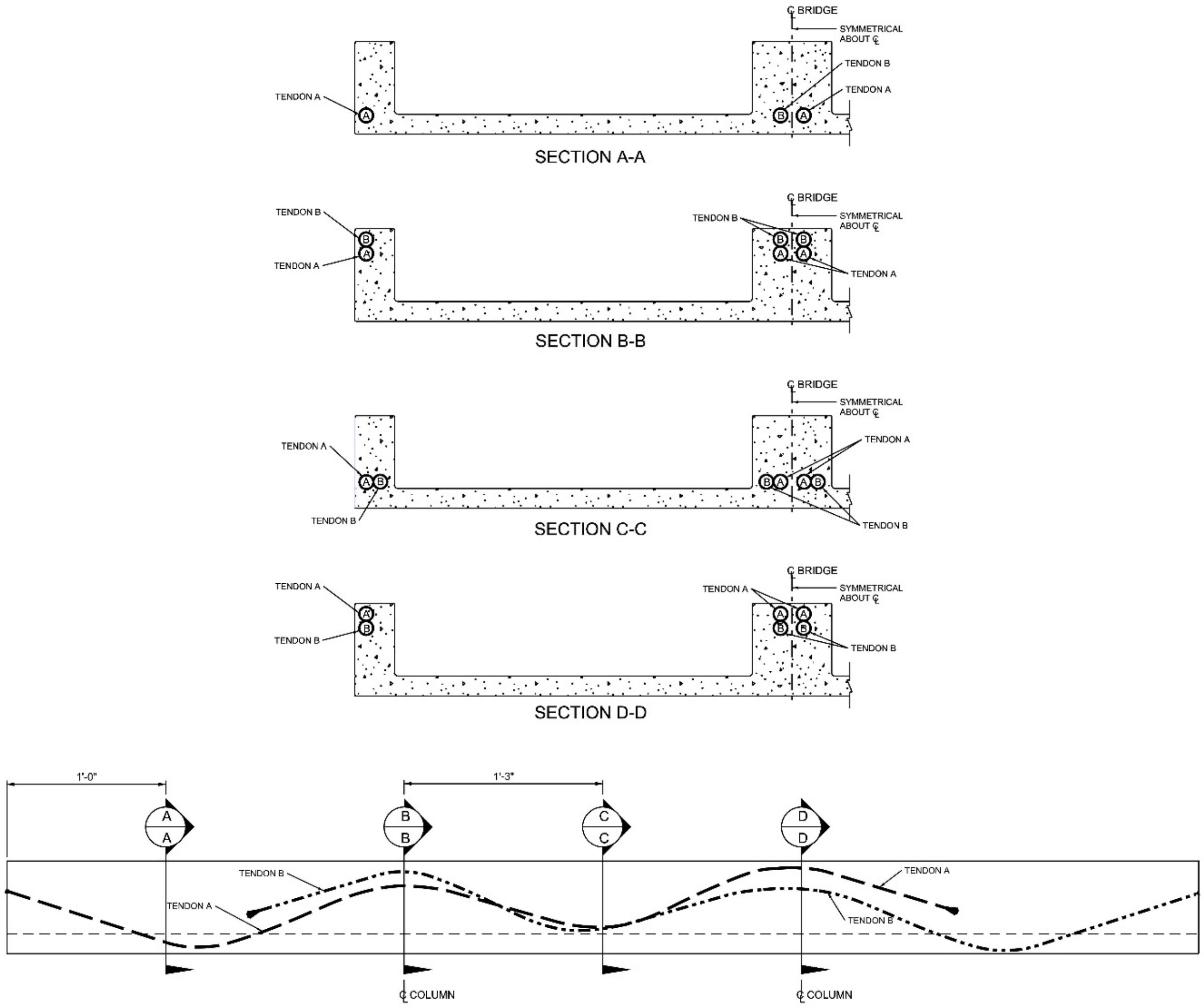


Figure 1-1 – Location of Post-Tensioning Strands in Edge Beam

Some AV technology suppliers recommend a physical barrier between lanes on which vehicles travel in opposite directions and there is currently no industry standard that provides definitive guidance. If required by the selected AV supplier, a barrier should be provided to satisfy their recommended safety requirements. Depending on the operational requirements, gaps in such barriers may be necessary to allow a vehicle to pass a stalled vehicle or otherwise provide for continued operations during vehicle failure conditions. Specific configurations should be coordinated during detailed design considering such operational and failure management requirements.

There is equipment mounted on the existing deck system and anything that will interfere with the placement of the new deck panels and must be removed. In addition, there are areas of the guideway that are not configured as shown in this report. The scope of this project did not include the full design of a retrofit, so there are many areas that will require unique designs. Figure 1-2, where there is a siding, shows one example of a condition that is not fully compatible with the current concept and will require special design. Other examples include areas where previous retrofits increased the height of the upturned edge and center beams, areas where trackwork exists on only one of the two guideway lanes, and areas where crossovers and turnouts exist. Further, each AV technology has unique requirements, such as the means of control and "tracking" along the centerline of the lane and power collection that will have to be considered as part of a technology-specified detailed design process.

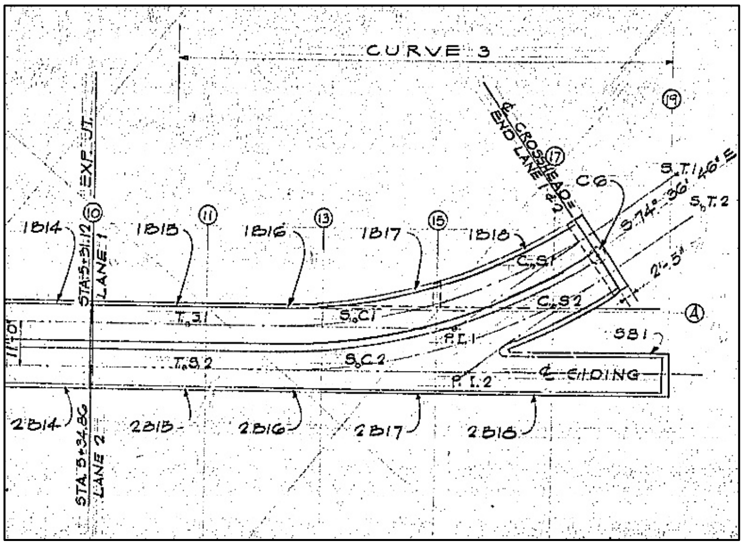


Figure 1-2 – Guideway at Siding

2. CONSIDERATION FOR FUTURE SYSTEM OPERATIONS

The system retrofit must also ensure that vehicles are able to turn around if they are not bidirectional. Because of the size of the proposed vehicles, it may be possible for vehicles to make K-turns to reverse direction. However, the existing guideway network is narrow and may not provide the necessary space required for vehicles to make K-turns without reconstructing whole sections, but there are some alternatives. Turntables, similar to what has been used in railroad depots, have become more common and may fit the needs of this project. Turntable installation would require some system redesign to accommodate the mechanics. The viability of this option and the guideway modifications required to accommodate it should be evaluated considering the selected AV technology during detailed design of the retrofit. See Figures 2-1 and 2-2 for an example of a turntable system from Mutrade Industrial Corporation.

Figure 2-1 – Round Table Base

Figure 2-2 – Round Table with Vehicle

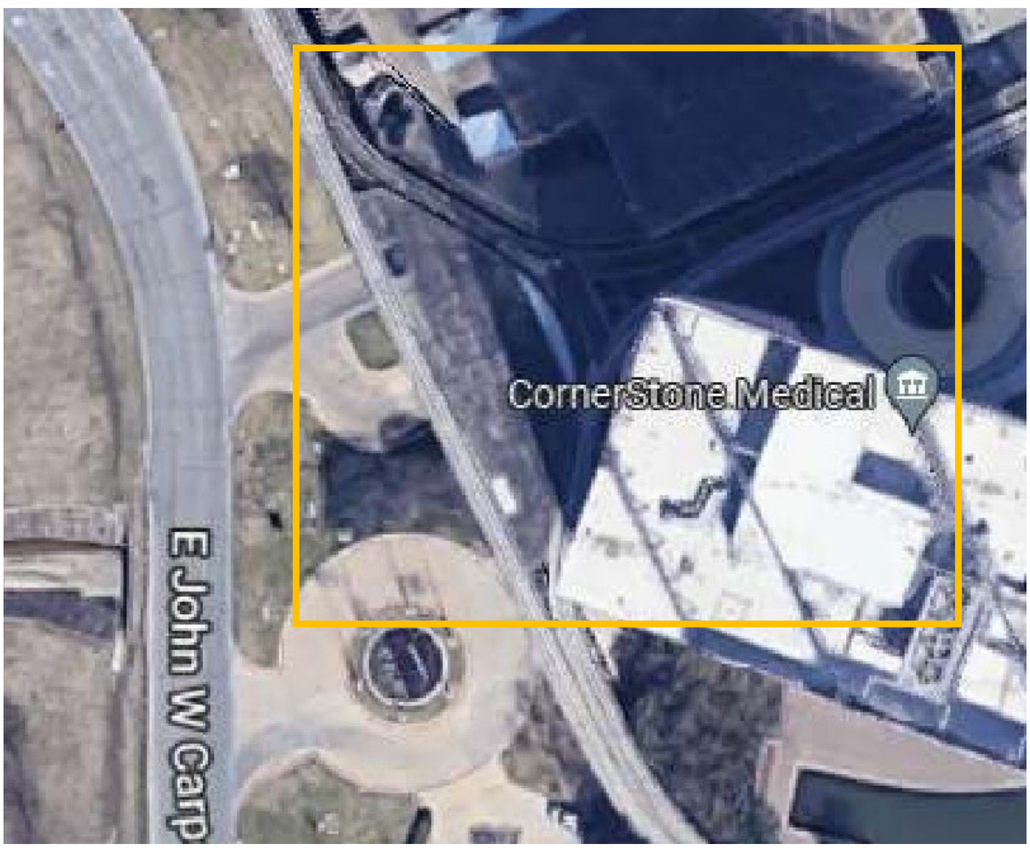


Figure 2-3 – Existing CALTEX Section

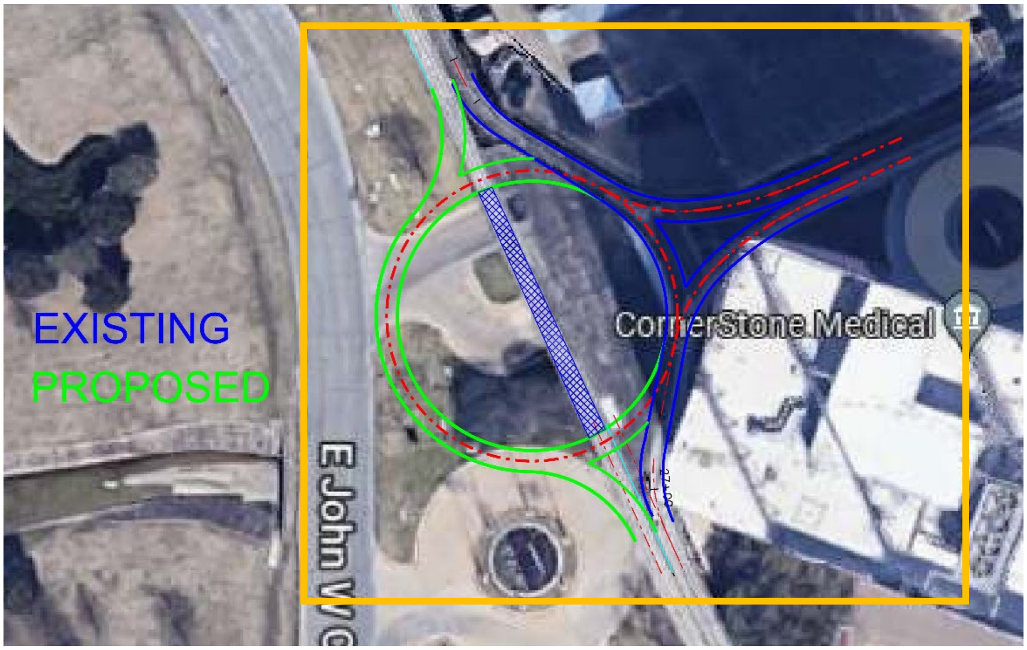


Figure 2-4 – Potential Retrofit Roundabout

At the CALTEX segment, located near CornerStone Medical between Las Colinas Boulevard and the northbound Carpenter Freeway Frontage Road, there is a Y-shaped guideway segment as shown in Figure 2-3. This configuration allows northbound vehicles to either turn out to the eastbound guideway lane and travel toward the DART station or continue to travel in the northbound direction. Westbound vehicles traveling from the DART station must travel toward the north through this area. Southbound vehicles can only continue southbound through this area and are not able to access the east-west guideway lanes that provide service to the DART station. The area was constructed to accommodate a future, three-berth passenger station between the northbound and southbound lanes. The existing platform floor elevation was constructed to match original APT system vehicle floor level, about 3’-8” above the existing guideway deck and about 1’-10” above the top of the upturned guideway girders located along guideway edges and between lanes of dual-lane guideway sections.

This area can be reconfigured into a roundabout as illustrated schematically in Figure 2-4. A roundabout at this location would allow vehicles entering the area from any direction to depart in any direction (including U-turn movements) – significantly increasing the versatility of the guideway network for single direction vehicles. To convert this area to a roundabout will require significant modifications to the existing guideway and station platform structures at this location. Figure 2-4 shows existing guideway sections in blue and the potential retrofit sections in green. The hatched center tangent guideway section could be either removed or closed off to traffic to maintain efficient roundabout flows. The configuration shown in Figure 2-4 is based on 75 ft curve radii to match existing curves in this area and would require demolition of parts or all of the existing platform structure since it is located above the potential retrofit guideway deck elevation. Depending on the selected AV technology’s minimum turn radius, it may be possible to elongate the roundabout in the north-south direction (so it is oval instead of circular) to minimize impacts to the existing platform/guideway structure in this area selected, but this geometry is not recommended. The platform and guideways in this area are complex, integrated structures supported on common column/bents and footings, see Figure 2-5.

Figure 2-5 – Existing Area Under Potential Retrofit Roundabout

The existing guideway system does not have superelevation in horizontal curves and the retrofit concept does not envision providing superelevation, which, if provided, would allow higher vehicle design speeds through horizontal curves. Based on the Las Colinas Area Personal Transit System Planning and Design Manual, speeds through horizontal curves should limit lateral accelerations experienced by passengers to 0.05 g maximum. It is recommended that this criterion be used in detailed design. However, since AVs are typically lighter than the APT vehicles for which the APT System guideways were designed, it may be possible to operate at higher speeds through horizontal curves as long as the resulting centrifugal forces (CF) do not overstress existing guideway structures or create a chance for the vehicle to "skid out" through horizontal curves in all environmental conditions. These considerations should be carefully evaluated during detailed design considering the selected AV technology and related factors such as coefficient of friction between vehicle tires and the new deck surface and applicable ride comfort criteria.

Spiral transitions exist at the beginning and ends of all existing horizontal curves along the alignment to limit the rate of change of lateral acceleration ("jerk") to less than 0.06 g/second, as is required for guided transit technologies. EVs typically do not require these spiral transitions so future curves for new guideway sections may be designed as simple horizontal curves if compatible with the selected AV technology. Consideration should be given to including spiral transition curves in any new guideway sections to provide consistency and preserve the versatility of the existing APT guideway network.

The guideway at the stations will require special design. The elevation of the new deck will not match the existing elevation at the stations, and in some cases, the height of the vehicle may be limited by the elevation of the roof at the stations.

[1] It must be noted that as-built design drawings for the existing APT guideway show design speeds with some horizontal curve data that would result in lateral accelerations that exceed the 0.05 g ride comfort limit defined in the Las Colinas APT Planning and Design Manual.

APPENDIX K

TABLE OF REFERENCES

Note: If a figure in the report does not appear in this list, it is an original work as part of the report.

Page / Figure or Table	Image or Title	Source	Citation
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55 / Figure 6.1.2-2	Expanded View of Polymer Deck Panel	Orenco – InfraCore Bridge Technology	NA
55 / Figure 6.1.2-3	Polymer Panel for Potential Retrofit Deck	Orenco – InfraCore Bridge Technology	NA
57 / Figure 6.1.4-1	Typical Existing W-Beam Section	DCURD – The Las Colinas Area Personal Transit System Planning and Design Manual	
57 / Figure 6.1.4-2	Typical Existing U-Beam Section	DCURD – The Las Colinas Area Personal Transit System Planning and Design Manual	
59 / Figure 6.1.5-1	Single 250 kW Output Charging Pad and Equipment	WAVE	NA
60 / Figure 6.1.5-2	Dual 125 kW Output Charging Pads and Equipment	WAVE	NA
62 / Figure 6.2.1-1	Schematic Diagram of DFW Skylink APM Alignment	DFW Airport	NA
Appendix A			
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A-14 / Figure 1.2.6-2	Einride "Open" Cabin Configuration	Einride	https://www.einride.tech/
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A-18 / Figure 1.2.9-1	e.GO MOOVE People Mover	Global News Wire	GlobeNewswire.com (2019, December 19). *Cerence to Bring First-of-its-Kind Voice and Multi-Modal Interaction to Autonomous, Electric Vehicle at CES 2020*. GlobeNewswire.com website. https://www.globenewswire.com/en/news-release/2019/12/19/1962790/0/en/Cerence-to-Bring-First-of-its-Kind-Voice-and-Multi-Modal-Interaction-to-Autonomous-Electric-Vehicle-at-CES-2020.html
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A-19 / Figure 1.2.10-1	Continental CUbE	Continental Automotive	Continental-Automotive.com. Continental-Automotive.com website. https://www.continental-automotive.com/Passenger-Cars/Autonomous-Mobility/Functions/Driverless-Mobility
A-20 / Figure 1.2.11-1	IAV HEAT	IAV	IAV (2019, July 31). *First autonomous shuttle bus*. IAV website. https://www.iav.com/en/news/first-autonomous-shuttle-bus/

A-21 / Figure 1.2.12-1	Cruise Origin	CNBC	CNBC (2020, January 23). *Debut of GM's Cruise Origin shows the future of ride-sharing, autonomous vehicles in a box.* CNBC website. https://www.cnbc.com/2020/01/23/debut-of-gms-cruise-origin-shows-the-future-of-ride-hailing-autonomous-vehicles-is-a-box.html
A-22 / Figure 1.2.13-1	Zoox	Wired	Marshall, A. (2020, December 15). *Why Do Many Self-Driving Cars Look Like Toaster on Wheels?* Wired website. https://www.wired.com/story/self-driving-cars-look-toasters-wheels/
A-23 / Figure 1.2.14-1	REE E-Shuttle	REE Automotive	REE. Automotive REE Automotive website. https://ree.auto/segments/e-shuttle/
A-24 / Figure 1.2.14-2	REE Leopard	REE Automotive	NA
A-25 / Figure 1.2.15-1	Apolong	BBC News	BBC News (2018, July4). *Baidu's self-driving buses enter 'mass production'.* BBC News website. https://www.bbc.com/news/technology-44713298

A-26 / Figure 1.2.16-1	**May Mobility**	**Fort Worth Business Press**	**Fort Worth Business Press (2021, March 23).** ***Arlington partnering with Via, May Mobility on self-driving vehicle program for downtown, UTA*****.** **Fort Worth Business Press website.** **https://fortworthbusiness.com/business/arlington-is-expanding-its-self-driving-vehicle-program/**
A-27 / Figure 1.4.1-1	**New Flyer**	**Government Technology**	**Descant, S. (2021, January 29).** ***New Flyer Introduces First Autonomous Bus in North American*****.** **Government Technology website.** **https://www.govtech.com/fs/new-flyer-introduces-first-autonomous-bus-in-north-america.html**
A-28 / Figure 1.4.2-1	**Irizar Autonomous Bus**	**Sustainable Bus**	**Editorial staff (2021, February 20).** ***Irizar converts an e-bus into autonomous driving. The begin of operations in Malaga.*** **Sustainable Bus website. https://www.sustainable-bus.com/news/autonomous-bus-irizar-malaga/**

A-29 / Figure 1.4.3-1	**Volvo Autonomous Bus**	**Volvo Buses Global**	**Volvo Buses Global (2019, March 5).** ***NTU Singapore and Volvo unveil world's first full size, autonomous electric bus*****.** **Volvo Buses Global website.** **https://www.volvobuses.com/en/news/2019/mar/volvo-and-singapore-university-ntu-unveil-world-first-full-size-autonomous-electric-bus.html**
A-30 / Figure 1.4.4-1	**Iveco Autonomous Bus**	**NextStage AM**	**NextStage AM (2021, October 6).** ***After the success of its shuttle, EasyMile will run an autonomous bus in 2022 with Iveco*****.** **NextStage AM website.** **https://nextstage-am.com/en/after-the-easymile-shuttle-will-run-an-autonomous-bus-in-2022-with-iveco/**
A-32 / Figure 1.5.1-1	**Stanley Robotics**	**Stanley Robotics**	**Stanley Robotics website.** **https://www.stanley-robotics.com/meet-our-robots/**
A-33 / Figure 1.5.2-1	**Oceaneering Concept Cargo**	**E-mail received from Kiel Clasing (Oceaneering)**	**E-mail received from Kiel Clasing (Oceaneering) (2022, April 1).**
A-34 / Figure 1.5.3-1	**Citroen Skate**	**New Atlas**	**Lavars, N. (2021, October 3). Self-driving Cirtroën Skate carries swappable pods for inner-city travel.** **New Atlas website.** **https://newatlas.com/automotive/citroen-skate-autonomous-interchangeable-pods/**

A-35 / Figure 1.5.4-1	**Outrider**	**Outrider**	**https://www.outrider.ai/**
A-36 / Figure 1.5.5-1	**Kodiak Robotics**	**Kodiak Robotics**	**https://kodiak.ai/**
A-37 / Figure 1.5.6-1	**Honda Autonomous Work Vehicle**	**Honda News**	**Honda News (2021, November 15).** ***Honda Tests Prototype Autonomous Work Vehicle at Solar Construction Site with Black & Veatch*****.** **Honda News website.** **https://hondanews.com/en-US/honda-corporate/releases/release-bc2bc74408027960dba69cafec03cca8-honda-tests-prototype-autonomous-work-vehicle-at-solar-construction-site-with-black-veatch**
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B-2 / Figure 1.1.1-1	**Conceptual Diagram for Selective Energy Exchange Between Coupled Resonators**	**WiTricity**	**WiTricity website.** **https://witricity.com/technology/**
B-2 / Figure 1.1.1-2	**Conceptual Diagram Illustrating Key Characteristics**	**WiTricity**	**WiTricity website.** **https://witricity.com/technology/why-magnetic-resonance/**
B-3 / Figure 1.1.2-1	**Conceptual Diagram for Resonant Magnetic Induction**	**Momentum Dynamics (now InductEV)**	**NA**
B-3 / Figure 1.1.2-2	**Conceptual Diagram Illustrating Components in Roadway and Vehicle**	**Momentum Dynamics (now InductEV)**	**NA**

B-4 / Figure 1.1.3-1	Continental Automated Wireless Charging Technology	Continental Press	Geldhäuser, S. (2017, May 31). *Automated Wireless Charging from Continental: Convenient and Efficient*. Continental Press Release. https://www.continental.com/en/press/press-releases/2017-05-31-inductive-charging/
B-4 / Figure 1.1.4-1	Plugless Power Wireless Charging in Parking Space	Plugless Power	Plugless Power website. https://www.pluglesspower.com/autonomy/
B-5 / Figure 1.1.4-2	Plugless Power Wireless Charging	Plugless Power	Plugless Power website. https://www.pluglesspower.com/autonomy/
B-6 / Figure 1.1.5-1	HEVO Wireless Charging Concept Diagram	HEVO	HEVO website. https://hevo.com/how-it-works.html
B-7 / Figure 1.2.1-1	Wireless Charging Concept for Roadways	Magment	Magment website. https://www.magment.co/magment-magpad/
B-7 / Figure 1.2.1-2	MagPad	Magment	Magment website. https://www.magment.co/magment-magpad/
B-7 / Figure 1.2.1-3	Magnetizable Concrete Product	Magment	Magment website. https://www.magment.co/magment-technology/

B-8 / Figure 1.2.2-1	**Wireless Charging Concept for Roadways**	**Designboom**	**Designboom (2020, October 9). Electreon wireless'electric roads in tel aviv to charge cars on the go.** **Designboom website.** **https://www.designboom.com/technology/israeli-startup-electreon-electrify-roads-tel-aviv-06-03-2020/**
B-8 / Figure 1.2.2-2	**Wireless Charging Concept for Roadways (Detail)**	**NA**	**NA**
B-9 / Figure 1.2.3-1	**IPT PRIMOVE Dynamic Charging**	**IPT Technology**	**IPT Technology website.** **https://ipt-technology.com/e-mobility-wireless-dynamic-charging/**
B-9 / Figure 1.2.3-2	**IPT PRIMOVE Dynamic Charging Installation in Mannheim, Germany**	**IPT Technology**	**IPT Technology website.** **https://ipt-technology.com/e-mobility-wireless-dynamic-charging/**
Appendix C			
C-1 / Structural Information Normal Weight and Lightweight Concrete 8000 psi Beam	**Design Values for Normal Weight Concrete vs Lightweight Concrete 8000 psi Beam**	**Virginia DOT**	**Virginia DOT website.** **https://www.virginiadot.org/business/resources/materials/virginia_concrete_presentations/6b-davis-precast_prestressed_concrete_practices.pdf**

Appendix D			
D-3 / Table 2.1-1	Common Construction Material Weights	"World's First Thermoplastic Bridges", Chandra, et al, 2009	
D-3 / Figure 2.1-1	Stress-Strain Curve	"World's First Thermoplastic Bridges", Chandra, et al, 2009	
D-4 / Table 2.1-2	Material Properties of RSPC	"World's First Thermoplastic Bridges", Chandra, et al, 2009	
D-4 / Table 2.1-3	Lifetime Cost	"World's First Thermoplastic Bridges", Chandra, et al, 2009	
D-5 / Table 2.1.4	Expected Life	"World's First Thermoplastic Bridges", Chandra, et al, 2009	
D-5 / Figure 3-1	Property Comparison	Orenco - InfraCore Bridge Technology	
D-6 / Figure 3-2	Stress-Strain Diagram	Orenco - InfraCore Bridge Technology	
D-6 / Figure 3-3	Typical Cross Section of Deck	Orenco - InfraCore Bridge Technology	
D-7 / Table 3-1	Environmental Data	Orenco - InfraCore Bridge Technology	
D-8 / Figure 3-4	Vehicular Bridge	Orenco - InfraCore Bridge Technology	
D-8 / Figure 3-5	Vehicular Bridge	Orenco - InfraCore Bridge Technology	
D-8 / Figure 3-6	Vehicular Bridge	Orenco - InfraCore Bridge Technology	

Appendix E			
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G-12 / Figure G-10	**Transverse Slab Units with Attached Bridge Railing**	**Connection Details for Prefabricated Bridge Elements and Systems, Publication No. FHWA-IF-09-010**	
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Appendix H			
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J-4 / Figure 2-1	**Round Table Base**	**Mutrade**	**Mutrade website.** **https://www.mutrade.com/car-rotating-turn-table/**
J-4 / Figure 2-2	**Round Table with Vehicle**	**Mutrade**	**Mutrade website.** **https://www.mutrade.com/car-rotating-turn-table/**