



INTERNATIONAL **M**ONORAIL **A**SSOCIATION



IMA
Planning Guide
for Monorail Systems

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International Monorail Association (IMA)

'IMA Planning Guide for Monorail Systems'

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Foreword

Around 80 percent of monorails worldwide fulfil a transport task in public transit and, thanks to their economic advantages and shorter implementation times, the trend is rising. Monorails are effective not only in undeveloped areas, but also offer crucial advantages in densely populated or rapidly growing urban environments where their implementation is relatively easy. The elevated construction reduces the space requirement to a minimum, preserves existing road allowances, and does not lead to a displacement of existing surface traffic, as opposed to many cases where trams or dedicated bus routes are introduced. Some monorails manage very small curve radii of as little as 18 meters and gradients of up to 12 percent, which makes them ideal for locations and regions with a challenging topography and urban conditions. Monorails are also among the quietest transport systems in that they have rubber tires. The prefabricated construction of the infrastructure, such as guide beams, supporting pillars, and trackside components manufactured at the outskirts of a city, enables the structures to be erected quickly with minimal disruption to traffic. The elevated crossing-free operation eliminates the need for additional track safety devices outside the stations and allows fully automatic and driverless operation according to level 4 automation (GoA4).

Faced with an escalating demand for public transportation in metropolitan areas, transportation authorities are challenged to evaluate needs-based technologies and plan appropriate transport infrastructures. In doing so, they must meet the sometimes divergent goals of high capacity and reliability, urban compatibility, minimal environmental impact, and budget restrictions. To further promote the use of monorails, the International Monorail Association (IMA) has worked with monorail experts worldwide to develop a planning guide to assist in the early planning of monorails and to also compare them with other modes of transport.

The 'IMA Planning Guide for Monorail Systems' offers a comprehensive framework that classifies monorail systems in the broader transportation context. It covers key features and elements of a monorail system, considering both the vehicle technology and the civil infrastructure including wayside elements. The guide outlines system configuration options and details the critical steps for a successful integration into the urban environment, along with all operational considerations. Topics related to investment, funding and certification are also covered. Finally, examples of successfully implemented monorail systems are presented alongside systems currently under construction.

This first edition of this Planning Guide builds on the 'Performance Specification for a Turnkey Mass Transit Monorail System' first published in 2022, and aims to make a major contribution in promoting alternative mass transit solutions. It is an important step towards establishing monorails as an efficient, reliable, safe, and environmentally friendly public transport solution.

The Executive Board Members of the International Monorail Association would like to extend their gratitude to all the volunteer professionals, especially Carlos Banchik, Prof. Ahmed Ghallab, Matthew Hofford, Sanjay Jamuar, Marko Kroenke, Gregor Supp, Rodolfo Szmidke, Peter Timan, Ian Veigl, and Johannes Winter for their outstanding contributions to this effort.

The IMA Executive Council, September 2024

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1 Introduction

The interest in developing monorail systems has increased around the world in the last two decades based on its unique benefits such as sustainability, efficiency, fast construction, and cost-effectiveness. A testimony to this fact is the partial list of new monorail systems starting in 2003 with the Okinawa Urban Monorail in Japan, Chongqing Lines 2 and 3 in China, Sao Paulo Lines 15 and 17 in Brazil, Daegu Line 3 in South Korea, Mumbai Monorail in India, Changsa Maglev Express in China, Bangkok Yellow and Pink Lines in Thailand, Wuhu Lines 1 and 2 in China, Wuhan Suspended Monorail in China, Fenghuang Maglev in China, Cairo East and West of Nile Lines in Egypt, Panama City Line 3 in Panamá, Santiago de los Caballeros Monorail in Dominican Republic, and Monterrey Lines 4 and 6 in Monterrey in Mexico.

The purpose of this document is to provide a comprehensive and practical guide for planning and implementing monorail systems based on the experience and expertise of the International Monorail Association (IMA) and its members. The document aims to assist cities, authorities, investors, operators, and other stakeholders who are interested in developing monorail systems using the latest state of the art technology.

Key elements of this Planning Guide are the monorail system description in the context of public transport with systems configuration, classification and definition of all aspects of the system. The environment and urban integration with sustainable principles and the stages of operating concepts with operations plans are explained. Also, the models of investment and funding with procurement methodologies are outlined. One of the main chapters is on urban transit technology selection and includes a part of the planning process and identifies the success factors in a turnkey procurement process. The Planning Guide then concludes with a summary of accomplished monorail systems as well as discussing the regulatory framework and safety regulations related to certification.

Many experts and members from the International Monorail Association contributed to the document including operators, large project developers, system integrators, rollingstock and components suppliers, civil infrastructure designers, urban planners, academic researchers, consultants and certification institutes. The completed version is planned to be published at the IMA conference in September 2024 in Neumarkt, Germany and also presented at the InnoTrans 2024 in Berlin, Germany.

The 'Monorail Planning Guide' is part of a series of documents like the 'Performance Specification for a Turnkey Mass Transit Monorail System'. Both are offered as free downloads from the homepage of IMA.

We invite the reader of this document to find answers to their questions about monorails from the many experts worldwide who see them as a way to enhance mass transit service with a low-carbon, automated, electric system.

2 Public Transport

2.1 General Framework

2.1.1 Glossary and Abbreviations

The following are definitions of the terms used in this document to achieve common understanding of the concept for Monorail system planning.

Automatic Control

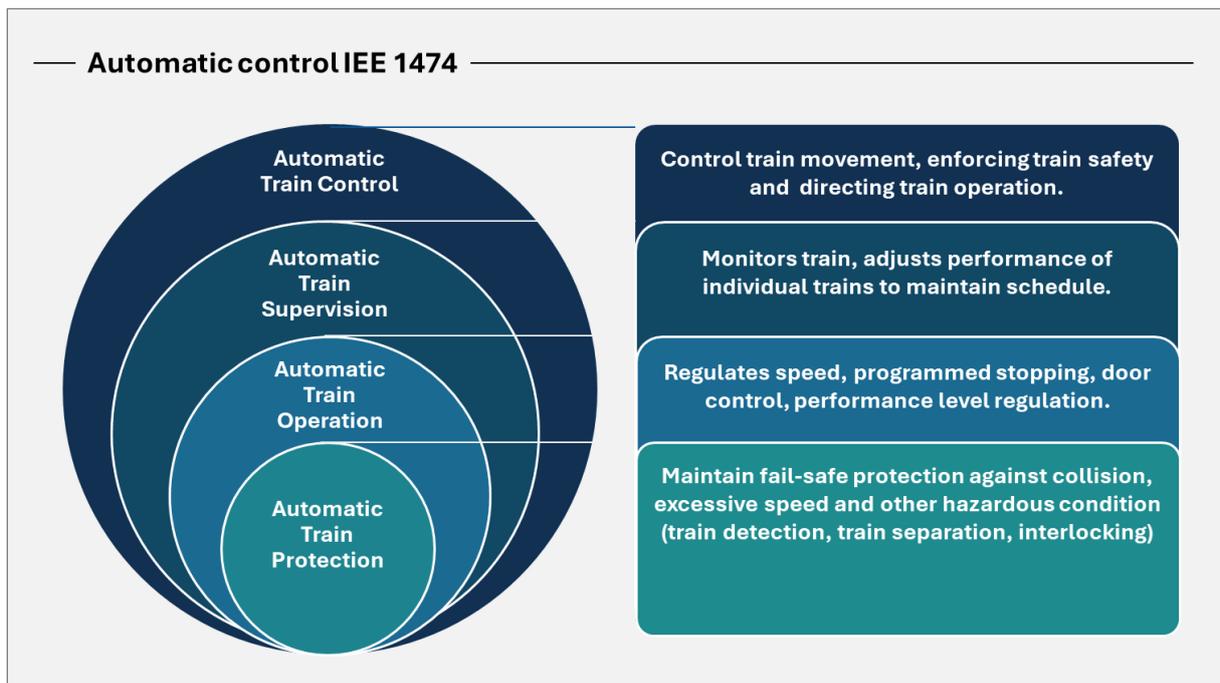


Figure 1: Automatic control definition, IEE 1474

Source: IEE 1474, illustration by IMA

Automatic Train Operation (ATO)

A sophisticated monitoring and control system that supports autonomous vehicle operations with short headways for a highly safe and efficient system with minimum running cost. ATO functionality permits reliable and frequent service operation of most exclusive right-of-way transit systems such as APM, Monorail, or Light Metro or Heavy Metro.

Automatic Train Protection (ATP)

ATP functions are responsible for ensuring safety in all aspects of the train control system. ATP functions include train presence detection, safe train separation, over-speed protection, etc.

Capacity

Refers to system design capacity. It is often defined as passengers per hour per direction (pphd) during peak hours of operation. 'Design capacity' refers to the future capacity of the system – the capacity a transit system is designed for. It means the system has been designed with provisions allowing it to be upgraded to meet capacity 20 years or 30 years in the future. The terms 'initial capacity' and 'ultimate capacity' are often used.

Commercial Speed

Refers to average speed for one round-trip including station stops. It is used for sizing the fleet of vehicles.

Grade of Automation (GoA):

Grade of Automation	Train operation	Setting the train in motion	Driving and stopping the train	Opening and closing the doors	Operation in the event of disruptions
1	ATP with a driver	Driver	Driver	Driver	Driver
2	ATP and ATO with a driver	Driver / Automatic	Automatic	Driver	Driver
3	Driverless	Automatic	Automatic	Automatic / Attendant	Attendant
4	Driverless, Unattended (UTO)	Automatic	Automatic	Automatic	Automatic

ATP – Automatic Train Protection
 ATO – Automatic Train Operation
 UTO – Unattended Train Operation

Figure 2: Grade of Automation (GoA)

Illustration by IMA

Headway

Refers to vehicle frequency in one direction, meaning the time between trains or buses. It often refers to the peak hour headway and is expressed in time units.

Maximum Operating Speed

Refers to the maximum speed the vehicle can run as defined by the vehicle supplier.

Owner/Operator

The responsible organization for the selection and procurement of the transit system, with planners and consultants often supporting this process.

SCADA

SCADA (Supervisory Control and Data Acquisition) is a control system architecture comprising computers, networked data communications and graphical user interfaces for high-level supervision of machines and processes.

Timing, Round-Trip Time

The round-trip travel time shall be defined as wheel-start to wheel-start of the same train at the same station/point on the route, in the same direction of travel during regular service operation. This considers the time delays related to communication and all station dwell times.

Multiple round-trip time may not consider some part of communications.

Timing, Travel Time

Travel time from one end to the other end on a transit line including station dwells, deceleration, acceleration, and cruising.

2.1.2 Monorail Systems Configurations

Monorail system configurations basically follow the same principles that have been outlined for Automated People Mover (APM) systems. A comprehensive source is the 'ACRP REPORT 37 Guidebook for Planning and Implementing Automated People Mover Systems at Airports (2010), LEA+ELLIOTT Dulles, Virginia'. The chapter 4.2 APM systems configurations of that document describes in a good way different alignments and reference is taken for this chapter to be used for Monorail applications.

This section describes overall system characteristics, including system guideway alignment and platform configurations. Also, several distinctive physical and operational characteristics of systems that define the system's alignment configuration are presented. The physical characteristics are used to determine the best configuration to suit a particular application in an urban or airport environment. The different system alignment configurations include:

- Single-lane shuttle,
- Single-lane shuttle with bypass,
- Dual-lane shuttle,
- Dual-lane shuttle with bypass,
- Single Loop,
- Double loop, and
- Pinched loop.

2.1.2.1 Shuttle System Configurations

Shuttle systems are the most basic configuration. Figure 3 and Figure 4 illustrate four basic types of two-station shuttle system configurations.

Single-Lane Shuttle

A single train shuttles back and forth between two endpoints on a single guideway. Two stations are most common, but additional stations can be accommodated. This simple shuttle is best suited to transporting passengers between two points in a low-demand environment. Because a single point failure along the guideway will shut down the single-lane shuttle, this configuration should only be used where passengers have the alternative of walking or where a standby means of conveyance is available.

Single-Lane Shuttle with Bypass

Two synchronized trains pass each other in the bypass area of the guideway. Because each train can be independently propelled, there is the potential for a degree of redundancy and failure management capability. A third station can be added in the bypass area. Single lane shuttles with bypass are limited to two trains. This configuration is slightly more complex operationally than the single-lane shuttle because the trains must be synchronized to avoid delays at the bypass. This configuration has a role in relatively low-demand situations to transport passengers between two points.

Dual-Lane Shuttle

Two trains shuttle back and forth independently in a synchronized manner on separate guideways. During non-peak times this configuration can be operated as a single-lane shuttle to allow for maintenance on the other lane/train, or in an on-call mode, like elevators. Two stations are most common, but additional stations can be accommodated.

Dual lane shuttles provide both vehicle and wayside redundancy for good failure management and are limited to two trains. This configuration serves higher demand levels than the single-lane shuttles for passengers traveling between two points. To provide Monorail system configurations in the context of the various components, Figure 3 shows the plan view of a two-station, self-propelled Monorail shuttle above a profile view of the same shuttle configuration.

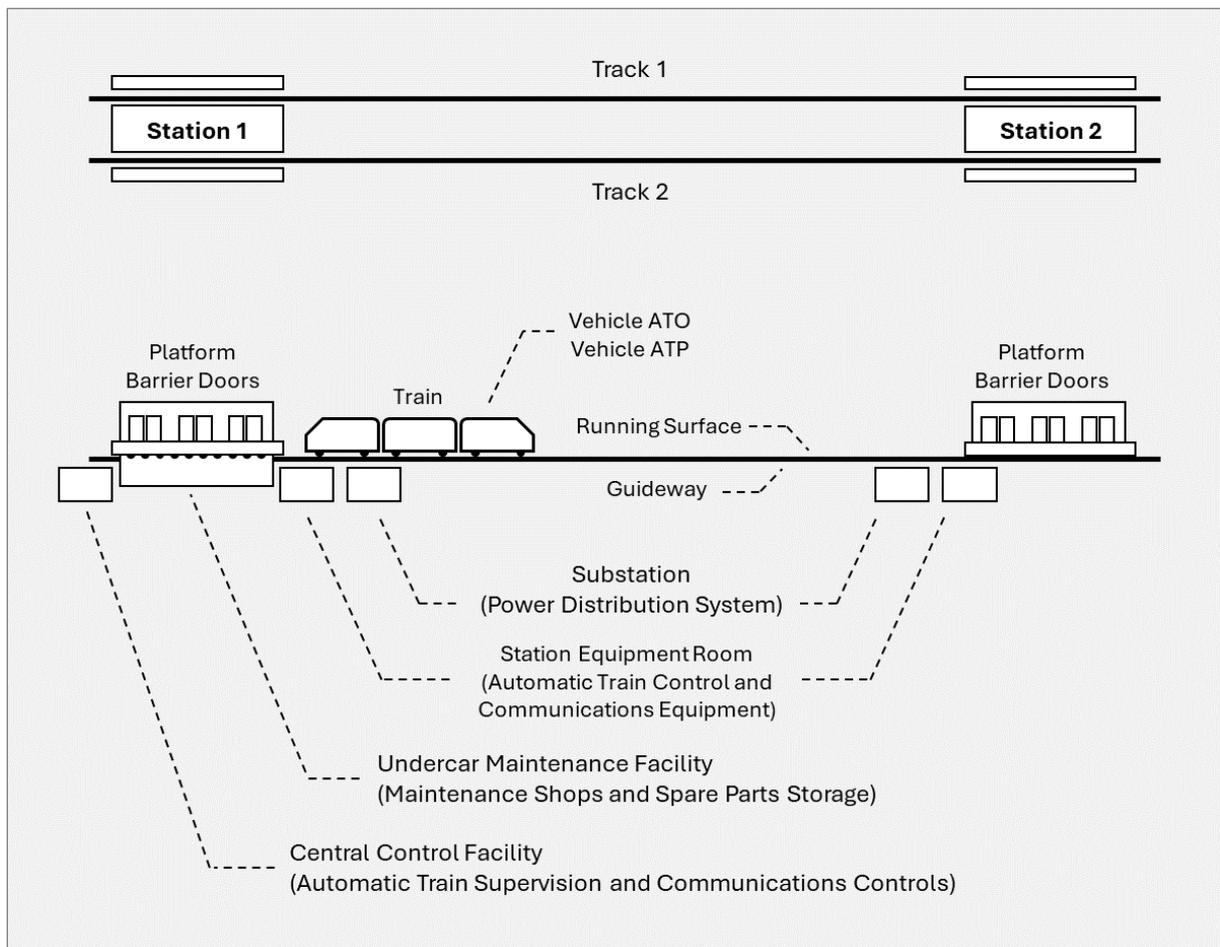


Figure 3: Standard self-propelled shuttle system

Source: Guidebook for Planning and Implementing Automated People Mover Systems at Airports (2010), chapter 4, illustration by IMA

A cable-propelled Monorail shuttle is similar in configuration to a self-propelled shuttle, but there are differences with a number of the Monorail components, as shown in Figure 4. Propulsion is a clear difference between cable- and self-propelled systems. Propulsion is provided at the station (bull wheel) for a cable system, while it is provided in the vehicle (onboard motor) for a self-propelled system.

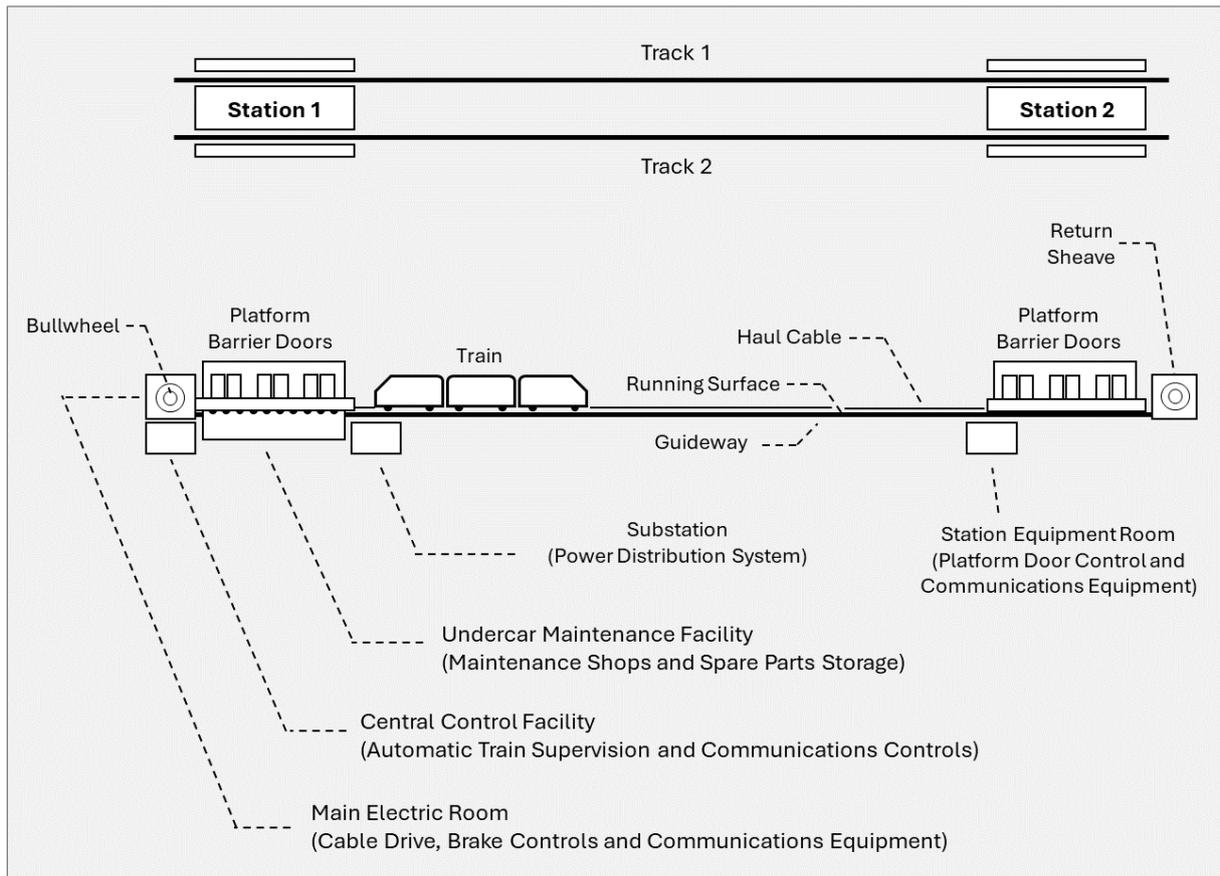


Figure 4: Standard cable propelled shuttle

Source: Guidebook for Planning and Implementing Automated People Mover Systems at Airports (2010), chapter 4, illustration by IMA

Dual-Lane Shuttle with Bypasses

Two synchronized trains pass each other on each lane in the bypass area of the guideway. This configuration doubles the capacity potential of the dual-lane shuttle configuration by allowing a maximum of four trains without requiring four full guideway lanes. This configuration is suitable for higher demand levels than the other shuttle configuration for transporting passengers between two points.

2.1.2.2 Loop System Configurations

Loop and pinched-loop system configurations differ from shuttle configurations and are described below. Figure 5 illustrates the range of loop-type Monorail system configurations.

Single Loop/Double Loop

Loop configurations allow multiple stations to be served with a self-propelled (but typically not cable-propelled) vehicle fleet. Distances and number of trains are not limited. As the scale of a single-loop system increases, the one-way movement of its trains becomes problematic. For example, in a multi-station loop, if the passenger's destination is the adjacent station in the opposite direction of the one-way train movement, the passenger must ride through the entire system and all other stations to reach the destination. Failures on a single loop can cause a shutdown of the entire system unless there are pre-planned backup shuttle routes between unaffected stations. The single loop should only be used for nonessential services that can

provide an alternative means of conveyance in the event of failures. Even then it has serious operational drawbacks.

The double-loop configuration solves these problems by offering trains traveling in both directions. Passengers can be instructed as to the shortest route to their destination station. Double loops provide redundancy to lessen the impact of failures. Double-loop configurations are suitable for nonlinear applications that serve multiple stations and have higher demand levels than can be served by single-loop or shuttle systems.

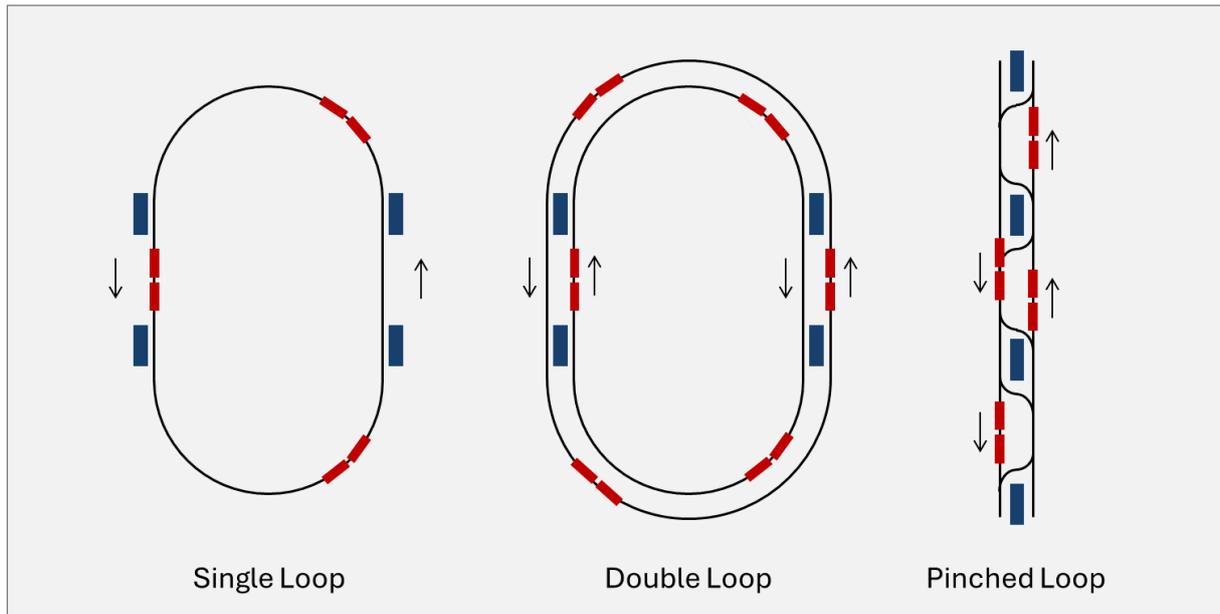


Figure 5: Loop systems

Source: Guidebook for Planning and Implementing Automated People Mover Systems at Airports (2010), chapter 4, illustration by IMA

Pinched Loop

Although having the visual appearance of a dual-lane shuttle, the trains in a pinched-loop configuration travel in a loop by reversing direction and changing lanes via switches at the end stations. Intermediate switches between selected stations are often provided for failure management purposes, allowing trains to be temporarily rerouted around a problem area that would otherwise disrupt service. Stations along the alignment are served in both directions of travel. Distances and number of trains are typically not limited. This configuration is well suited to linear, must-ride applications requiring high-capacity frequent service, multiple stations, multiple trains, and high reliability.

Advances in cable-grip subsystems (detachable grips) now allow cable-propelled technologies to be used in limited pinched-loop configurations with multiple cables/cable drives, typically serving two or three stations and with cable transfer done at stations.

Figure 6 shows the pinched-loop configuration within the context of the different Monorail system components. It is important to note that the pinched-loop system includes switch machines for crossovers and yard access, as well as an expanded central control equipment room, which typically includes train control functions for the yard access and departure testing.

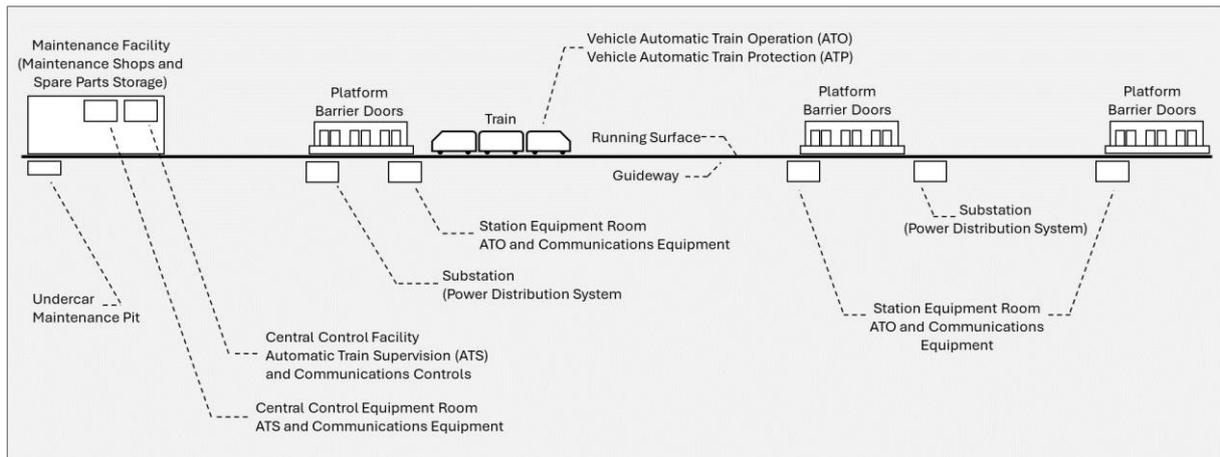


Figure 6: Standard pinched loop system

Source: Guidebook for Planning and Implementing Automated People Mover Systems at Airports (2010), Chapter 4, illustration by IMA

2.1.2.3 Network

The next level of system configuration is an entire network of lines, circles, loops in any kind of combination like a metro or tram system for a city or urban area.

2.1.3 Classification of Urban Passenger Dual Rail vs. Monorail

One of the ways that urban passenger rail can be defined is based on the type of structures required for the system operations. This type of classification divides the rail systems into dual rail and monorails. The following section offers additional details on many of the main categories described below.

Dual Rail – the Conventional Rail

Conventional rail systems can be attributed to wheel-rail systems, whose vehicles are guided on two rails. Applications range from common regional transport to connect the countryside to urban areas, to long-distance applications to connect different cities, to high-speed transport. Classic railways are used in urban transport in the form of LRVs and metros. Automatic people movers (APMs), despite most of them having rubber tires and often running on concrete mainline structures, are classified as two-rail systems and are not considered as monorails. The same applies to Automatic Guideway Transit (AGT). Figure 7 shows the common rail applications on a double rail basis.

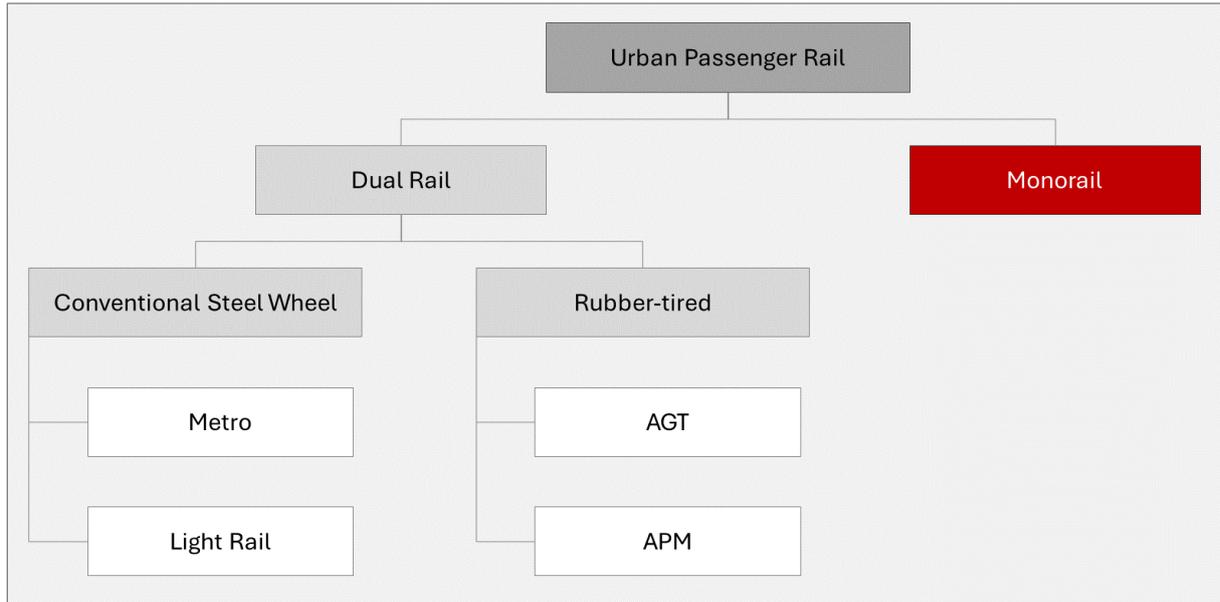


Figure 7: Classification of common urban passenger rail applications

Source: SCI Verkehr GmbH / International Monorail Association, World Market Study on Monorail Systems, illustration by IMA

Monorails

A monorail is a transport system that travels either on (classic or straddle monorail) or under (suspension monorail) a single narrow track – often called guide beam. The beam can take on different shapes and be made of different materials. The monorail guide beam consists of a single structural rail that takes the vertical, lateral and the longitudinal loads. Monorails are usually driven by onboard electric motors. The types commonly referred to the term monorail can thus be classified according to their carrying and guiding principle and vehicle placement.

Monorails have been around for more than a century; however, only recent developments have enabled transport authorities to consider monorails as a real alternative in public transportation to meet their needs in mass urban transit. Monorails are often easier to integrate into existing urban areas as they are elevated and comparatively easy to build, taking up little valuable traffic and pedestrian space at the street level, and requiring no expensive tunnelling. The special track design of monorails generally supports a cost-effective, elevated construction method and a very fast implementation. Despite a significantly increasing number of applications, monorail systems still maintain a niche existence.

Following Prof. Eryu Zhu, Beijing Jiaotong University, the main system approaches can be summarized as follows:

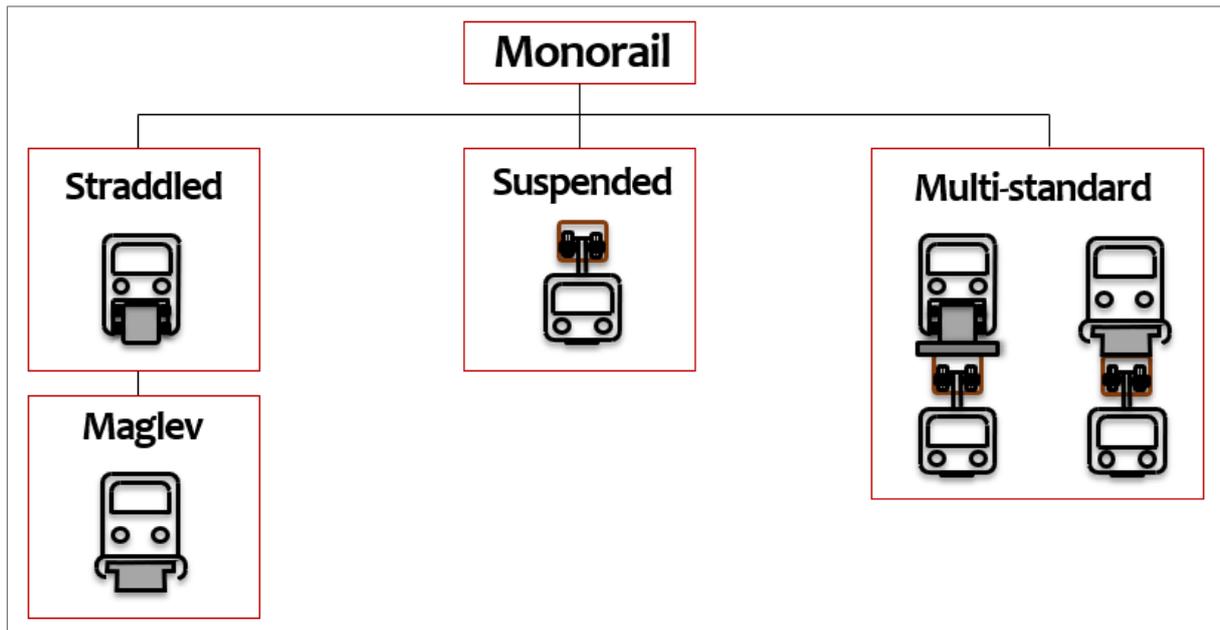


Figure 8: Classification of monorail systems by vehicle placement

Source: SCI Verkehr GmbH / International Monorail Association, World Market Study on Monorail Systems, illustration by IMA

Suspended Monorails

In addition to the first suspended monorails (the Wuppertal suspension railway), where steel wheels with flanges on both sides carry the vehicle and guide it on the steel rails, suspended railways are also designed with guideway girders consisting of an open section steel beam. Two vertical wheels to the left and right of the opening carry the vehicle, and horizontal rollers guide the vehicle on the vertical beam's inner walls. The width of the hollow section can be up to 2 m. Nevertheless, there exist many rubber-tired suspended monorail systems running on the inner side of the hollow section and guided on the beam's inside side walls.

Straddled Beam Monorails

The most widespread type of monorail is the so-called straddled beam monorail. Many of the straddled monorail systems are based on the Alweg system from 1952, where the vehicle embraces both sides like a saddle around the track, which is formed from a narrow concrete beam with a rectangular cross-section.

Depending on the system, the guide beam width varies between 500 and 900 mm and the height typically between 1 and 2 m. The vehicle's load wheels are supported by the beam. Due to the small support width of the carrying wheels, guide tires are arranged on both sides in two vertically superimposed areas so that the vehicle is held upright and guided along the track. Straddled monorails with a narrow guideway beam are available in high-floor and low-floor versions. The latter requires central wheel housings inside the vehicle for the load wheels.

Maglev

Maglev systems, short for magnetic levitation, are advanced transportation systems where vehicles are levitated and propelled along a guideway using magnetic forces. Since most maglev systems embrace the track on both sides like straddled monorails, maglev systems are classified as monorails and are considered as monorail systems in this document.

Further system approaches

Beyond the above-mentioned types of system, there are other technologies that have not yet found their way into revenue service. For example, some concepts such as the multi-standard monorail, where a combined running beam is to be used for both system approaches - i.e., a parallel combination of suspended and straddled monorail. Also, there are ideas for so-called cantilevered monorails, in which the lateral surfaces of the guideway beam are used to support two laterally guided monorails.

Intended use and performance-oriented classification of monorails

Monorail systems aim to offer an economic alternative to conventional railways. They are mostly straddled monorails with rubber-tired wheels on steel or concrete beams and serve as public transportation with line lengths ranging from 10 to 30 km, or even more than 50 km in some cases (Chongqing, China and Cairo, Egypt).

Depending on the application, the transport capacity of monorails varies from a few thousand to over 40,000 passengers per hour per direction (pphpd). It thus reaches the values of medium sized metro systems. Lower infrastructure costs in combination with automation of the operation up to GoA4 (due to segregated track infrastructure) favor an economic operation even with lower transport demand.

Wheel size and wheel material are the main factors determining the maximum speed, which is between 60 and 100 km/h for wheel-guided systems. Maglev systems have a top speed well above 100 km/h, with the Transrapid in Shanghai taking on a special role as designed for long-distance transport system but used in public transport with 430 km/h.

The individual systems differ in specific infrastructure costs due to the respective track design, the system height and width, the flexibility in routing, which is influenced by the minimum curve radius and the maximum gradient, as well as the complexity of switches.

Due to the elevated construction and the high-grade capability, monorails are ideally suited for use in urban areas where no track-bound local transport system is yet available and topographical and urban development features make the use of classic railway systems difficult. The lower vibration and noise emissions of rubber tires or magnetic fields in the support system are a further advantage for use in urban areas.

According to Prof. Christos Pyrgidis, Aristotle University of Thessaloniki, monorails can be characterized based on selected performance parameters as shown in the following table:

Table 1: Typical characteristics of a monorail system

Criterion	Usual expression	Comments
Line length	10 - 30 km	
Horizontal alignment radius	40 - 70 m	Minimum implemented so far 18 m
Longitudinal gradient	0 - 10 %	Maximum implemented so far 12 %
Maximum running speed	60 - 100 km/h	
Commercial speed	15 - 40 km/h	Average trip time (including station time, boarding, dwell time) divided by line length for a typical route
Transport capacity	Small: 2,000 pphpd ¹ Standard: 4,800 pphpd Large: 12,500 pphpd	For public transportation with 4-car trains at 90 sec. headway typically 22,500 pphpd (can go up to 48,000 pphpd with up to 8-car trains)
Frequency	3-15 min. minimum 60 sec	
Distance between stops	800 - 1,500 m	

Source: Professor Christos Pyrgidis, Aristotle University of Thessaloniki, SCI Verkehr GmbH / International Monorail Association, World Market Study on Monorail Systems

2.1.4 Brief Description of Modes of Transportation

The following sections briefly discuss each transit technology and explain the features of each technology, its ideal application, and advantages and disadvantages.

2.1.4.1 Automated People Mover (APM)

APM typically uses rubber-tired technology. APM is a fully automated driverless transit system operating in its own right-of-way. APM is ideal for elevated systems but can also be in tunnel or at-grade.

APM Capacity

The capacity of a vehicle for mass transit application is around 150 persons per car at 6 passengers/m².

Headway

Typical lowest headway with ATO is 90 seconds.

System Capacity

System capacity of typical APM assuming at 90 seconds headway is:

4 car train: 150 passengers × 4 cars × (3,600 sec./90 sec.) = 24,000 pphpd.

6 car train, providing a system capacity of 36,000 pphpd

System Design

The APM system is typically designed to offer 30 years of service and very high reliability over its operating life.

- Mainly elevated; but can be at-grade or in tunnel
- Capital cost is higher than tram/LRV but lower than heavy metro for medium capacity systems
- Flexible alignment

- Mainly driverless
- Travel time is low
- Very safe due to ATO and segregated
- Typical vehicle capacity @6pax/m²: 150 passengers per car
- Typical system capacity: 24,000 pphpd with 4-car trains at 90 seconds headway
- 30-year design life and very high reliability



Figure 9: APM Tampa, Alstom Transportation, 2018

Source: Photo by Marko Kroenke



Figure 10: Mitsubishi Crystal Mover, Tampa, 2018

Source: Photo by Marko Kroenke

2.1.4.2 Bus Rapid Transit / Bus Rapid Transit System / Transit-way (BRT/BRTS/T-way)

BRT typically operates on a mix of dedicated lanes in city's streets, and on dedicated guideway that may be elevated or in tunnel.

Capacity of a regular 12 m long city bus is 65 passengers at 6 passengers per square meter. BRT uses articulated buses that can double the length of a regular bus, with a capacity of 150 passengers at 6 passengers/m².

Headway

Regular city buses normally operate at 10 minutes or longer headway. BRT can have shorter headway because it has a dedicated lane. However, it cannot have very short headway because there are still intersections on the alignment. The lowest typical headway during peak time is roughly 5 minutes.

System Capacity

With a 10-minute headway (600 sec.), the possible system capacity for a regular bus is $65 \times (3,600 \text{ sec.}/600 \text{ sec.}) = 390$ pphpd. With 5-minute headway (300 sec.), the possible system capacity of BRT is $150 \times (3,600 \text{ sec.}/300 \text{ sec.}) = 1,800$ pphpd.

System Design

The BRT system is typically designed to offer 15 years of service and reliability is lower than rail systems. A bus or BRT system requires a very high staffing level to provide drivers.



Figure 11: BRT São Paulo, 2014

Source: Photo by Marko Kroenke



Figure 12: BRT São Paulo, 2024

Source: Photo by Rodolfo Szmidke

2.1.4.3 Bus

Buses operate in the city using existing streets. Buses are worldwide the mode of transport used the most. The main reason being the low cost of buying and maintaining the vehicles. The number of passengers per vehicle though is very limited. A standard 12m city bus can handle around 100 passengers per vehicle, while a longer articulated bus can reach capacities of up to 190 passengers.

Most buses still rely on combustion engines as their main source of power, which is an increasingly big problem within city limits due to the air pollution being monitored more intensively in recent years. Battery powered buses and trolleybuses are an alternative to reduce pollution. With battery buses still being significantly more expensive and still not fully capable of replacing the services formerly used by buses with combustion engines due to the limited capacity of the batteries and the relatively long charging times.

- Mainly use existing streets
- Ideal solution for low-capacity systems
- Capital cost is low for existing streets but can be higher with transit-way
- Drivers are needed
- Travel time could be long
- High incidence collisions and injuries
- Typical vehicle capacity @6pax/m²: 65 per bus; 150 passengers per articulated BRT.
- Typical system capacity: 390 pphpd for bus at 10 minutes headway; 1,800 pphpd at 5 minutes headway for BRT
- 15-year design life and relatively low reliability



Figure 13: Battery electric bus (Proterra), Montreal moving on exhibition, 2017

Source: Photo by Marko Kroenke

2.1.4.4 Heavy Metro / Mass Rapid Transit (MRT)

Heavy metro typically operates in underground tunnels. Using tunnels, they achieve high capacity, full grade separation and no visual intrusion at surface level. Heavy metro is an ideal solution for high density cities where demand is high, and road congestion is very severe. A typical heavy metro would have at least 6-car trains with car lengths in the 22 m range.

Heavy metro tends to be high cost due to a high percentage of tunneling and large underground stations with associated infrastructure. Construction time for heavy metro is typically much longer than for any other urban transit systems, because tunneling is much slower than construction for elevated or at-grade systems. Investment in heavy rail is justified if the demand is very high and surface space is very expensive.

Heavy Metro Capacity

A typical heavy metro vehicle's capacity is 300 passengers per car at 6 passengers/m².

Headway

The headway for metros can vary due to system design between 120 and 90 seconds.

Possible System Capacity

The system capacity of heavy metro assuming 6-car train at 90 seconds headway is 54,000 pphpd.

System Design

The heavy metro system is typically designed to offer 30 years of service and achieves very high reliability.



Figure 14: Metro Amsterdam, Alstom, 2020

Source: Photo by Marko Kroenke

2.1.4.5 Light Metro / Light Rail Transit (LRT)

Typically uses lighter and shorter metro vehicles than heavy metro to reduce impact on civil structure and reduce civil cost. Light metro mainly uses elevated structure but can also be at-grade or in tunnel. Light Metro systems typically operate on dedicated right of way and can be fully automated providing reliable, frequent service, and flexible in operation according to ridership demand such as high traffic during sporting events.

The elevated light metro is much less expensive than underground metro due to the lower construction cost of elevated guideway, normally less than half of underground tunnel. Some sections of the alignment can be at grade or in tunnels. The capacity of the light metro is typically lower than heavy metro. However, the low capacity is often justified because of the much lower capital cost of the system compared to heavy metro.

Light metro uses much lighter and shorter trains than heavy metro to reduce civil impacts and costs. However, limitations such as horizontal curve and grade are like those of heavy metro. Therefore, constructing elevated metro systems is typically costly and often involves extensive relocation or destruction of valuable infrastructure. For these reasons, light metro systems are sometimes not an option.

Vehicle capacity of Alstom INNOVIA Metro 300 LIM is 186 persons at 6 passengers/m².

Headway

The typical lowest headway with ATO is 90 seconds

System Capacity

Assuming 90 seconds headway, the system capacity of a light metro system is:

- 4-car train: 186 passengers × 4 cars × (3,600 sec./90 sec.) = 29,760 pphpd.
- 6-car train, with a capacity of 44,640 pphpd at 90-second headway.

System Design

The light metro system is typically designed to offer 30 years of service and achieves very high reliability especially due to the safe driverless operation.

- Mainly elevated; can be at-grade or in tunnel
- Capital cost is slightly higher than monorail or APM, much lower than heavy metro in the intermediate capacity range
- Alignment is less flexible than APM or Monorail unless LIM (linear induction motor) is used
- Mainly driverless
- Travel time is low
- Very safe due to ATO and segregated
- Typical vehicle capacity @6pax/m²: 180 per vehicle
- Typical system capacity: 28,800 pphpd with 4-car trains at 90 seconds headway
- 30-year design life and very high reliability



Figure 15: Toronto Scarborough Line, Alstom Transportation INNOVIA 200 Metro LIM, 2014

Source: Photo by Marko Kroenke



Figure 16: London Docklands Light Railway (DLR), Alstom Transportation Bo7

Source: Photo Marko Kroenke

2.1.4.6 Light Rail Vehicle (LRV)

In general, tram or LRV operates primarily in city streets possibly with some sections of its own right of way off streets. They have the lowest system capacity and lowest speed urban rail systems. A benefit of tram/LRV is its permanent transit way in the city that will attract more development investment and residential growth compared to bus. Stations are at street level permit easier and faster access; provide quicker connections to other surface transit lines than elevated or underground systems; and are easier for passengers with restricted mobility,

eliminating a need for elevators. Tram/LRV is an ideal solution for short trips within a city core. Tram/LRV operates with electricity and generates less pollution downtown.

The degree of traffic congestion relief is limited because tram/LRV operates in city streets in mixed traffic. It is noisy, especially on curves. It takes away street lanes thus increasing congestion. Staffing requirements are lower than by bus or BRT.

Travel speed is very important to passengers because it means time. Tram/LRV typical maximum operating speed is 70 km/h. Typically, a tram/LRV has an average speed of about 20 km/hour depending on the number of intersections, level of congestion on the road, time of the day and the station dwell time according to the traffic of each station. Travel time is also not totally predictable because of other traffic in the street and accidents or road closures.

Like the bus, safety is also a concern for tram/LRV. Accidents are common for LRV/tram because they interface with other road traffic, bicycles and pedestrians and the low noise generated by the electric LRV/tram. For segregated LRV systems, accidents at rail crossings are often deadly. High costs are associated with accidents including insurance and vehicle repairs. According to FTA statistics, there were 180 collisions, 945 injuries and 40 fatalities in Light Rail operations in the U.S. in 2014.

Noise, vibration and the fixed catenary lines are typical complaints from residents and businesses along tram/LRV alignments. The steel wheel and steel rail are one of the main sources of noise, especially on sharp curves.

Capacity

The capacity of a typical 100% low floor 32 m long tram is 220 persons at 6 passengers/m². We assume LRV application with dedicated right-of-way uses two of the 32 m trams coupled together.

Headway

The typical practical headway for a tram is roughly 10 minutes. Typical practical headway for an LRV is 5 minutes.

System Capacity

The system capacity of tram at 10 minutes headway is $220 \times (3,600 \text{ sec.}/600 \text{ sec.}) = 1,320$ pphpd. System capacity of LRV at 5 minutes headway is $220 \times 2 \times (3,600 \text{ sec.}/300 \text{ sec.}) = 5,280$ pphpd.

System Design

The LRV system is typically designed to offer 30 years of service and achieves high reliability.

- Mainly use existing streets. Can have own right-of-way
- Better than bus in attracting real estate developments along the alignment
- Capital cost is relatively low because of at-grade alignment but sensitive to utility relocation costs
- Drivers are required
- Travel time could be long
- High incidence collisions and injuries
- Typical vehicle capacity @6pax/m²: 220 per tram/LRV
- Typical system capacity: 1,320 pphpd for tram at 10 minutes headway; 5,280 pphpd for LRV at 5 minutes headway
- 30-year design life and high reliability



Figure 17: LRV Frankfurt, Alstom Transportation Flexity, 2019

Source: Photo by Marko Kroenke



Figure 18: Santos LRV, Brazil, 2023

Source: Photo by Rodolfo Szmidke

2.1.4.7 Monorail

Monorail is a typically elevated transit system using vehicles running on a single guide beam. The vehicle uses in most application rubber-tired technology to achieve small curves, high gradients and low noise. Monorail systems operate on dedicated right of way and can be fully automated providing reliable and frequent service. In this document, Monorail refers to mass transit grade monorail. There are applications such as straddle type or suspended type.

Monorail guideways comprise slender beams that provide flexibility in alignment and ease of construction with minimum visual impact. The ability to follow existing rights of way results in minimal land requirements, reducing the need for divisive property expropriation and the need to destroy existing valuable or culturally sensitive buildings. Designed to integrate seamlessly into different environments, including through buildings and structures, Monorail system infrastructure meets the most stringent urban transit, environmental and safety standards.

Monorail systems in general deliver modern aesthetics, spacious interiors and a comfortable ride. The sleek, futuristic, monorail vehicle design is also an attraction to riders and visitors to the city.

Monorail systems using grade separated, exclusive right-of-way are ideally suited to automated driverless operation taking advantages of the driverless benefits including frequent, reliable service and low staffing levels.

Monorail systems minimize the costs and disruption of civil construction. The pre-cast, post-tensioned elevated guideway structure is constructed off-site to allow for exceptionally rapid assembly on site (at least, one beam a day compared to 2 to 3 weeks for a U-viaduct for LRT cast-in-situ). In addition, the elevated guideways avoid the need for potentially expensive and time-consuming tunnelling works, a major advantage when introducing a new transit system in existing dense urban areas.

Monorail offers excellent ride quality and low noise levels by using low-noise metro tire technology, allowing it to be placed close to buildings if desired. Monorail systems today are designed to meet international mass transit standards.

Maximum operating speed of monorail is typically 80 km/h with commercial speed approximately 30 km/h - 40 km/h. Monorail power supply comes directly from the power rails on the beam without any overhead catenary resulting in a better design and better operability and maintainability.

Monorail Capacity

The ALSTOM INNOVIA Monorail 300 vehicle's capacity is approximately 143 persons per car at 6 passengers/m².

Headway

Typical lowest headway with ATO is 90 seconds. Shorter headways are possible depending on the system alignment and train configuration.

System Capacity

The system capacity of a typical monorail with 4 cars, assuming a 90 second headway is 22,880 pphpd (143 passengers per car × 4 cars × (3,600 sec./90 sec.).

7 cars Innovia 300 system maximum capacity of 48,000 pphpd with 78 seconds headway.

This capacity level is not typical for monorails and represents the upper limit. At this limit, it is worthwhile carrying out detailed studies in order to shed sufficient light on economic efficiency and other decision criteria (e.g. construction time, feasibility of other modes of transport in very congested areas such as urban fit).

System Design

The monorail system is typically designed to offer 30 years of service and achieves very high reliability especially due to the safe driverless operation.

- Mainly elevated
- Capital cost is higher than tram/LRV but much lower than heavy metro for medium capacity systems
- Flexible alignment
- Mainly driverless
- Travel time is low
- Very safe due to ATO and segregated
- Typical vehicle capacity @6pax/m²: 140 per car
- Typical system capacity: 22,400 pphpd with 4-car trains at 90 seconds headway
- 30-year design life and very high reliability



Figure 19: Jacksonville Monorail, 2018

Source: Photo by Marko Kroenke



Figure 20: Chiba Suspended Monorail, 2019

Source: Photo by Marko Kroenke



Figure 21: H-Bahn Düsseldorf Airport, 2020

Source: Photo by Marko Kroenke

2.1.4.8 Tram / Streetcars

Trams or streetcars operate in city streets on tracks, but with mixed traffic, meaning road vehicles such as buses, cars and trucks share the same traffic lanes.

Trams are available in a higher range of capacities. The smallest versions are comparable to a standard bus but the number of passengers per vehicle can be increased significantly up to 400 passengers. Trams also do have the advantage that they can form longer trains by coupling to units together which leads to a very flexible number of passengers per train. Trams are almost exclusively electric powered making them emission free at the place of operation.

2.1.4.9 Automated Guideway Transit (AGT)

AGT's are a class of transportation systems in which unmanned vehicles are operated on fixed guideways along an exclusive right of way. This definition covers systems with a broad range of characteristics and includes many types of technology. To provide an organizing structure for the assessment, three major categories of AGT systems have been distinguished:

Group Rapid Transit (GRT)

- Mainly use existing streets repurposed for GRT
- Segregated or mixed traffic with limitations
- Typical battery-operated vehicles with charging stations
- Ideal solution for low-capacity systems
- Capital cost is low where existing streets are used
- Full autonomous operations require performance limitations to allow sufficient safety level.
- Typical speed reductions to limit collisions and injuries
- Individual vehicles enable increased use of point-to-point operations
- Can reduce overall trip time and improve passenger experience
- Typical vehicle capacity @6pax/m²: 15 to 24 per GRT
- Typical system capacity: <500 pphpd at 3 minutes headway
- <1,500 pphpd at 1 minute station headway per berth
- 10-year design life



Figure 22: Rivium (Rotterdam), 2getthere autonomous shuttle, 2017

Source: Photo by Marko Kroenke

Personal Rapid Transit (PRT)

A type of automated transit system that is on-demand, uses an exclusive right-of-way, provides point-to-point service, and usually accommodates no more than three to four passengers per vehicle.



Figure 23: Ultra Pod at Heathrow Airport, 2018

Source: Photo by Marko Kroenke

2.1.4.10 Cable-propelled Automated People Mover

Cable-propelled automated people movers are a type of transit system where vehicles are moved along a track or guideway using a cable propulsion mechanism. These systems are commonly found in environments like airports, theme parks, or city centers, where short, frequent, and reliable transport is needed. Unlike traditional rail or road vehicles, these APMs do not have an onboard engine; instead, they rely on stationary motors to move the cables that pull the vehicles along. This allows for quieter, energy-efficient, and low-maintenance operations.



Figure 24: APM HIA Doha Airport

Source: Photo by Johannes Winter (claystreetX GmbH)

There are two primary types of cable-propelled automated people movers: cable-hauled trains and cable-driven shuttle systems. Cable-hauled trains typically operate on fixed routes with multiple cars linked together, moving back and forth between stations on a single track. These systems are ideal for higher-capacity needs, often found in airport terminals or large campuses. Cable-driven shuttles, on the other hand, are smaller, often operating in a loop, and are designed for short distances and high-frequency service. The vehicles can stop at multiple stations, and their design allows for easy integration into confined urban spaces.

Both types of these APMs offer step-free access, making them fully accessible for people with reduced mobility, wheelchairs, or strollers. With their reliable performance, low environmental impact, and ability to fit in dense or specialized settings, and are increasingly seen as a modern, sustainable solution for urban and institutional transit needs.

2.1.4.11 Cable Cars

Urban cable cars, also known as aerial cableways or gondolas, have become an increasingly popular mode of transportation in cities around the world. Utilizing cable propulsion technology, these systems offer efficient, eco-friendly alternatives to traditional transit options, especially in congested urban areas or challenging terrains. While often associated with mountainous regions or tourist attractions, urban cable cars have evolved to serve as practical public transit solutions. They transport passengers over rivers, up steep inclines, or across bustling cityscapes, offering both functionality and a unique travel experience.

There are two main types of aerial cableways: aerial tramways and gondolas.

Aerial tramways use a fixed track cable and typically have one or two large cabins, capable of carrying between 40 and 220 passengers, that move back and forth between two stations.

On the other hand, gondolas consist of smaller, detachable cabins that travel continuously in a loop, carrying anywhere from 4 to 40 passengers per cabin. Gondolas offer greater flexibility with multiple stations and routes, but their total length is usually limited to about 5 kilometers.

Both systems offer step-free access, making them suitable for all users, including those with wheelchairs, scooters, or bicycles, making urban cable cars a versatile addition to modern public transport networks.



Figure 25: Cable Car London, 2019

Source: Photo by Johannes Winter (claystreetX GmbH)

2.1.5 Fleet Sizing and Headway Calculation

Equations

System Performance Analysis

Key Performance Indicator	Comment
$\text{Operating Fleet Size} = \frac{\text{Round Trip Time (s)}}{\text{Operational Headway (s)}}$	
$\text{Operational Headway (s)} = \text{System Headway (s)} \text{ OR } \text{Turnback Headway (s)}$	It shall be the greater of the two values.
$\text{System Headway (s)} = \frac{3600 \left(\frac{s}{h}\right) \times \text{Train Capacity (passengers)}}{\text{Desired System Capacity (pphd)}}$	
$\text{Turnback Headway (s)}$	See descriptions below

Turnback Headway [s]

- Occurs at end stations for pinched loop operations
- Turnback Headway must be less than System Headway so as to not impact capacity of the system

Turnback Switches

Influences on the system capacity are as follows

- Turnback time at end stations determines the minimum possible headway on the system
- Turnback time is dependent on the switch parameter as follows
 1. Track alignment and vehicle speed through the switch
 - Influenced by switch radii, track spacing, spiral lengths
 2. Distance of switch from station
 3. Dual Track Spacing (e.g. side versus center platform)
 4. Switch Position: rear versus front turnback
 - Rear turnback provides higher capacity (pphd) with more trains
 - Front turnback requires fewer trains, but offers lower capacity/longer headway
 5. Signaling and switch beam movement delay times
 6. Switch movement time
 7. Train length
 - Time to pass through the switch

Rear Turnback

Turnback Headway Element (behind station)	Sketch Reference
Pseudo station approach time (t_a)	A → B
+ Signaling delays and switch movement	C, D
+ Pseudo station exit time (t_e)	E → F
+ Signaling delays and switch movement	G, H
=	

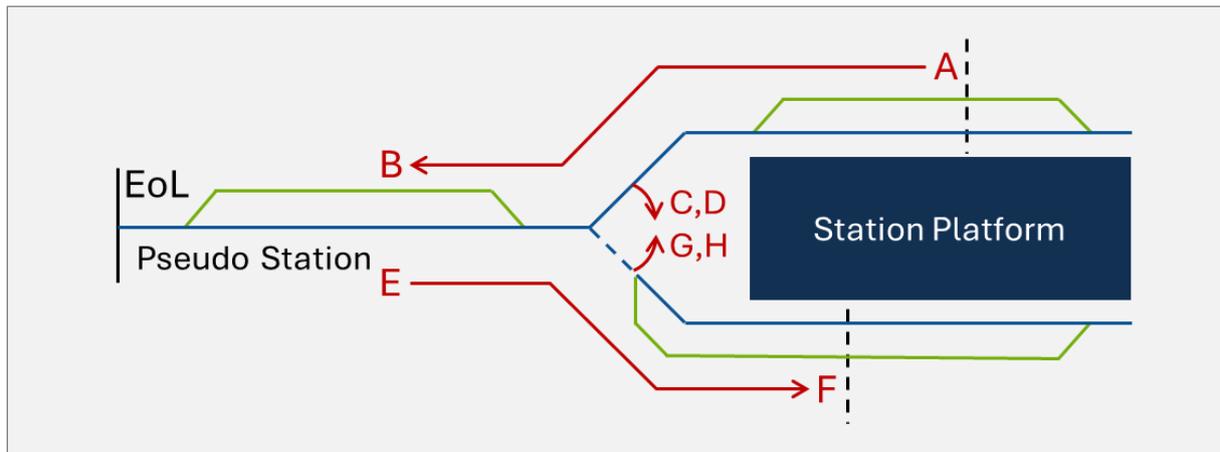


Figure 26: Turnback using rear crossover

Source: Illustration by IMA

Front Turnback

Turnback Headway Element (behind station)	Sketch Reference
E01 Station (platform B) approach time (t_a)	A → B
+ Dwell time at E01 station (t_{dw})	B
+ E01 Station (platform B) exit time (incl. 1s propulsion enable delay) (t_e)	B → C
+ Signaling delays	D
+ Switch movement	E
=	

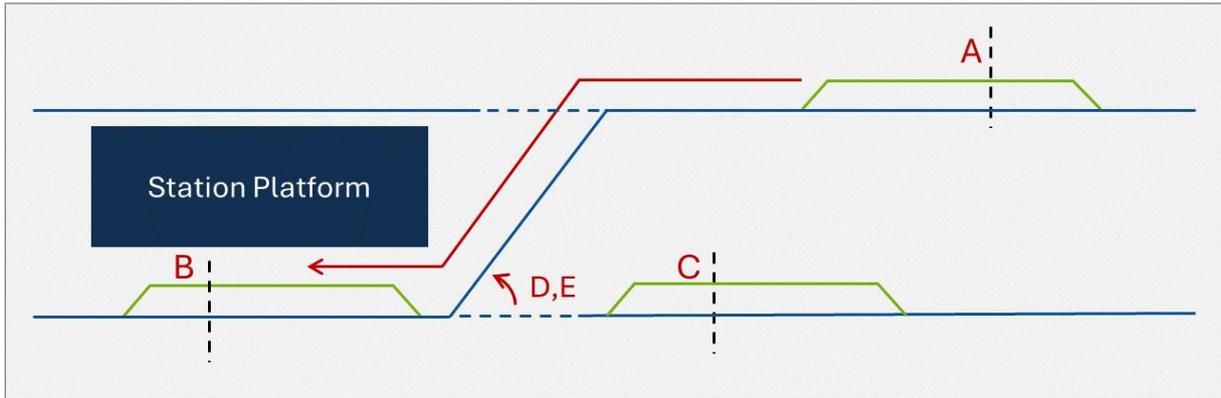


Figure 27: Turnback using front crossover

Source: Illustration by IMA

2.1.6 Monorail Systems

Monorail System

Monorail is a transport system that runs on a single rail. Monorail is a unique mass transit system which can be erected in any congested and crowded city for ease and safe transportation without loss of time. Monorail is a lightweight system, in which, train runs on a narrow guideway beam. The monorail system can achieve turning radius down to 50m.



Figure 28: Monorail Line 15, São Paulo, 2024

Source: Metro SP/IPT

2.1.6.1 A System of Systems

Choosing a turnkey supplier is the most effective approach for optimal rail service that addresses passenger capacity needs. In the cost sensitive world of public transportation, a turnkey supplier is the most efficient choice. System Integration is the process of transforming operational requirements into a system configuration that best satisfies the operational needs of the railway. It incorporates all related technical parameters and interfaces in a manner that optimizes the entire system. It also combines the efforts of all engineering disciplines and specialties into one single engineering effort.

For system integration to be effective, it requires an expert party to define and control the interfaces to ensure compatibility. This party brings together all subsystems in a logical sequence with appropriate testing at each stage. They also perform the testing and verification process to confirm that the operational requirements are met.

The size of the project depends on the application; regardless, the approach is the same. Partnering for system integration can add significant value. The system integrator is with the developer every step of the way, problem analysis, system selection and design, all the way through to final project realization. The integrator works with transportation authorities and planners on project concept and configuration and can offer appropriate system performance specifications to guide the project. In later stages, working closely with fixed facility designers and architects to ensure fully functional designs for stations, guideways and operations, maintenance and storage facilities (OMSF).

The process of designing a rail system is interactive and iterative between the system integrator and civil and mechanical partners. The customer develops the top-level requirements from the mobility needs of the public, entering this process at different points depending on the particular project. Rail projects take time to establish full conceptual definition, ridership estimates, detailed system requirements and contract terms. The systems engineering approach involves:

- transforming the operational requirements of the customer into a rail system that best meets the daily operational needs
- integrating the related technical parameters and ensuring compatibility of all system interfaces to optimize the complete system
- integrating all engineering disciplines and specialties into one single engineering effort

Systems engineering experts provide a standard methodology for the efficient and effective management of engineering in the design and supply of complete systems. System integration encompasses the engineering activities that fuse the various subsystems into a complete system that will satisfy the requirements of stakeholders.

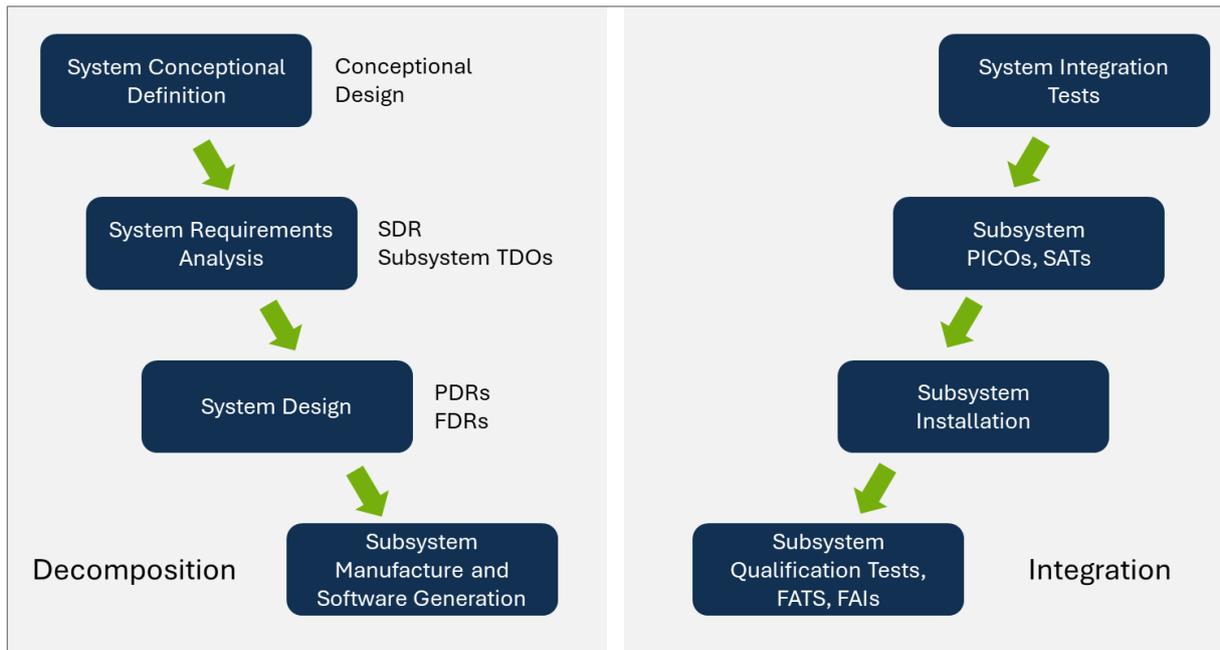


Figure 29: Simplified system engineering cycle

Source: Illustration by IMA

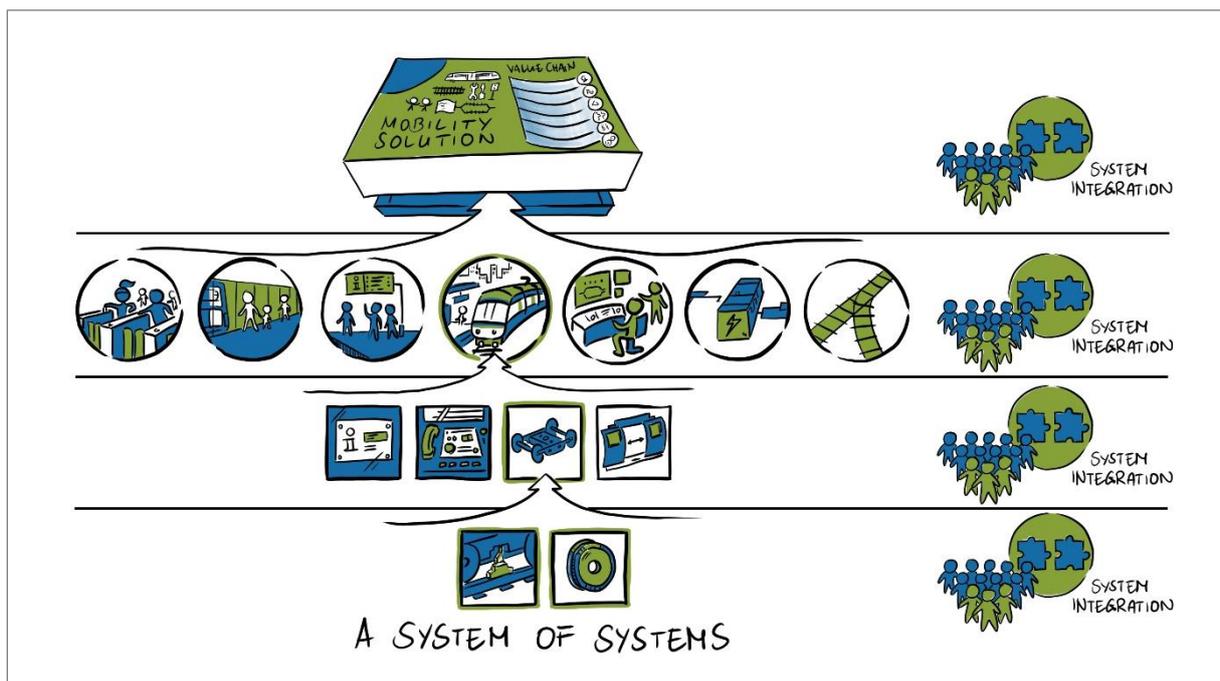


Figure 30: A System of Systems

Source: Illustration by IMA based on Bombardier Transportation

From Left to right: Fare Collection, Platform Screen Doors, Communications, Vehicles, Signaling and Control System, Power Supply and Distribution, Guideway and Civil Infrastructure

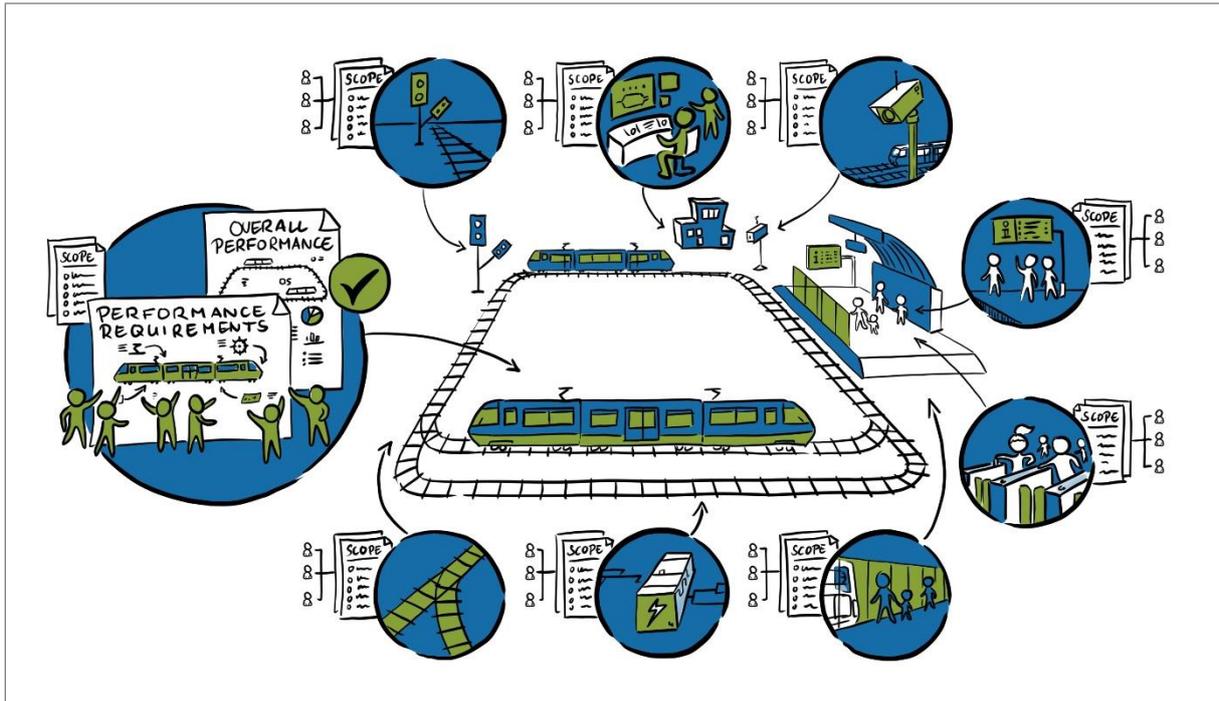


Figure 31: Interfaces to wayside, rollingstock, civil, operation, passengers

Source: Illustration by IMA based on Bombardier Transportation

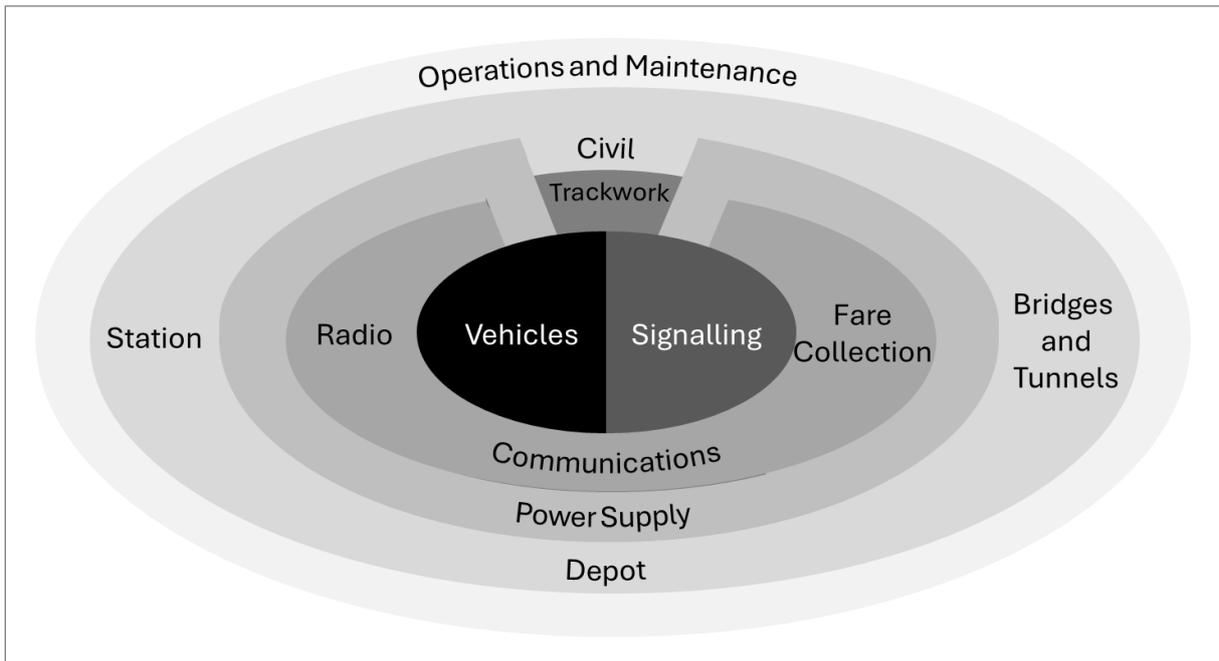


Figure 32: Total Turnkey Systems elements

Source: Illustration by IMA based on Bombardier Transportation

Contractual Work Scope

When designing a system, customers and suppliers need to recognize that there is only one integrated system comprised of three parts – Infrastructure and Electrical & Mechanical Equipment (E&M) Installation and the Operations and Maintenance (O&M) provision. Therefore, its partners must integrate the Civil and E&M scopes through all steps of the project, including

design, supply, construction and installation. This includes coordinating the design effort, including information flow and design review. Typically, the scope of supply breaks down like this:

Table 2: Contractual Work Scope

<p>1. Infrastructure</p> <ul style="list-style-type: none"> ▪ Elevated or at grade guideway structure ▪ Passenger stations ▪ Maintenance depot and storage building ▪ Tunnel, bridges, retaining walls ▪ Sump pumps, ventilation ▪ Fire alarm, building climate/energy control ▪ Equipment monitoring ▪ Ducts, cable trays/ways ▪ Construction/installation safety ▪ Operations control center (room and infrastructure) ▪ Municipal and ancillary civil work ▪ Construction QA
<p>2. Electrical & Mechanical Equipment Installation</p> <ul style="list-style-type: none"> ▪ Rolling Stock ▪ Wayside power supply and distribution (AC/DC) ▪ Track, fasteners, turnouts ▪ Control and Communication Systems ▪ Workshop equipment ▪ Operation and maintenance planning ▪ Platform door system ▪ SCADA ▪ Fare collection system ▪ System safety ▪ Access control requirements ▪ Switch and switch control systems ▪ Test and commissioning ▪ System quality assurance ▪ Power distribution and traction power substations ▪ Installation and wiring
<p>3. Operations & Maintenance Provider</p> <ul style="list-style-type: none"> ▪ Infrastructure ▪ Electrical & Mechanical Equipment

Design Process

In the early stages, the customer develops a fundamental rail system design. At this stage, they will determine where the guideway goes, where stations are located and how many passengers will be using the system during peak- and off-peak hours and what their travel patterns will be.

Based on the fundamental system design, the process for the E&M scope focuses on operations analysis, dealing with normal operation and failures. It is iterative with top-level train design determining the composition of trains, their frequency and number required to meet the passenger service demands. Working with the service patterns and the system availability

requirements to determine the availability allocation to major subsystems. To do this, it requires wayside alignment details including location of stations, crossovers and location as well as the values for grades, curves and superelevation, which means working closely with the civil guideway designers, performing subsidiary but critical tasks, to provide additional design requirements and constraints for subsystems.

Then developing plans to cover noise control, electromagnetic capability (EMC), maintainability, a system safety program, RAMS (reliability, availability, maintenance and safety) and a system security plan. The early fundamental system design enables the civil partners to develop the first level design of the E&M subsystems and elements of the civil infrastructure. The civil partners require an initial estimate of the E&M requirements. Participating together in meetings and review a preliminary version of the Civil Design Interface Manual. The degree of detail in this manual depends on when the partner issues the design process and how much existing technology is already in use.

Systems Integration

The systems integration team is responsible for integrating the engineering activities from various subsystems into a complete system designed to satisfy the requirements of the stakeholders. Their tasks consist of:

- hierarchical decomposition of requirements and allocation to subsystems
- identification and derivation of system safety requirements
- transformation of operational requirements into a system configuration to best satisfy operational needs
- identification and quantification of system goals
- creation of alternate system design concepts
- performance of design trade-offs
- selection and implementation of a balanced and robust design
- design verification properly integrated in accordance with specifications
- providing performance analysis and system simulations
- ensuring compatibility of all system interfaces in an optimal manner
- integrating efforts of all engineering disciplines and specialties (such as RAMS) into a cohesive effort

System Simulation

Using simulation studies and various simulation tools to validate requirements. The simulation tools analyze train performance, the impact of the track configuration, the effects of different signaling and propulsion systems, the impact of system delays and failures, and systems operational safety and robustness, and can be used to calculate headway and line capacity. For example, using software to simulate train performance and system operation under signaling and propulsion types, and this is a key part of the proposal design and optimization process. Validating the simulation tools to industry standards in advance.

System Performance Analysis

The system integrator is responsible for ensuring the system meets the performance requirements and that the wayside subsystems understand these requirements. Preparing the

System Performance and Failure Management Analysis document that describes the design failure routes to use on the system, the performance levels of the system under normal and specific failure modes, failure route descriptions, restrictions, line capacity, safety and stopping distances, and vehicle parameters including capacity, weights, and emergency brake rates. The Energy Efficient Guideway Design describes the steps to produce an energy efficient guideway design and include round-trip times, and calculations for headway and passenger flow, power consumption and distribution, and safe train separation.

Requirements Engineering and Management

The system integrator uses the Requirements Management Process to ensure customer, supplier and internal requirements are properly managed throughout the lifecycle. The Requirements Development Procedure is the process used to develop all project design requirements and provides the definition and analyses of the customer requirements, and the product-derived requirements. The Requirements Traceability Matrix or Systems Compliance Verification Matrix ensures that tracing all requirements to project completion.

Systems Design

The system integrator develops the system architecture from the customer and contract specification using our standard products to the maximum extent possible, provide overall system design and integration, review and approve subsystem designs and technical requirements descriptions, and evaluate designs for compliance to system design requirements and contract technical specifications.

2.1.6.2 Outline of the Monorail

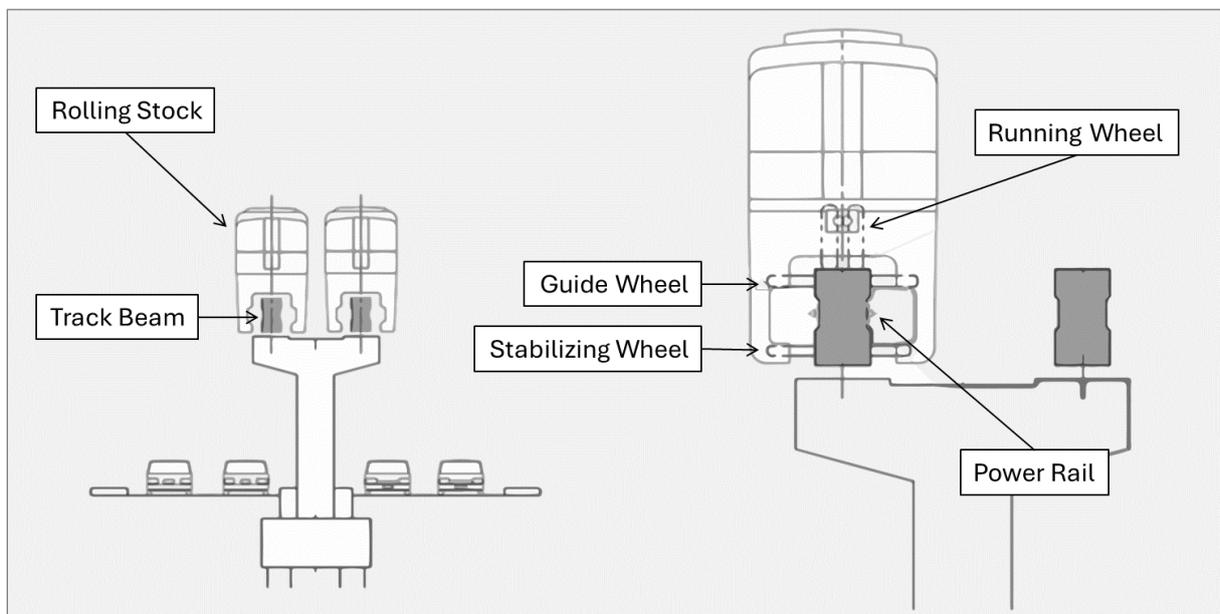


Figure 33: Outline of the monorail system

Source: Illustration by IMA

Monorail straddle type

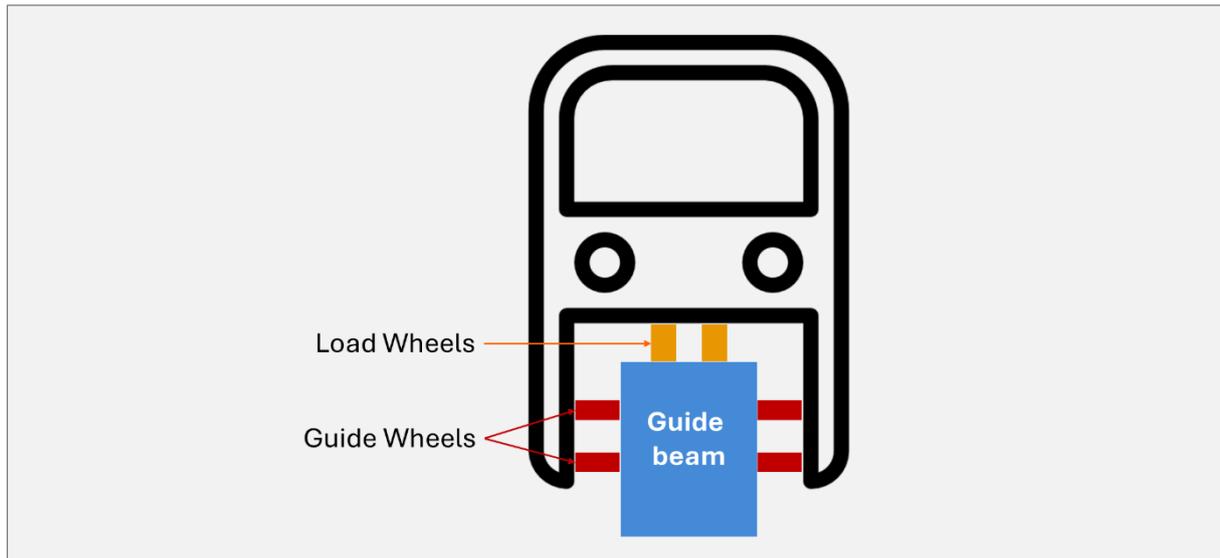


Figure 34: Guideway elements

Source: Illustration by IMA

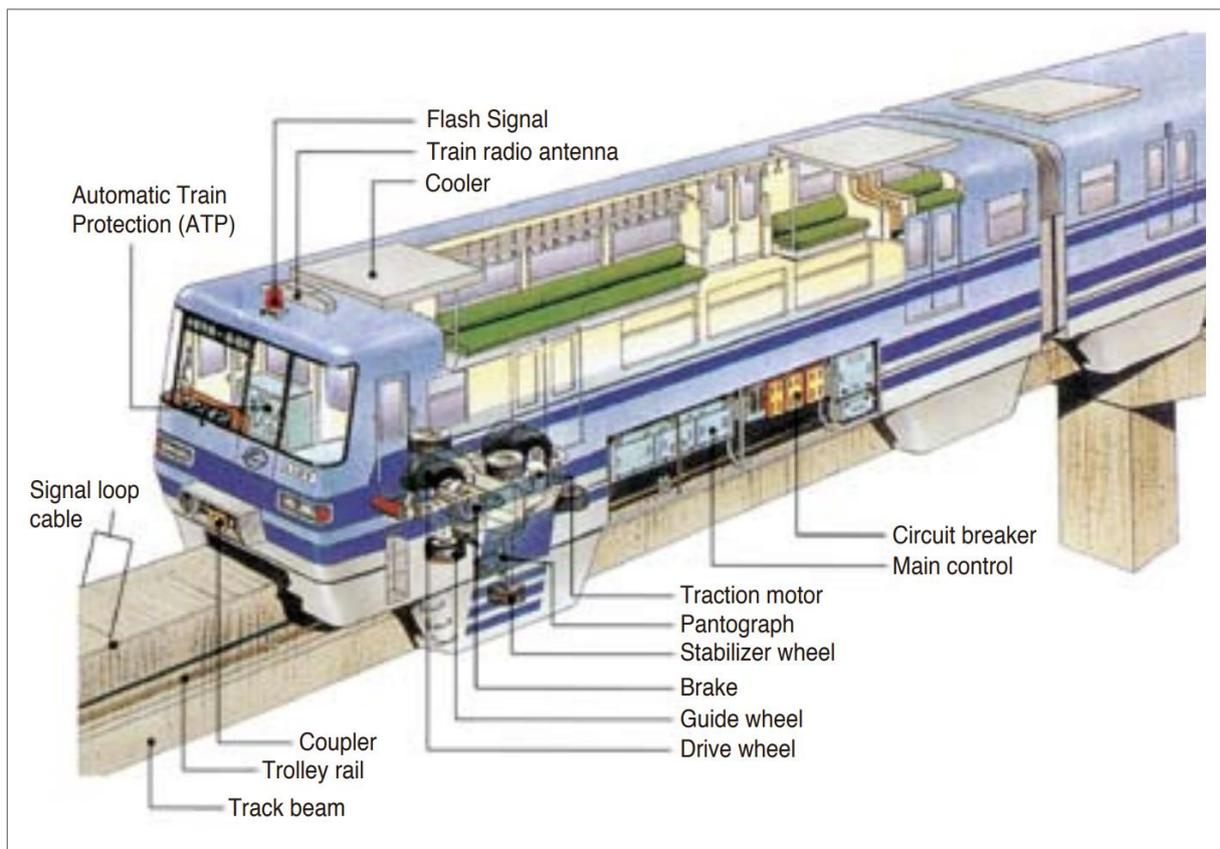


Figure 35: Subcomponents of straddled monorail

Source: Japan Monorail Association based on Hitachi Rail

Monorail suspended type

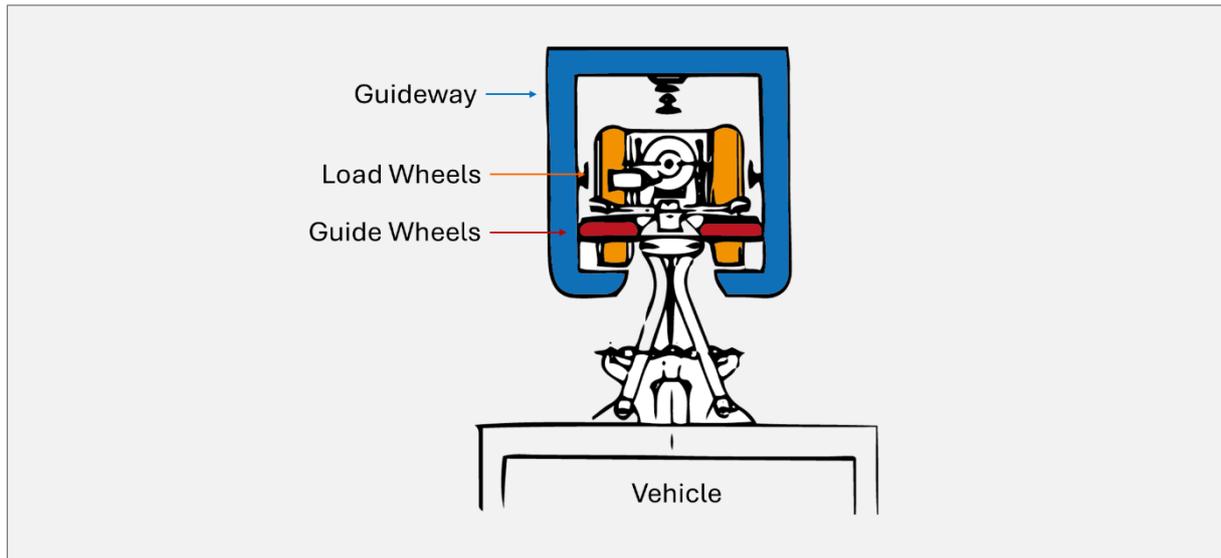


Figure 36: Track of SAFEGE Monorail

Source: Illustration by IMA

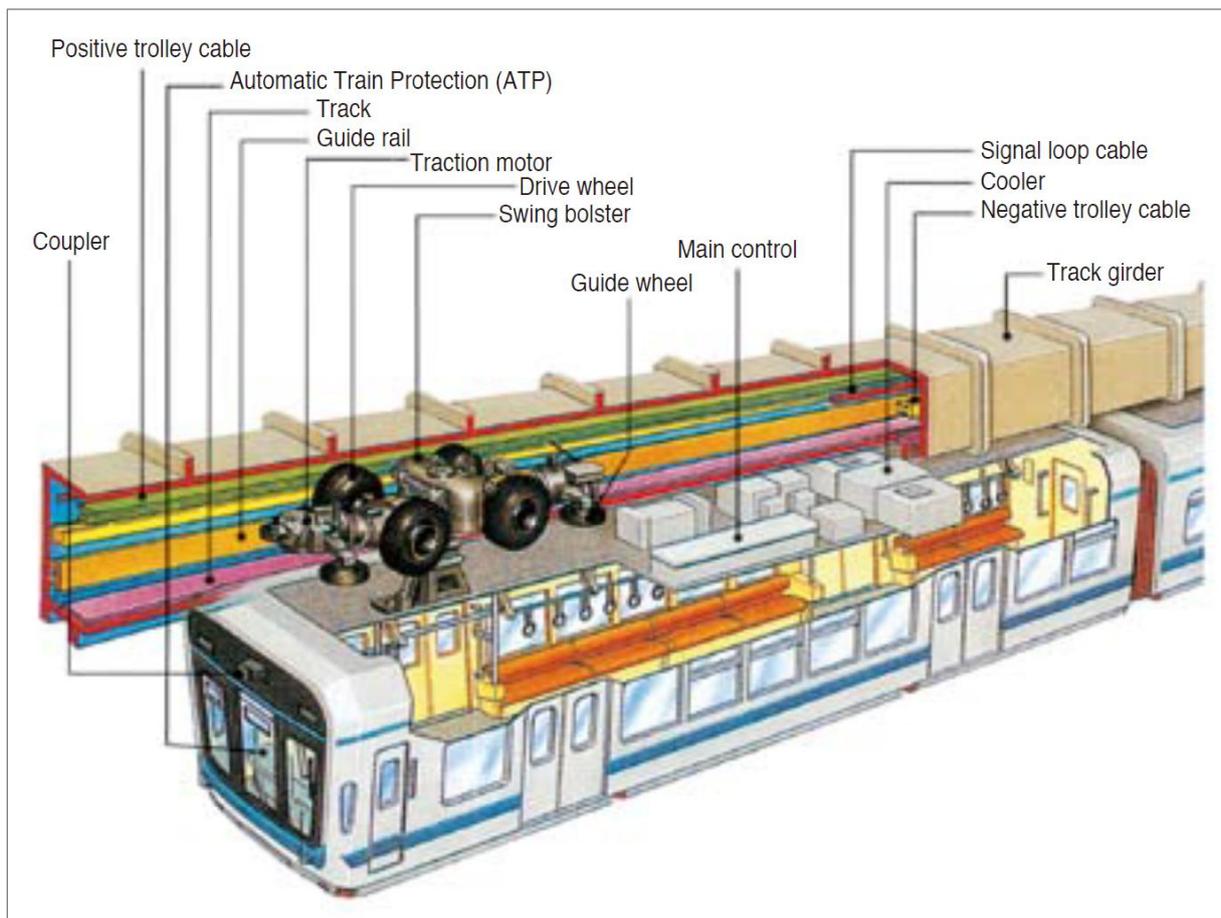


Figure 37: Subcomponents of suspended monorail

Source: Japan Monorail Association based on Hitachi

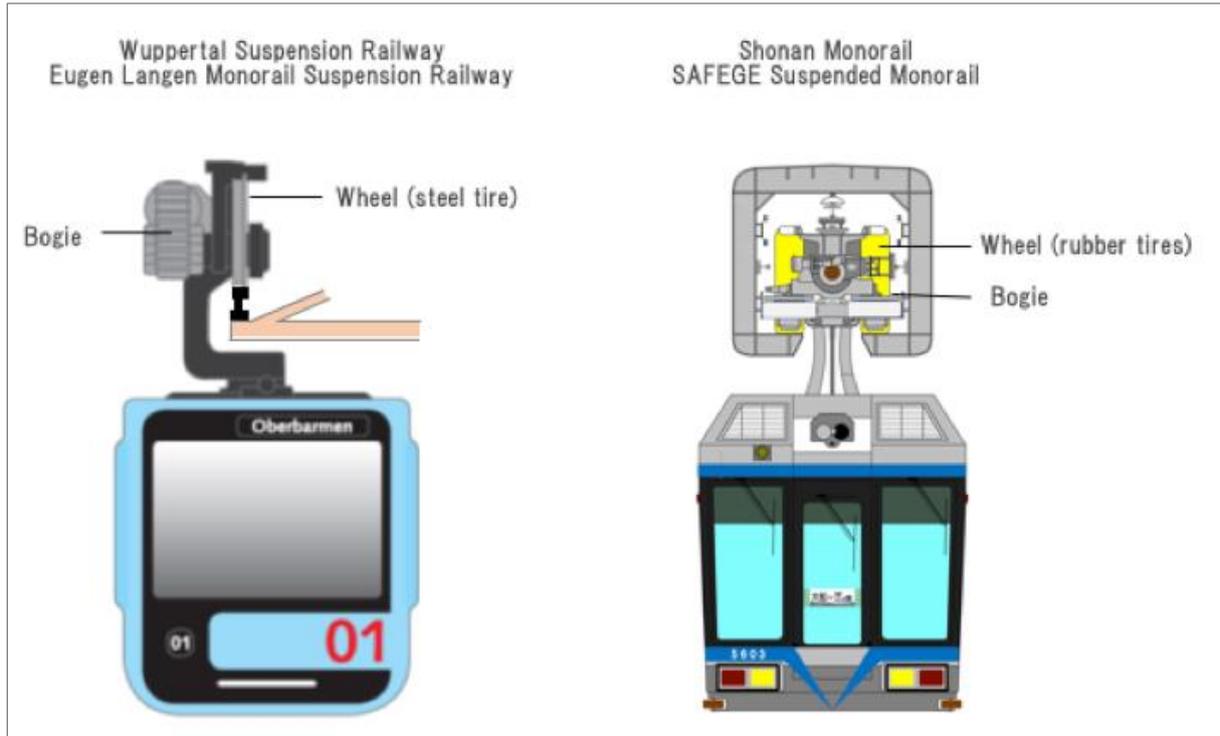


Figure 38: Comparison of suspended monorail types Eugén Langen vs. SAFEGE

Source: Japan Monorail Association

2.1.6.3 Stations & Alignment

Monorail stations can use central or lateral platforms, depending on the necessities of the project and the space available. Usually, the stations have two levels, a mezzanine with ticketing facilities and system rooms, and the platform.

Passenger stations serve as the interface between the vehicles and the facilities the system serves. Access mezzanines can be placed above or below the boarding platforms offering design flexibility. When possible, the boarding access to the platforms can be designed from street level with sufficiently wide medians (about 6m). With careful station planning, passengers can more safely, efficiently, and easily move into and out of the system.

Station Equipment

- Passenger Information Displays
- Public Address
- Platform Screen Doors
- CCTV
- Emergency Stop



Figure 39: Station with central platform (Okinawa monorail), 2024

Source: Photo by Rodolfo Szmidke



Figure 40: Station with side platforms (Kitakyushu Monorail), 2024

Source: Photo by Rodolfo Szmidke

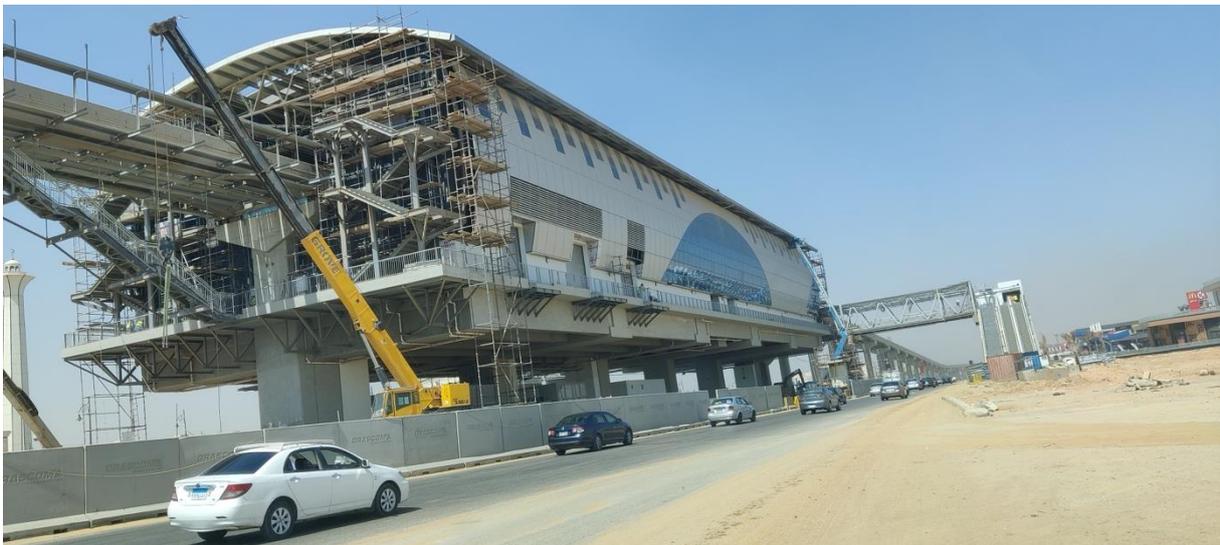


Figure 41: East-of-Nile Cairo Monorail Station under construction, 2024

Source: Photo by Ahmed Ghallab



a) Connection between switch and station

b) Connection between guideway beams and station

Figure 42: Different types of connection between main line and station (East-of-Nile Station under construction, Cairo, 2023)

Source: Photo by Ahmed Ghallab



Figure 43: East-of-Nile station under construction, Cairo, 2023

Source: Photo by Ahmed Ghallab

2.1.6.4 Main line structures

Monorail lines allow mainline structures with tight radius curves, superelevation (cant) up to 10%, and slopes of up to 6% gradients with fully automatic modes of operation rather than other transit systems.

Structural system of monorail consists of:

- Guideway beams
- Pier caps
- Columns / Straddle bents
- Piles

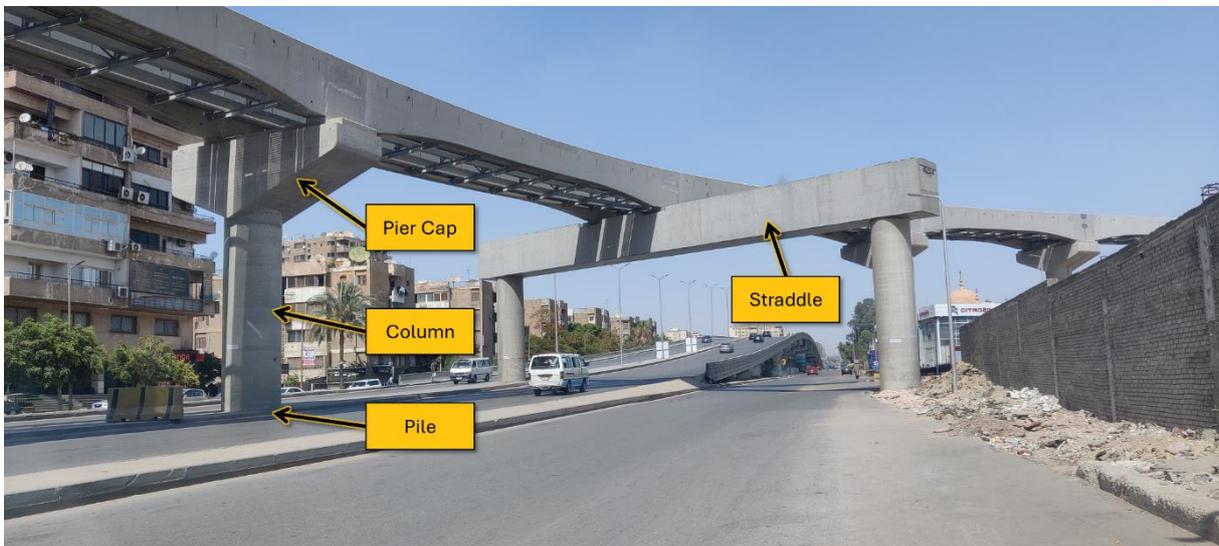


Figure 44: East-of-Nile Cairo Monorail, 2023

Source: Photo by Ahmed Ghallab

Expansion columns located at distances between 100 to 150m contain steel expansion joints, and pintels between structures that provide displacement compatibility between adjacent structures, or mechanical bearings to allow for the expansion and contraction of the structures.

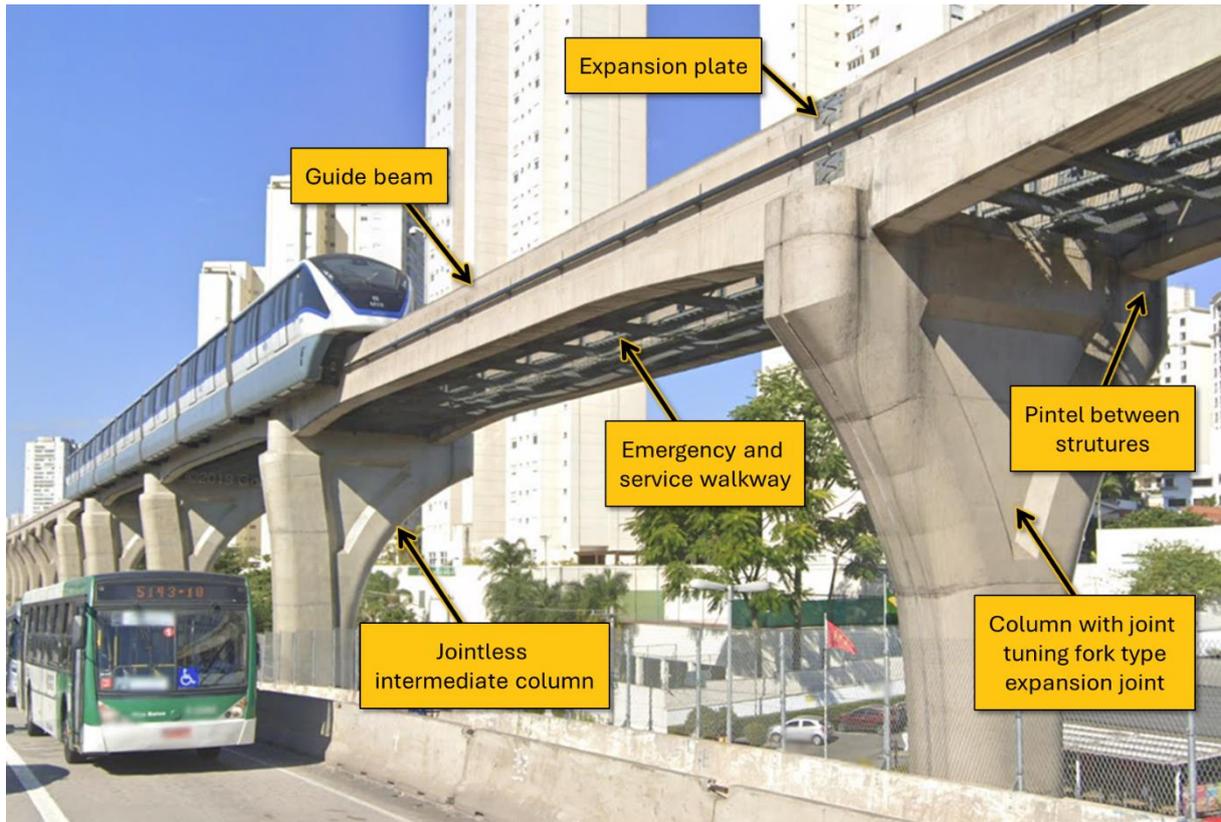


Figure 45: São Paulo Line 15, 2019

Source: Google Street View

Some monorail lines have different structure configuration. Besides having a continuous guideway on 120m, they have joints on the beam at each collum with bearings and finger plates, so they have nearly 20m of spam. When they need to have a bigger spam, they use metallic beams.



Figure 46: Tama Monorail Structure

Source: Photo by Rodolfo Szmidke, 2024

SAFEGE monorails use a continuous steel box beam fixed on columns, so they have different spans depending on the necessity of crossing streets, roads, rivers, etc. They also have joint expansions, and they use finger plates to allow the comfort movement of the train.



Figure 47: Chiba Monorail Structure

Source: Photo by Rodolfo Szmidek, 2024

The following pictures contain different aspects of mainline structures such as concrete and steel guideway beams, columns, assembly of guideway beams.



Figure 48: Osaka Monorail, 2024

Source: Photo by Rodolfo Szmidke

Finger plates are metallic structures used at the guideway joints to provide comfort to the passengers when the train passes on the joint. It is composed of base plates that are fixed on the concrete structure of the guideway, and finger plates that are fixed on the base plate with bolts. The size of the teeth of the finger plate depends on the type of structure, being longer when the continuous structure has 120m, and smaller on the case of the joints on each collum.



Figure 49: Finger plate from São Paulo monorail



Figure 50: Finger plate from Okinawa monorail

Source: Photo by Rodolfo Szmidke, 2015 and 2024



Figure 51: Finger plate from SAFEGE Chiba Monorail



Figure 52: Finger plate from SAFEGE Shonan Monorail

Source: Photos by Rodolfo Szmidke, 2024

Pintels are metallic devices that limit the transversal movement of the structures, allowing the longitudinal movements, like the expansion and contraction of the concrete/steel materials from the temperature variation. It is usually composed of one internal metallic component filled with grout and two metallic gloves that will provide the movement.

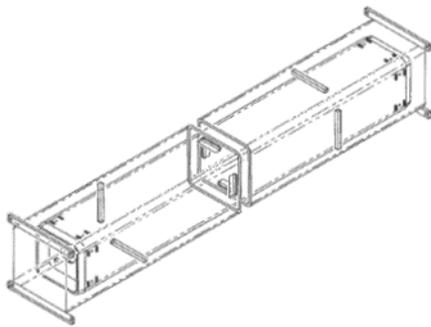


Figure 53: Pintel design

Source: São Paulo Metro



Figure 54: Pintel structure at Santiago de Los Caballeros monorail

Source: Photo by Maikel Garcia, 2024

Bearings are components installed under the beams and have a similar function to the pintels, avoiding transversal movements of the structure while allowing the longitudinal expansion and contraction of the materials. The bearings can be fabricated using elastomeric materials or with steel components.



Figure 55: Osaka monorail steel bearing with Seismic Restrainer



Figure 56: Bangkok monorail with bearing

Source: (55) Photo by Rodolfo Szmidke, 2024, (56) Carlos Banchik, 2024



Figure 57: Civil construction of Cairo Monorail, 2023



Source: Photo by Ahmed Ghallab

The following pictures contain more pictures of monorail mainline construction.



Figure 58: Cairo Monorail, 2023



Source: Photo by Ahmed Ghallab

2.1.6.5 Switches

These structures allow the redirection of trains. There are two main types based on their operation; simple beam replacement switches consist of one or many steel beams with a fixed pivot and free ends, or more complex segmented switches with beams composed of short segments that are configured to redirect the trains. A pivot switch is shown below.

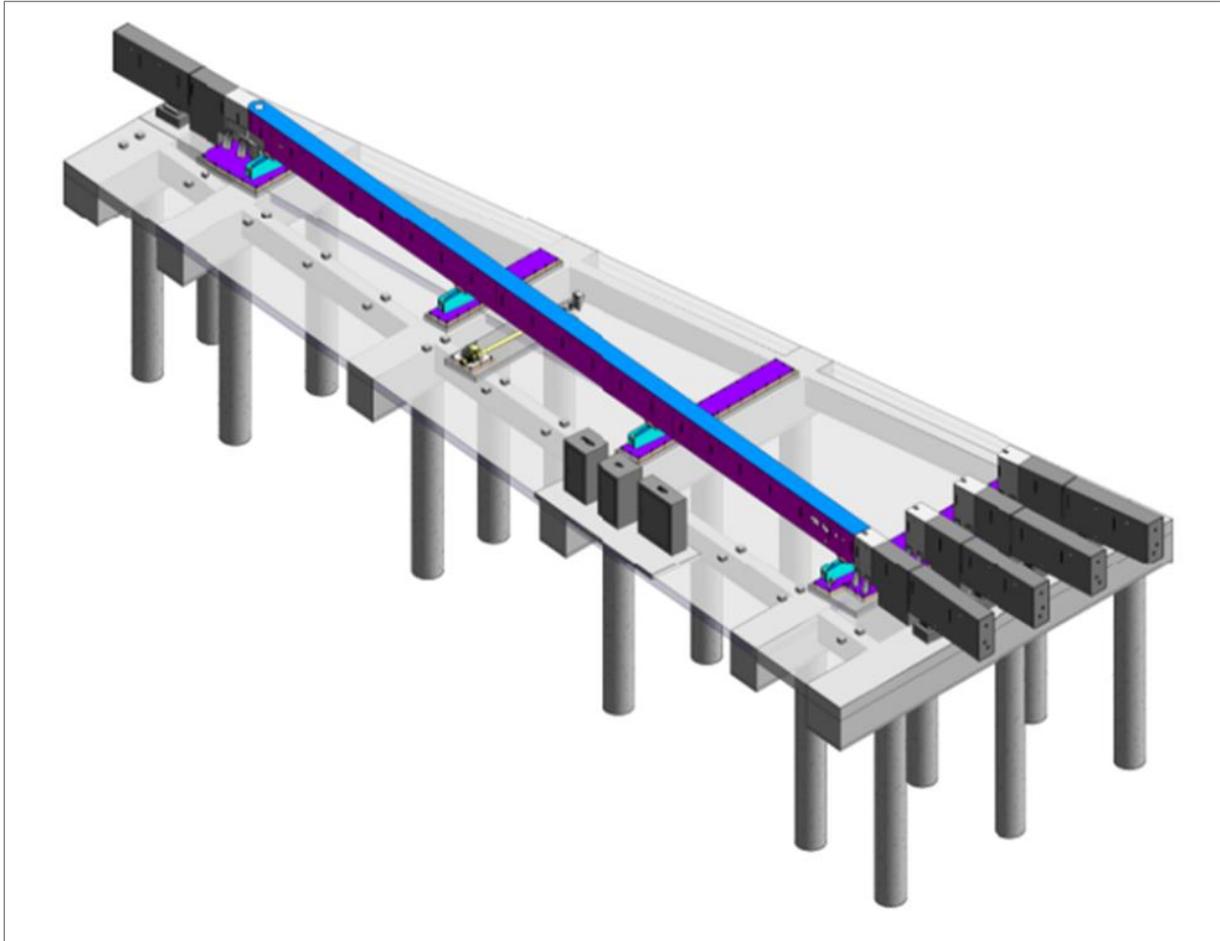


Figure 59: Pivot switch

Source: Innova (2024)

The switch below is a series of segmented switches that allow the feeding of spur lines off a mainline in an iconic installation in Osaka Monorail.

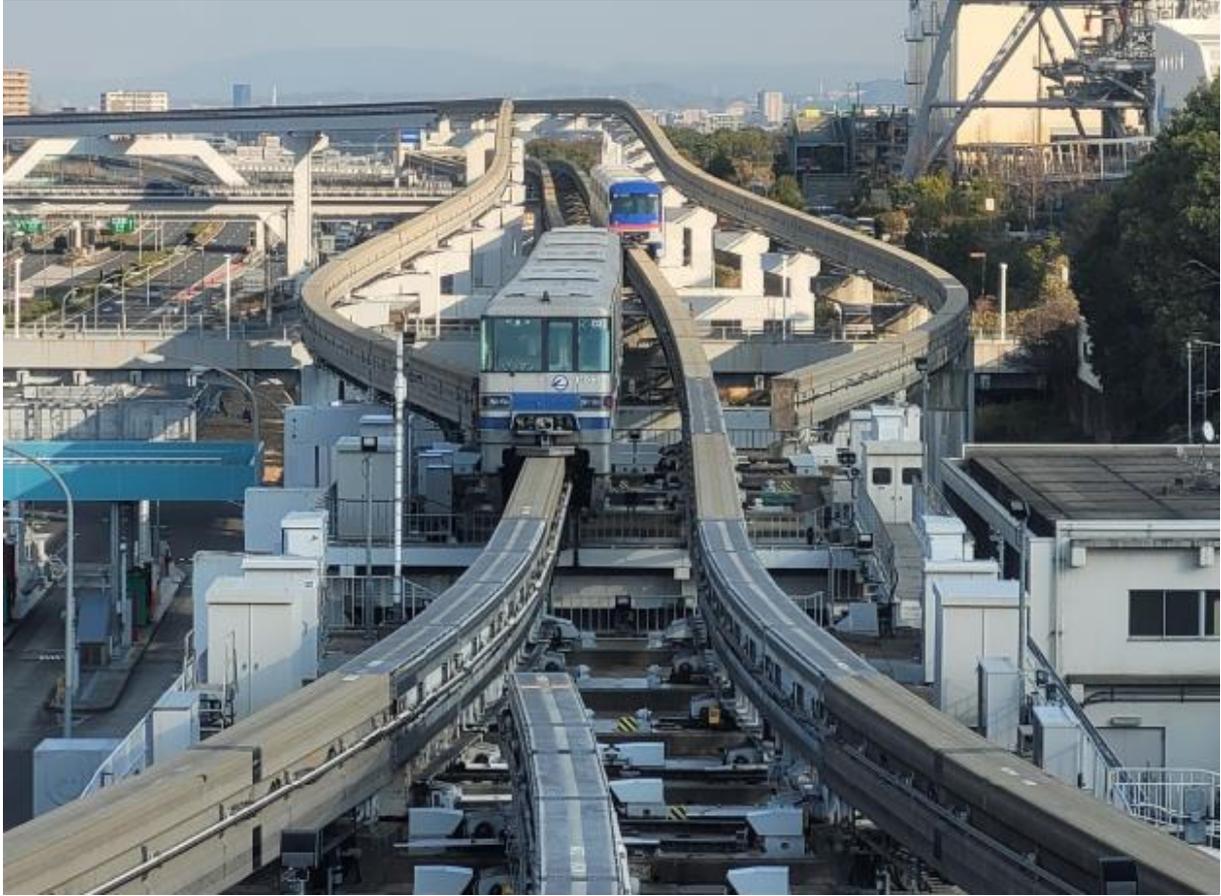


Figure 60: Osaka Monorail, 2024

Source: Photo by Rodolfo Szmidke

The switch below is a crossover segmented switch.



Figure 61: Switch of Okinawa Monorail, Japan, 2024

Source: Photo by Rodolfo Szmidke

2.1.6.6 Emergency Walkway

The walkway is a passive system wide walkway that provides enhanced passenger safety without compromising visual aesthetics'. NFPA 130 requires the installation of continuous means of evacuation along the mass transit alignment.

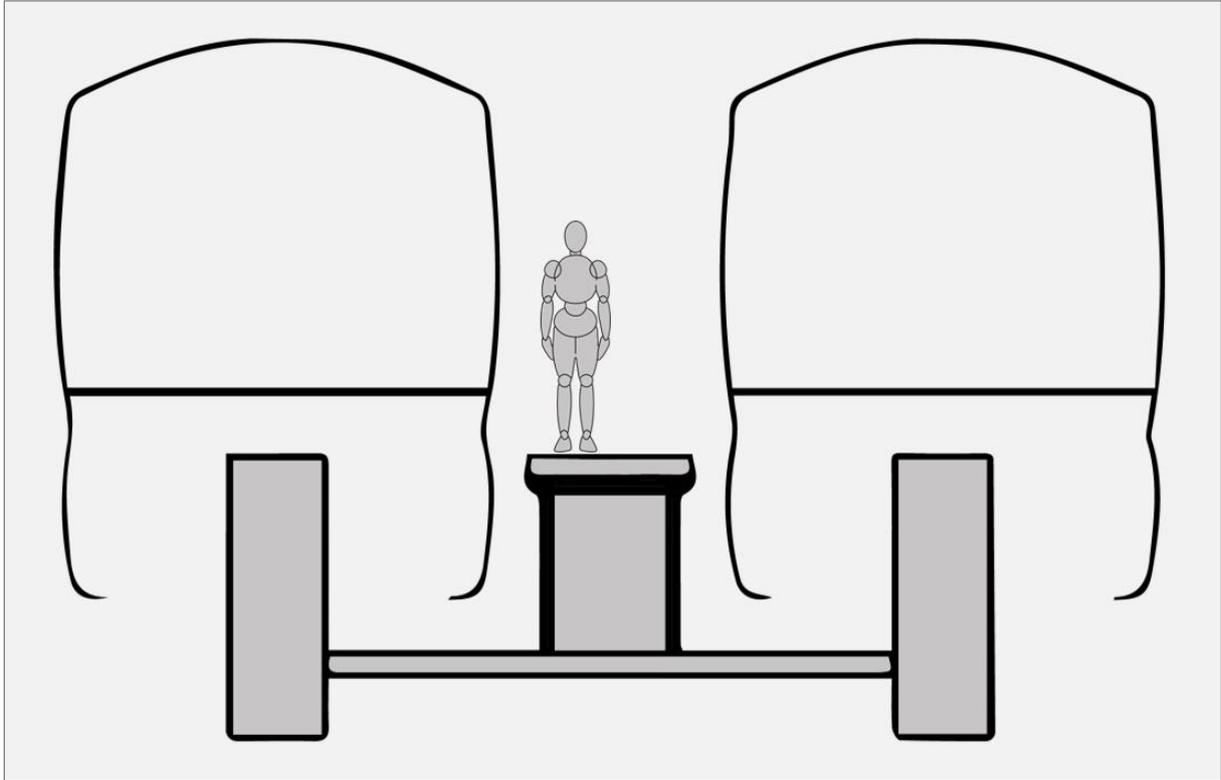


Figure 62: Emergency guideway in the middle of dual lane track structures, same level as vehicle floor height

Source: Illustration by IMA based on Bombardier Transportation

Pictures below show a sample of emergency evacuation structures from Line 15 in São Paulo and the first installation in Las Vegas Monorail circa 2002.



Figure 63: Track, Line 15 São Paulo, 2017

Source: Photo by Rodolfo Szmidke



Figure 64: Emergency Guideway and cable way, São Paulo Line 15, 2023

Source: Photo by Rodolfo Szmidke



Figure 65: Las Vegas Monorail during construction, 2002

Source: Photo by Carlos Banchik

2.1.6.7 Vehicle Dynamic Envelope

The vehicle dynamic envelope is the minimum clearance on all sides of the vehicle. These dimensions account for the space of the vehicle in motion.

The vehicle structure gauge is defined as the clearance to any permanent obstruction or structure, and is based on the vehicle dynamic envelope, built up to include additional effects due to chording in the middle of the vehicle or overthrow at its nose or tail, superelevation, construction tolerances and running clearances.

According to p-REES Module 1-F Railway Alignment Design and Geometry the following items are typically included in the development of the Vehicle Dynamic Envelope:

- Static vehicle outline
- Dynamic motion (roll) of springs and suspension/bolsters of vehicle trucks
- Vehicle suspension side play and component wear
- Vehicle wheel flange and radial tread wear
- Maximum truck yaw (fishtailing)
- Maximum passenger loading
- Suspension system failure
- Wheel and track nominal gauge difference
- Wheel back-to-back mounting and maintenance tolerance

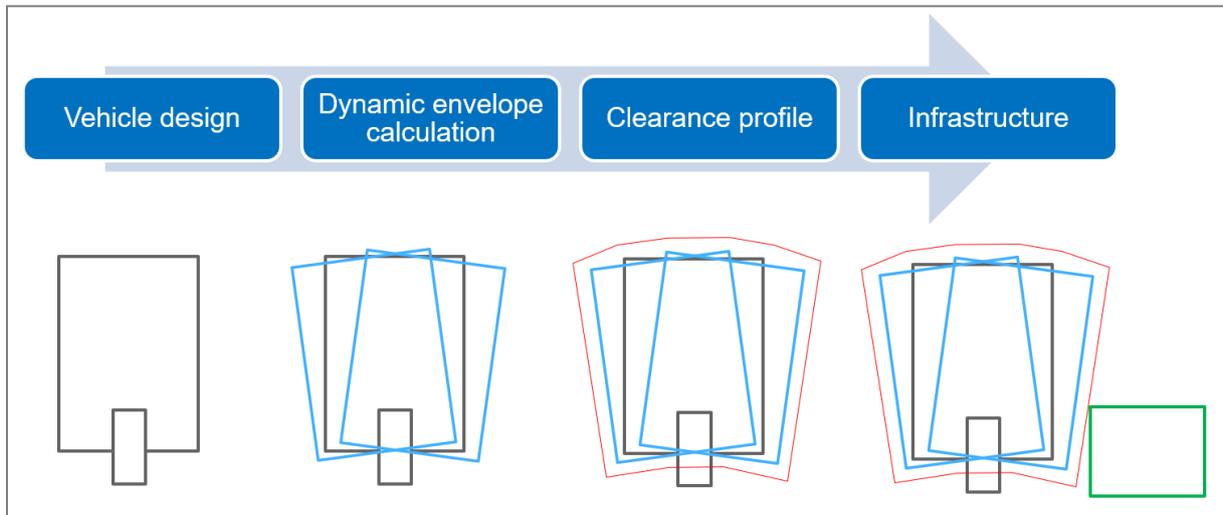


Figure 66: Process of defining the clearance gauge

Source: Derap AG, illustration by IMA

2.1.6.8 Depot and Maintenance Facilities

Depots allow for the centralized cleaning, maintenance and storage of trains. They contain a series of pivot switches that allow the trains to be distributed in different facilities based on the needs.

A maintenance depot is normally provided that includes a workshop area that accommodates access to roof-mounted, interior and undercar equipment on the vehicles, an electrical shop, a machine shop, equipment areas for brake, HVAC, propulsion systems, a storage area for parts and tools, utility facilities, and personnel and office space.



Figure 67: Line 15, Oratorio Depot, 2024

Source: Photo by São Paulo Metro/IPT



Figure 68: Kitakyushu Monorail, 2024

Source: Photo by Rodolfo Szmidke



Figure 69: São Paulo Line 15 Depot

Source: Photo by Viviane Ricarda Lima Veiga, 2020



Figure 70: Tokyo Haneda Monorail, 2024

Source: Photo by Rodolfo Szmidke

2.1.6.9 Monorail Bogie Maintenance Workstation

The monorail bogie maintenance workstations (BMWS) are inserted into a monorail train concrete rail beam to facilitate removing and installing one or more monorail train bogies.



Figure 71: Monorail bogie maintenance workstation inserted in concrete beam

Source: Handling Specialty, Grimpsy, Canada

Operators are able to utilize a sophisticated control and user interface screen to access a single BMWS, which in turn allows access to a single bogie unit. Alternatively, the screen can be used to activate up to four monorail bogie maintenance workstation units, thereby enabling access to bogies on two rail cars simultaneously.

The systems facilitate the hydraulic detachment of the bogie(s) from the train car through the provision of a supporting mechanism. Subsequently, an electromechanical drive is engaged to lower the bogie and traverse outward from the monorail beam, thereby facilitating comprehensive access to the bogie.

The process allows operators to perform maintenance tasks on the bogie unit or replace it entirely by reversing the aforementioned process.

The BMWS may be utilized in either an individual or synchronized mode. The operator utilizes the synchronized mode during the 'Bogie Removal' and 'Bogie Installation' processes. This mode enables the lifts to travel in unison with one another. Individual mode, on the other hand, facilitates the movement of individual lifts with detached bogies, following the synchronized

portion of the ‘Bogie Removal’ process and preceding the synchronized portion of the ‘Bogie Installation’ process.



Figure 72: Monorail bogie maintenance workstation

Source: Handling Specialty, Grimpsy, Canada

General Sequence of Operations

Home Position

In the home position, the BMWS units are in line and the platform flush with the top of the monorail beam. The BMWS locking bars are fully extended into the side/center supports and the bogie supports are flush with the lift/beam.

Removing Bogie

The following operations are initiated through the HMI with BMWS in home position:

1. Position Bogie: Operator positions cars so that bogies are centered on the BMWS units.
2. Support Bogie Frame: Bogie support cylinders extend coming into contact with the bogie and supporting the bogie frame.
3. Position Jacks: Operator manually positions and raises the jacks until jack is in correct position, touching monorail train.
4. Retract Locking Bars: The BMWS raises above home position to take pressure off locking bars which are then retracted.

5. Lift cars to fully raised position: The BMWS platform raises until the pre-programmed height is reached. The raised position allows the operator to position the support stands under the cars.
6. Placement of Car Support Stands: Operator places support stands under cars and adjusts support stands to engage car body.
7. Retract Side Plates: The BMWS side plates retract taking pressure off the run tires.
8. Cars lowered onto Support Stands: The BMWS lowers until the cars are resting on the car support stands. This motion transfers the weight of the cars onto the car support stands and unloads the secondary bogie suspension.
9. Operator unfastens bogie from car.
10. Fully Lower Individual BMWS: BMWS fully lowers platform to allow the bogie to clear the underside of the car.
11. Traverse Individual BMWS's to maintenance position: The BMWS loaded with the bogie traverses perpendicular to the monorail beam into the bogie maintenance position.
12. Individual BMWS's can now be operated independently through the hand-held pendant in local mode.

Installing Bogie

The following operations are initiated through the HMI with the BMWS in the maintenance position:

1. Operator places bogie in correct position on BMWS.
2. Traverse Individual BMWS's to home position: BMWS Traverse Motor moves BMWS toward Home position. Traverse continues until HOME traverse limit switch is reached.
3. Align Individual Bogies and Load Secondary Suspension: The BMWS raises as required in order to re-connect the bogie to the car and load the secondary suspension. Lift Motors raise the platform until a pre-programmed height is reached which loads the secondary suspension but does not lift the vehicle off the support stands.
4. Extend Side Plates on Individual BMWS: Bogie Support cylinders extend to maintain pressure on bogie. Side Plate cylinders extend.
5. Operator inspects all BMWS's and then places all local pendants in remote mode. At HMI, place system in synchronized mode.
6. Cars are raised to maximum height which lifts the cars off of the support stands.
7. Remove vehicle support stands.
8. Lower car to home position and locking bar cylinders extend thereby transferring weight of platform and car onto Locking Bars. Bogie Support cylinders retract.

The BMWS is now in the HOME or 'STOWED' position: the BMWS is traversed to be horizontally in line with the guide beam and the lift platform is flush with top of the guide beam. The Locking Bars are extended and inside the side supports and/or center supports.



Figure 73: São Paulo Line 15 bogie maintenance, 2020

Source: Photo by Viviane Ricarda Lima Veiga

2.1.6.10 Central control and equipment rooms

Equipment rooms house the power distribution equipment, train control and communications equipment, and central operations control room. Planners typically locate equipment rooms near stations and the maintenance facility.



Figure 74: Operations and control center, São Paulo Line 15, 2023

Source: Photo by Marko Kroenke

2.1.6.11 Train Power Substation

Buildings to get the energy from the power supply and connect to the monorail line.

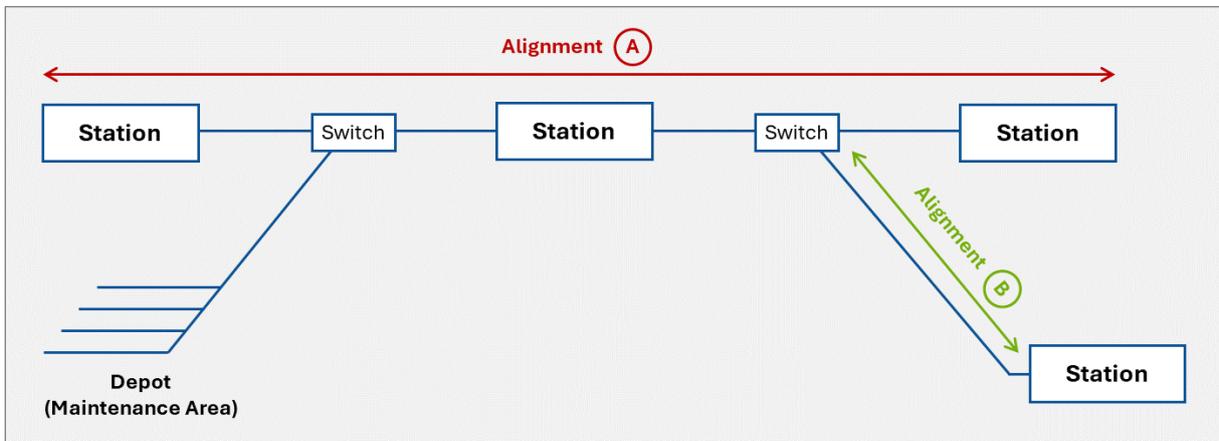


Figure 75: Schematic of monorail power supply for buildings and line

Source: Illustration by IMA

2.1.6.12 Power Supply and Distribution

Two independent medium-voltage AC transmission lines or cables typically supply the system with AC power. One of these transmission lines serves as the primary power supply, while the second serves as a backup. This power is converted to DC for distribution to the Monorails.

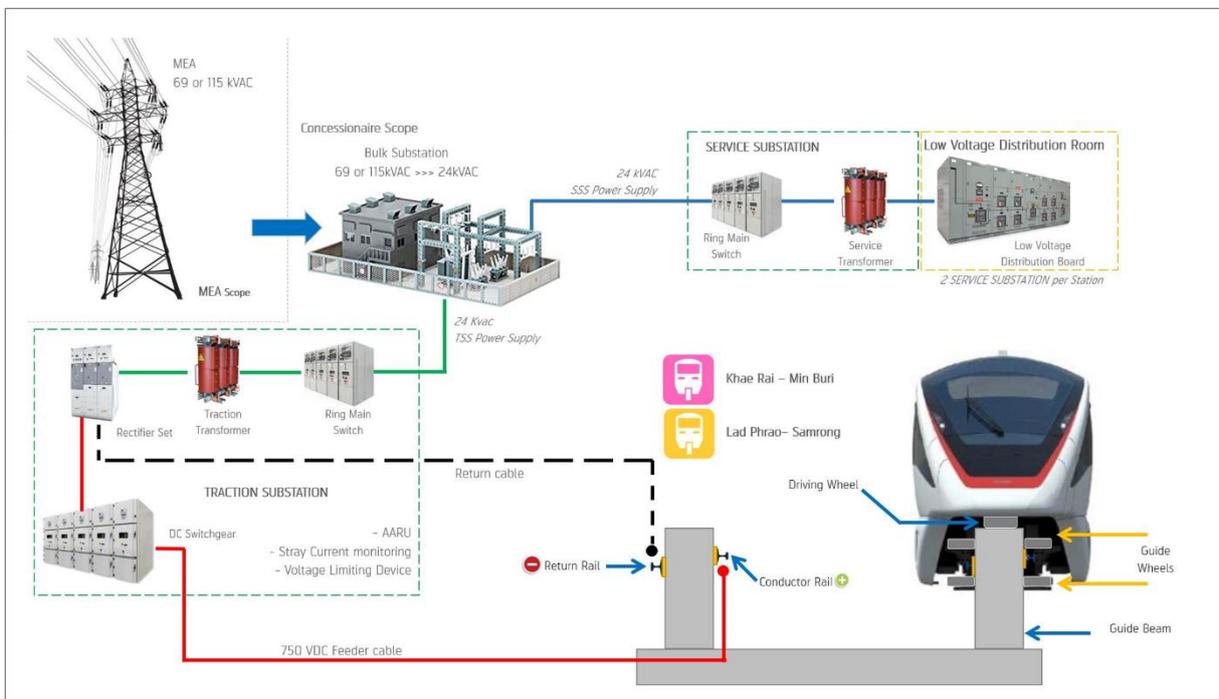


Figure 76: Power supply and distribution system

Source: <https://www.linkedin.com/feed/update/urn:li:activity:7191811617725026304/> based on The Electric Railway System

2.1.6.13 SCADA

SCADA is a control system architecture comprising computers, networked data communications and graphical user interfaces for high-level supervision of machines and processes. It also covers sensors and other devices, such as programmable logic controllers, which interface with process plant or machinery.

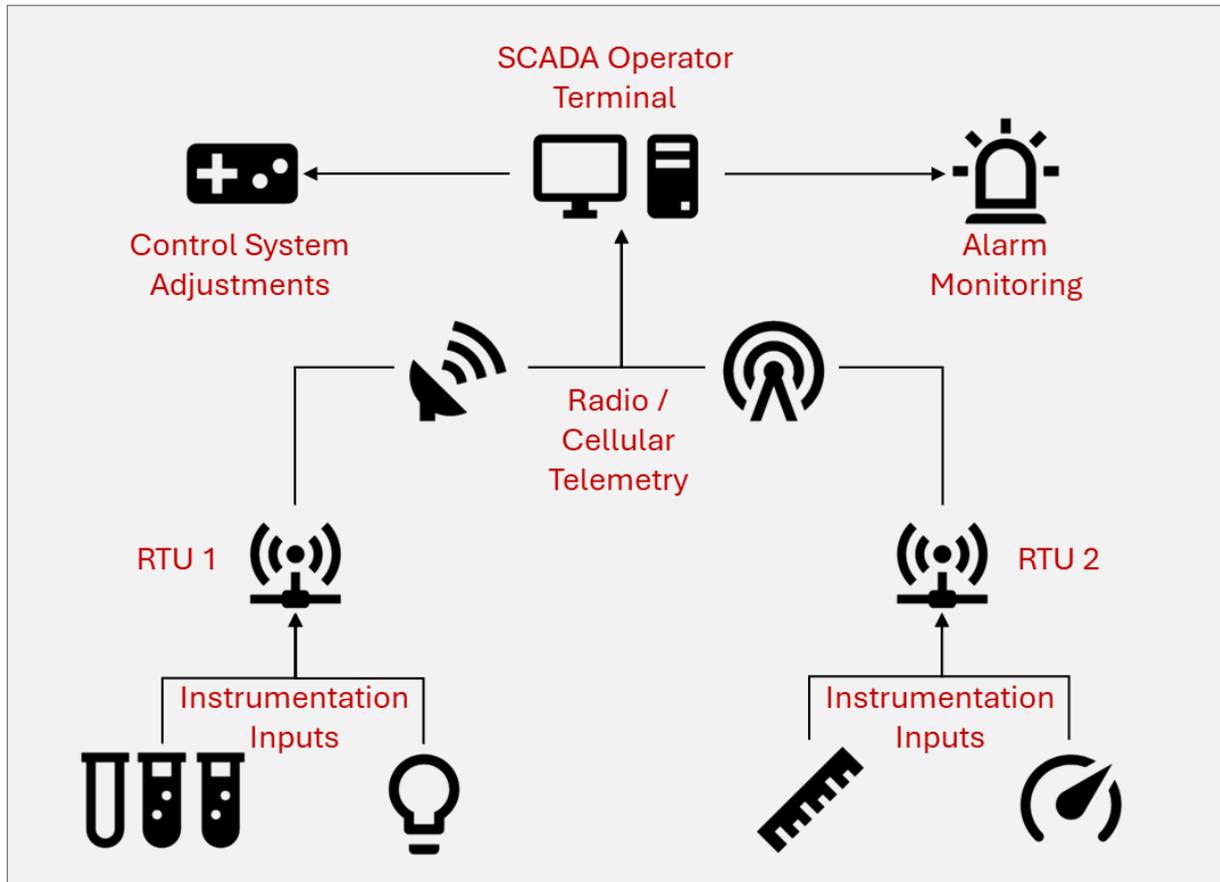


Figure 77: SCADA system components

Source: Illustration by IMA

Referring to the authors of ‘Externetworks’ (<https://blog.externetworks.io/how-scada-is-used-in-rail-operations/#how-scada-systems-are-used-in-rail-operations>) SCADA systems are composed of multiple components, including sensors and actuators, remote terminal units (RTUs), programmable logic controllers (PLCs), a human-machine interface (HMI), and a supervisory computer (SCADA) software. These components work together to collect sensor data and send commands to actuators to control the industrial process being monitored. SCADA systems are typically used in transportation.

SCADA systems use various technologies to collect and process data from industrial processes and equipment. Some of the key technologies used in SCADA systems include:

- **Sensors:** SCADA systems rely on sensors to measure parameters such as temperature, pressure, flow rate, and more. Sensors are typically connected to a programmable logic controller (PLC), which converts the sensor data into digital signals that the SCADA system can process.

- **Programmable Logic Controllers (PLCs):** PLCs are microprocessor-based controllers used to control industrial processes and equipment. They are often used to control motors, valves, and other devices that are used in industrial automation. PLCs can be programmed to respond to specific inputs and perform particular tasks.
- **Human-Machine Interfaces (HMIs):** HMIs are graphical user interfaces used to display data and allow operators to interact with the SCADA system. HMIs typically include displays, touchscreens, and input devices such as keyboards and mice.
- **Communication Networks:** SCADA systems rely on communication networks to transmit data between sensors, PLCs, and HMIs. Communication networks can be wired or wireless and may use protocols like Modbus, DNP3, and OPC to communicate data.
- **Data Storage and Analysis:** SCADA systems typically include data storage and analysis capabilities that allow operators to review historical data and identify trends and patterns in the performance of the industrial process or equipment. This data can be used to improve process efficiency, identify areas for improvement, and make more informed decisions about the system's operation.

SCADA systems used in rail operations monitor and control various processes such as train speed, track switch positions, signal status, and traction power. These systems are also used for monitoring the condition of railway infrastructure and detecting faults such as broken rails or malfunctioning switches.

SCADA systems in rail operations have been shown to increase efficiency and safety by allowing for real-time monitoring and control of critical railway processes. Benefits of SCADA Systems in Rail Operations Improved reliability, increased safety, reduced downtime, and enhanced operational efficiency are among the benefits of using SCADA systems in rail operations. These benefits are achieved through the ability of SCADA systems to detect faults and anomalies in real-time, allowing for prompt corrective actions.

Real-time monitoring of railway processes also allows for faster response times to train speed and other operational issues. This can reduce the time required to stop a train or take corrective action when needed, increasing safety and enhancing efficiency. SCADA systems are also used for predictive maintenance, which helps identify potential problems before they become significant.

2.1.6.14 Automatic Train Control

Communications-Based Train Control (CBTC) moving block technology which enables full driverless operation of the system.

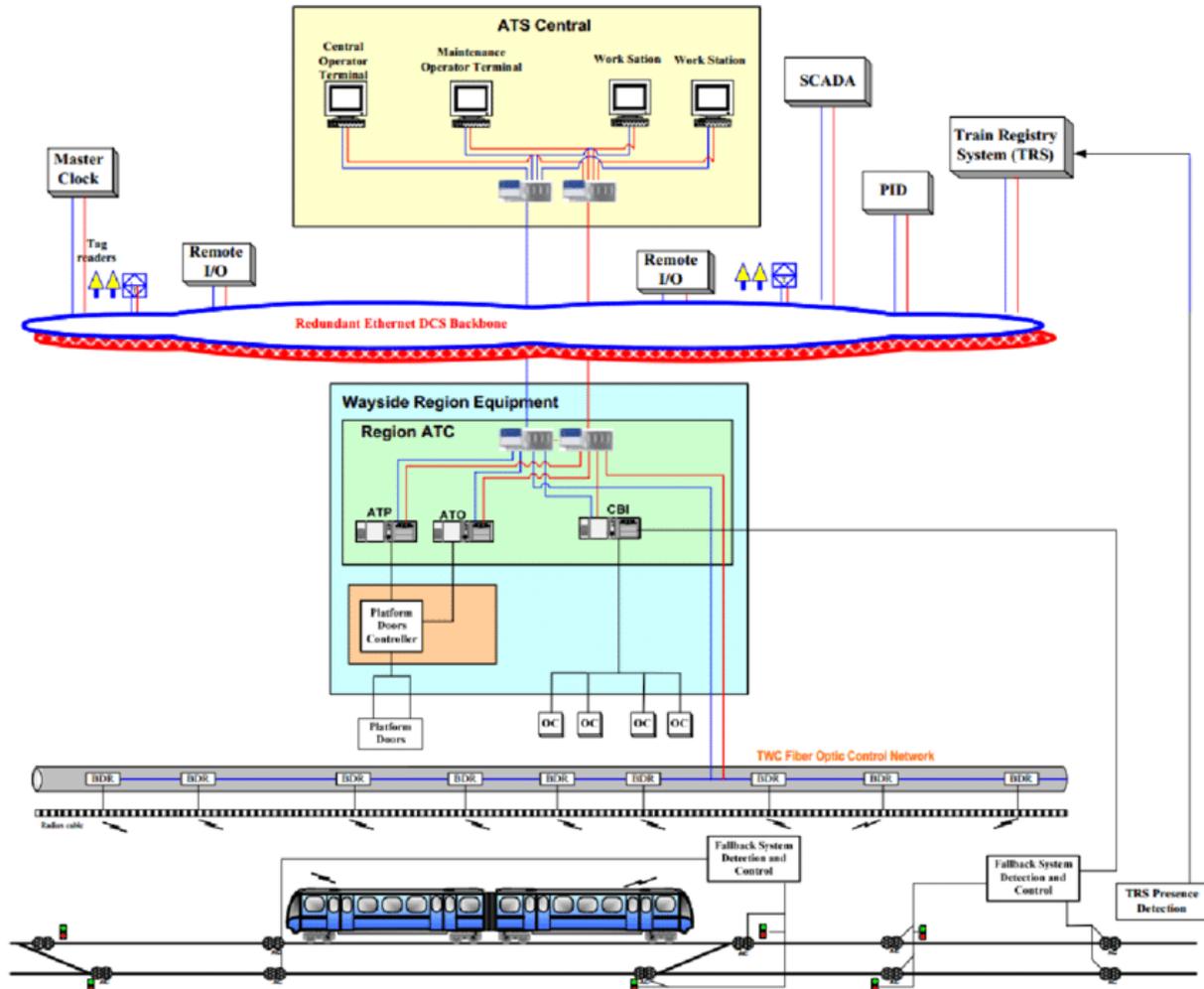


Figure 78: CBTC system architecture

Source: CBTC Simulation Platform Design and Study - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/CBTC-system-architecture_fig1_283187607 [accessed 13 Sept 2024]

2.1.6.15 Vehicles

Vehicle Subsystems

- Propulsion
- Brakes
- Fire Detection & Suppression
- Heating Ventilating and Air-Conditioning
- Passenger Doors
- Lighting
- Bogies

2.1.7 Construction Sequences

Elevated Guideway

The following pictures show some construction stages of the guideway section from Line 15, São Paulo 2010-2014.

Piles and columns



Figure 79: Piles and columns



Source: Photos by Rodolfo Szmidke

Capitels and launching guide beams



Figure 80: Capitels and launching guide beams



Source: Photos by Rodolfo Szmidke

Closure pours and system elements



Figure 81: Closure pour joints and system elements



Source: Photos by Rodolfo Szmidke

Stations

The following pictures show some construction stages of the Jardim Colonial station from Line 15, São Paulo 2019-2021.

Piles and foundation blocks



Figure 82: Piles and foundation blocks



Source: Photos by São Paulo Metro

Columns



Figure 83: Columns



Source: Photos by São Paulo Metro

Concrete and steel structures



Figure 84: Concrete and steel structures



Source: Photos by São Paulo Metro

Guideway and final services



Figure 85: Guideway and final services



Source: Photos by São Paulo Metro

2.2 Urban Integration and Environment

2.2.1 Urban Design and Development

Public transportation and how it relates to cities and their residents is changing fast, as cities become more congested at ground level and below ground, and as uses of space face increasing competition, having to demonstrate a strong added value for the use of limited resources. Thorough planning and urban integration are not only able to minimize the impact of that usage of resources, but to enhance them.

Adequate **urban design** and integration results in building communities and the (re-)generation of (new) spaces in the neighborhoods. When urban design principles are properly applied, both the traveler and residents benefit from the new infrastructure. Adequate design and successful integration create spaces for people, that can be used and shared by multiple social groups, enriching the existing local spaces, creating new landscape references by shaping (re-) development) and creating opportunities beyond the transportation element itself.



Figure 86: Monorail station integration in Chongqing, China



Source: Photos by Paulo Meca, 2024

Urban design must take care of the integration of mainline structures and stations into the communities monorails transits by, as well as optimizing and improving the land use of surrounding spaces, in a manner that is respectful of the environment, promotes economic development and social equity, whilst it should aim to (re-)generate public spaces for the enhance usage by the local communities, transforming what could be seen as a convenient but disrupting infrastructure into a unifying trigger of positive change for the community as a whole, enhancing livability and long term value, whilst maximizing transportation performance. The main goals should be:

- Maximize the performance of the transportation investment.
- Enhance the livability of the communities it serves.
- Create long-term value and,
- Sensitively integrate the project into the diversity of communities along the corridor.

Sustainable design and successful integration must have a fluid relationship with the landscape by minimizing negative impacts and maximizing the positives, creating equilibrium between the natural environment and the man-made infrastructures. This is true not only of the natural environment, but also the cultural and societal environment: new projects always create an opportunity to fuse the local traditions with modernity and a look into the future, in a manner that citizens of all generations, from a variety of backgrounds and beliefs can identify a part of themselves represented and therefore taking pride and ownership in the project and its builds.



Figure 87: Smart stations in smart cities

Source: Smart Stations in Smart Cities, International Union of Railways

More and more cities have policies aiming for **Transit-Oriented Development (TOD)**, envisioning placing higher population densities within walking distance of mass transit nodes to create an energy efficient city model. In the TOD urban model, the station becomes a centerpiece, essential and reference building, with the potential to become a destination. An alternative and complementary urban policy is **Development-Oriented Transit (DOT)**, where transport systems are used to enhance and improve the community and local (re-) development. There is great potential in meeting the synergies of TOD and DOT, and the conscientious application of the adequate planning principles for each specific situation plays a critical role in the successful integration of urban transportation systems.

The role of such an important infrastructure has to be defined on a case by case:

- If stations may become a dominant feature or they may fade away becoming architecturally invisible, it is a consideration that the local environment and community define, and it will impact the street and public spaces layout around.
- The level of impact and also of opportunities by the track infrastructure is strongly influenced by its placement – elevated, at-grade or underground. Different areas even in the same city may require different approaches and solutions. Whilst track alignment shows and displays a neighborhood to commuters, they can act and be seen as obstructive and noisy by local residents, so sensible planning is required to earn acceptance and prevent rejection.

Given that the roles of stations go beyond transit and possess a broad civic role, regardless of size and appearance, there are key considerations for adequate integration, such as:

- a. Stations should be located strategically in respect to their neighborhoods. They are places for the people and become part of the landscape. They can provide space for local business, retail, civic duty spaces, be an open green space for play and social interaction, or all of them. This needs to be addressed with the local community specifically.
- b. Stations need to make efficient connections, both with other forms of public transportation services, but also in relation to other urban and community buildings and facilities.
- c. Pedestrian reach and connectivity should be optimal, but also consider access by private vehicles (with limited parking opportunities), taxi and bicycles.
- d. Improve local use with multi-use functions and forms likely to attract a wide range of users by meeting a variety of needs and preferences.
 - Design with change in mind. The future is fluid and conditions are ever changing, so adaptability is essential, mainly when transport infrastructure is a catalyst for urban and community growth and change.
- e. Stations also act as an entrance into a neighborhood and can establish or reinforce the distinctive characteristics of that place and benefit the neighborhood. Therefore, station and infrastructure design should respond to the character of its local context, present and future, respecting residents and significant heritage places.

For many people the first impression they have of a neighborhood is the experience they have when in transit and upon arriving at a station. For commuters and other local residents, stations may be the most frequently visited building in their daily life, hence these buildings play important roles in the identity of the neighborhood as would a reception lobby give a great deal of its character to a building or hotel.

Community consultations, open communication with local representatives, consideration of the specific area requirements and needs, and generating a clear vision for the future go a long way towards successful integration and acceptance.

2.2.2 Project Development Steps

2.2.2.1 Overview

According to the Urban Rail Development Handbook the following 16 project development steps are recommended for successful project handling, considered in the respective phase as presented in the following flow chart.

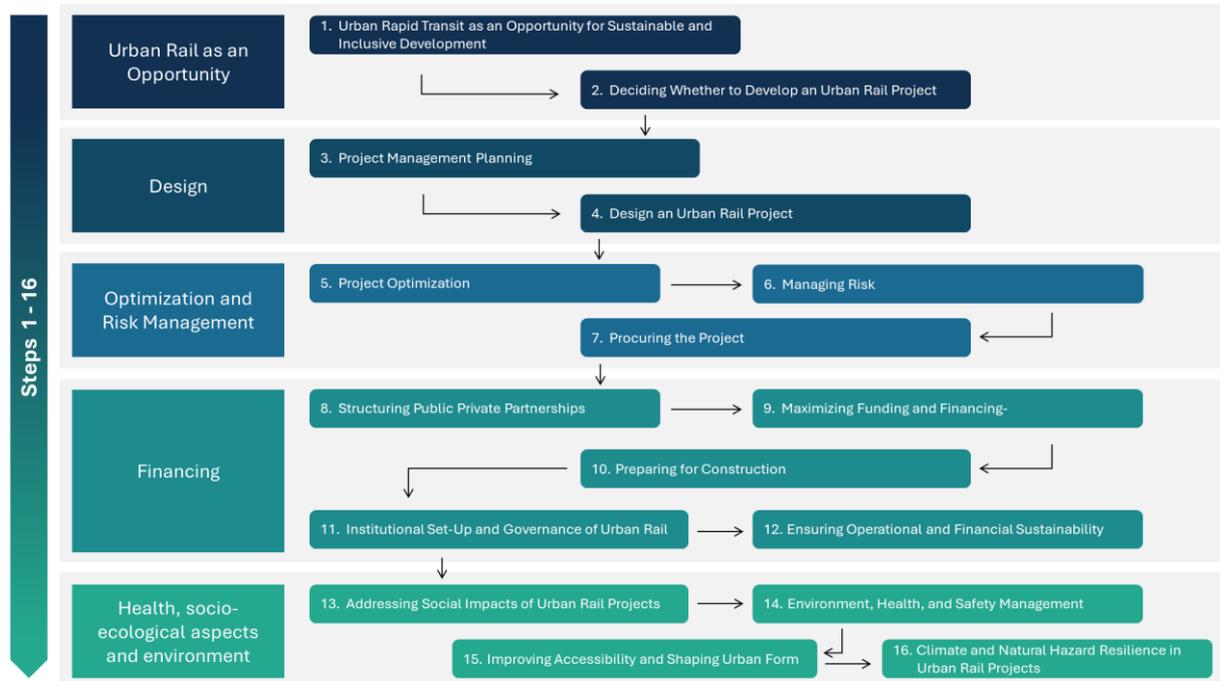


Figure 88: The urban rail development handbook

Source: Illustration by IMA based on Urban Rail Development Handbook

The superordinate project steps are therefore distinguished in ‘Urban Rail as Opportunity, Design, Optimization and Risk management, financing and Health, socio-ecological aspects and environment’.

Urban Rail as an Opportunity

1. Urban Rapid Transit as an Opportunity for Sustainable and Inclusive Development
2. Deciding Whether to Develop an Urban Rail Project

Design

3. Project Management Planning
4. Design an Urban Rail Project

Key Categories and Examples of Design Features for an Urban Rail System:



Figure 89: Key categories and examples of design features for an urban rail system

Source: Illustration by IMA

Optimization and Risk Management

5. Project Optimization
6. Managing Risk
7. Procuring the Project

Financing

8. Structuring Public Private Partnerships
9. Maximizing Funding and Financing
10. Preparing for Construction
11. Institutional Set-Up and Governance of Urban Rail
12. Ensuring Operational and Financial Sustainability

Health, socio-ecological aspects and environment

13. Addressing Social Impacts of Urban Rail Projects
14. Environment, Health, and Safety Management
15. Improving Accessibility and Shaping Urban Form
16. Climate and Natural Hazard Resilience in Urban Rail Projects

2.2.2.2 Planning steps for Monorails

For monorails the following planning steps – like for automated people mover systems – are recommended. This chapter refers to the ‘Guidebook for Planning and Implementing Automated People Mover Systems at Airports (2010)’ and its chapter 5.2 Airport APM Planning Process Steps.

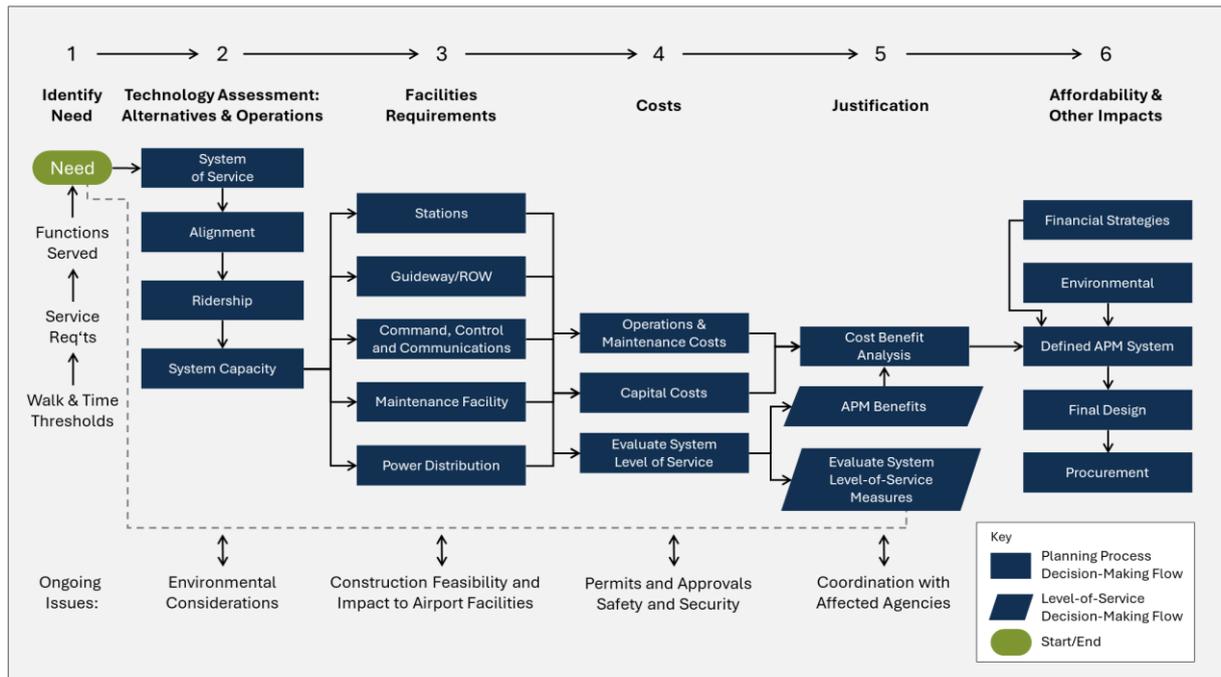


Figure 90: Planning steps for monorails

Source: Illustration by IMA based on Lea+Elliott

Step 1: Identify need—This is the process by which passenger conveyance needs to/from airport, or passenger activity centers that cannot be adequately accommodated by walking are identified and quantified. Quantification typically takes the form of wait time, connect time, and/or walk distance requirements and thresholds.

Step 2: Technology assessment: develop alternatives and analyze operations—The passenger activity generators identified in step 1 will help determine station locations. To connect the station locations, alternative routes/ alignments are developed and analyzed with respect to operations. This can be done using a single or a variety of different technologies. The analysis of operations will help in sizing the fleet to meet the demand ridership between stations and in providing a system capacity (passengers per hour).

Step 3: Determine facilities requirements—The fleet size determined in step 2 allows the related system facilities' requirements for power, maintenance, train control, guideway and its right-of-way (ROW), and stations to be developed.

Step 4: Determine costs—With the alignment, fleet, and related facilities now sized, the high-level capital and O&M costs of the system can be estimated. The level of service (trip times, service frequency) can also be double-checked against relevant passenger conveyance thresholds from step 1.

Step 5: Perform justification analysis—The costs developed in step 4 are then compared against the benefits of the system to determine if the system is justified

Step 6: Determine affordability and other impacts—The final planning step determines if the resulting system is affordable to the community. Other final checks of environmental impacts, feasibility, and constructability (first performed during preliminary planning in step 3) are also performed in this final step. If all these checks come up positive, then the system enters final design and implementation (procurement).

2.2.2.3 Constructability

One of the key factors in integrating monorail projects into urban areas is their constructability. The Construction Industry Institute (CII) introduced the concept of constructability in 1986. CII stated that “Constructability is the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives”.

Since the 1980s, constructability has been an important concept in the construction industry, offering significant benefits when applied. This section provides insights as to how to incorporate the implicit benefits of Monorail projects based on a paper by Bo Wang and Prof. El-Diraby, Constructability Analysis of Monorail Projects, dated 2003, an interesting formal analysis of monorail systems is performed.

Constructability, taken as an “attitude” during the life cycle of a project allows for the lessons learned during monorail construction to be incorporated into feedback loops like the one shown in Figure 91 (Kartam, 1996). The model proposed, offers a framework for understanding this process that starts at the Planning Phase where the project incorporate lessons learned from traditional mass transit Operations. This basic knowledge on the Operation Phase informs the Construction and Design Phases that incorporate the construction capabilities of the teams involved.

The interaction between Owners, Contractors and Engineers provides the first constructability improvements. Feedback to the Construction Phase also informs the Planning Phase, where there are traffic solutions to be implemented, as well as simplifications to cabletrays and systems deployments, etc.).

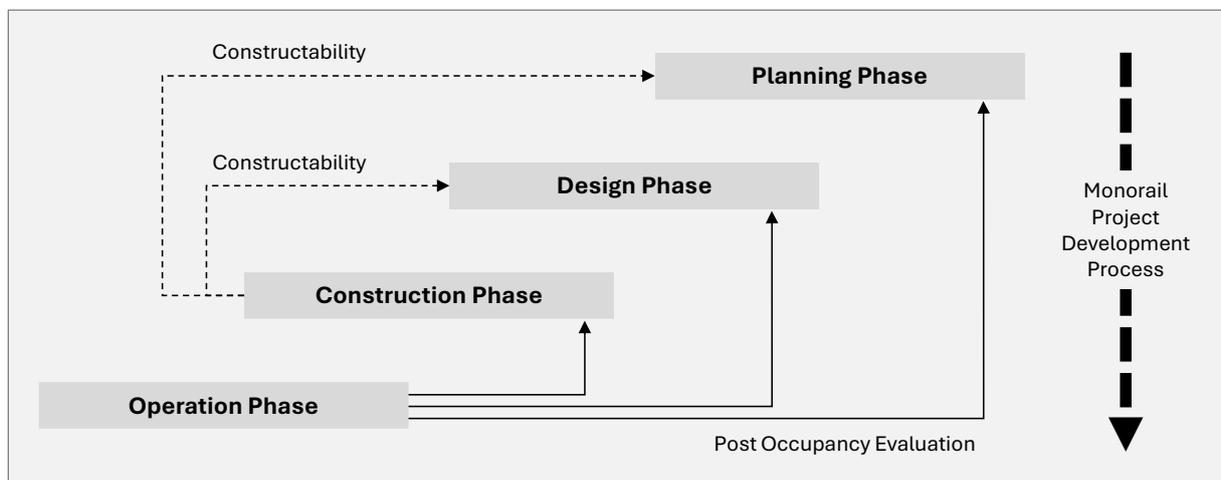


Figure 91: Constructability feedback model

Source: Kartam, 1996, illustration by IMA

The advantages of monorail systems have resulted in the development and operation of many monorails worldwide, with even more in planning or construction. To improve the ease of building these projects, better communication between engineers and contractors is crucial early on. The flowchart in Figure 92 formalizes a feedback system proposed in the paper mentioned earlier for sharing construction knowledge.

The sharing of knowledge and incorporation of the lessons learned can lead to savings between 10 and 20 percent mentioned in the paper.

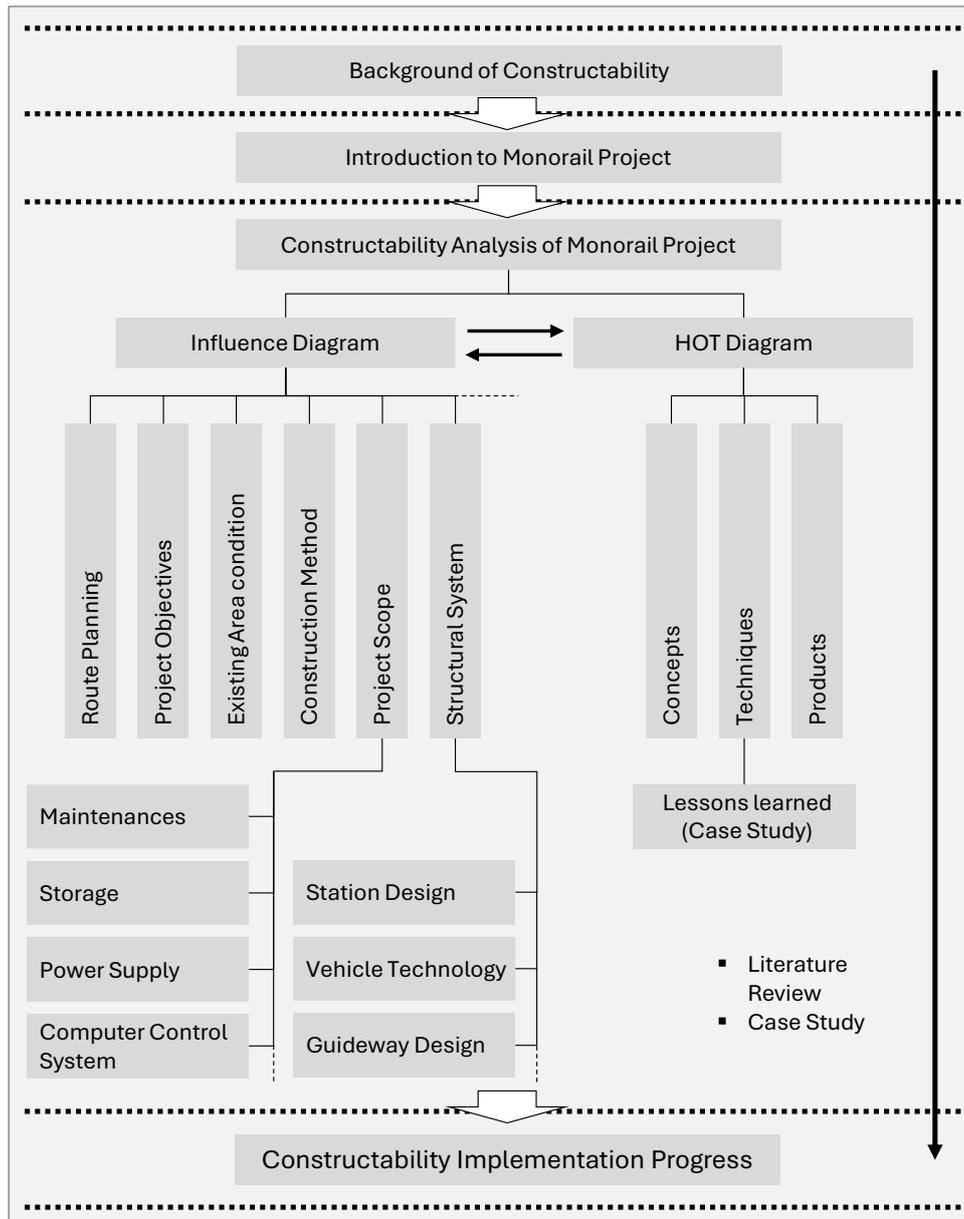


Figure 92: Research process for constructability

Source: Kartam, 1996, illustration by IMA

Benefits of Constructability

The Construction Industry Institute indicated in 1986 that constructability, through the early integration of construction knowledge and experience into engineering and design, offers significant benefits by minimizing changes, disputes, cost overruns, and delays during construction.

By shortening construction time and improving project management, constructability studies in a project can reduce overall project costs and capital investment risk.

Direct benefits of constructability include:

- Simplifies construction planning,
- Reduces both design and construction costs,

- Shortens the construction timeline,
- Ensures higher quality standards,
- Allows for more realistic commitments to future trades,
- Enables earlier occupancy for the owner

There are other benefits, more difficult to quantify, that include:

- Creating a team that works together toward shared project goals,
- Collaborating for mutual benefit,
- Training across different disciplines,
- Sharing expertise from previous projects,
- Builders gaining a better understanding of design, and designers understanding construction,
- Boosting innovation in both design and construction,
- Reducing the time needed to learn new skills,
- Gaining a competitive edge.

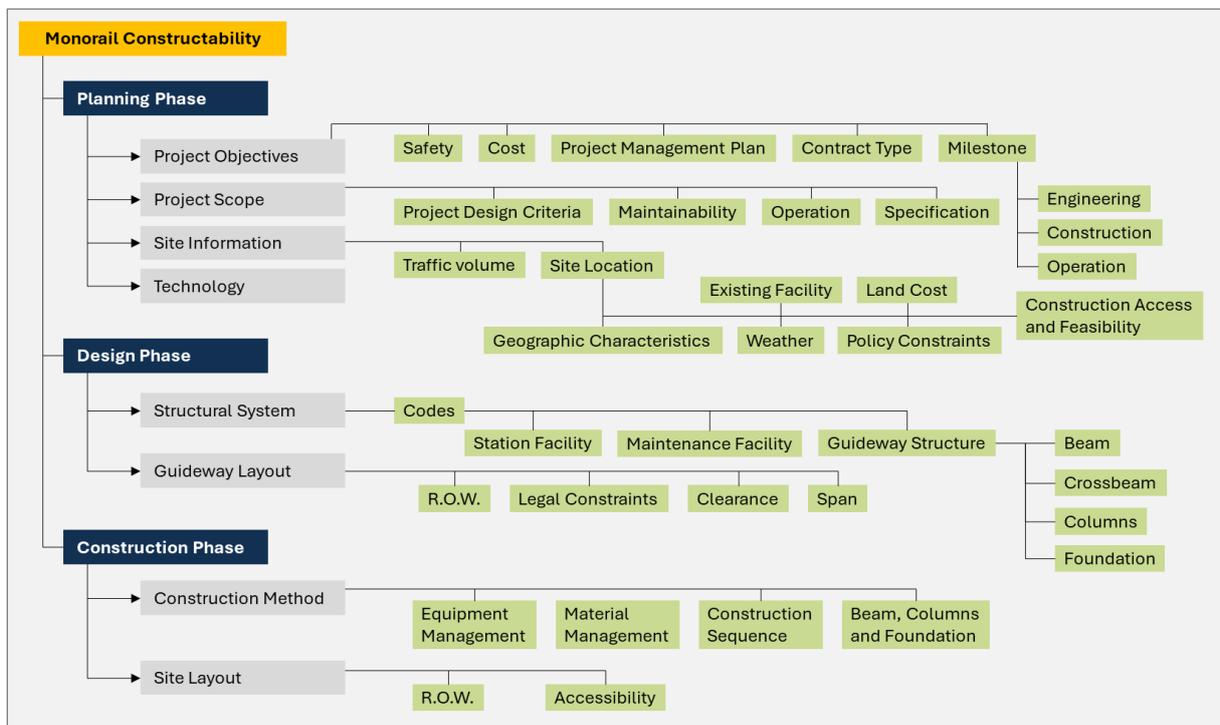


Figure 93: Monorail Constructability

Source: Illustration by IMA based on Bo Wang, 2003, Constructability Analysis of Monorail Project

2.2.3 Environmental Impact and Factors

Every infrastructure project inevitably impacts its surrounding environment, both positively and negatively. We accept the development of new infrastructure when the benefits outweigh the associated drawbacks, particularly when mitigation strategies are employed. If the balance tips towards more harm than good, projects often undergo reassessment, redesign, or are even abandoned altogether.

To ensure successful outcomes, it is crucial to evaluate all potential factors from the project's outset. This involves carefully considering how each decision influences the overall impact, and prioritizing thoughtful planning to avoid costly changes, delays, or negative public perception.

A structured approach to managing impacts includes:

- Avoidance – Wherever possible, eliminate negative effects while maximizing positive outcomes.
- Minimization – For unavoidable negative impacts, reduce their scale through thoughtful design, thorough planning, and exploration of alternative solutions.
- Mitigation – Address and lessen the consequences of remaining impacts.
- Compensation – Offset detrimental effects by providing additional benefits, ideally within the same area, whether they be environmental, social, or economic.

To anticipate and manage these impacts effectively, the following guidelines should be applied (adapted from The Urban Rail Development Handbook)

1. Design considerations: Strive to minimize harm to the environment and surrounding communities. Expert input from various fields can help identify and address potential negative effects of stations and mainline structures.
2. Community engagement: Involve local communities early in the planning process to gain insights into unforeseen concerns and foster solutions that benefit all parties.
3. Integration with urban spaces: While public transportation connects communities, surface tracks can divide them. Vertical planning, like using monorails, helps minimize disruption, but new challenges (e.g., noise, visual impact) must still be addressed.
4. Station design: Careful consideration of station size, height, and layout can mitigate negative effects such as unnecessary vertical movement or disturbances to neighbors.
5. Terrain and topography: Use the natural landscape to seamlessly integrate roads, bike paths, and pedestrian routes with the infrastructure, minimizing visual and environmental disruption.
6. Alignment impacts: Evaluate how both the horizontal and vertical alignments affect neighborhoods and natural environments, considering factors like noise from vehicles and visual impacts of elevated structures.
7. Environmental enhancements: Introduce green spaces, tree barriers, and public gardens to reduce noise, enhance visibility, and support community acceptance.
8. Compact designs: In densely populated areas, use compact station designs and integrate high-demand services to maintain vibrant street activity around large constructions.

9. Public safety: Ensure that station and track designs do not create unsafe or neglected public spaces that may degrade the local environment.
10. Art and landscape: In collaboration with the community, incorporate artwork or landscaping projects to enhance public spaces and foster local identity.

By incorporating these strategies, projects can be better planned to balance their benefits with their impacts, fostering sustainable, community-supported developments.

2.2.4 Sustainable Principles

”Sustainability [is] the long-term viability of a community, set of social institutions, or societal practice. In general, sustainability is understood as a form of intergenerational ethics in which the environmental and economic actions taken by present persons do not diminish the opportunities of future persons to enjoy similar levels of wealth, utility, or welfare”. Encyclopedia Britannica.

“Sustainability is often thought of as a long-term goal (i.e. a more sustainable world), while sustainable development refers to the many processes and pathways to achieve it.” UNESCO

Public transportation as part of the urban environment and its development, is one of those key supporting pathways towards achieving a more sustainable future. Availability of collective forms of transportation, and especially those powered by other than fossil fuels, has the potential to:

- Remove private vehicles from the streets, reducing air and noise pollution.
- Allow the (re-)utilization of existing spaces and freeing up road and parking spaces for new uses, thus reducing the overall surface dedicated to transportation.
- Improve the health of residents by encouraging movements on foot to and from the nodes of transportation and improvement of air quality.
- Improve social interaction and cohesion, by sharing spaces.
- Reduce greenhouse gas emissions.
- Reduce overall energy bill of transportation and of medical expenditure, hence freeing more financial resources for other goals.
- Improve safety of pedestrians and cyclists due to traffic reduction
- Create local job opportunities and bring economic benefits to the communities.

All the factors above have a very clear collateral benefit: Enhancing urban livability. Making the city centers more attractive and livable incites a return of higher density of population to the cities, rather than continue the suburb spread. This shift from endless expansion and take-over of the surrounding environment is in itself a major achievement towards sustainability.



Figure 94: Enhancing urban livability

Source: Urban Design Guidelines, California High-Speed Train Project, illustration by IMA



Transit Oriented Development (TOD) is a significant investment towards building sustainable and environmentally conscious communities, cities and after all, preserving a healthy planet for future generations. TOD is also a visible representation of the commitment to sustainability, any by displaying so clearly visibly, even in the smaller details, it has the potential to encourage residents to adopt other sustainable practices in their live choices as well.

Including sensible landscaping practices (use of drought resistant or local vegetation, for instance), the recycling of rainwater or the use of permeable pavements to reduce runoff and increase infiltration, the integration of renewable energies, the positive impacts towards sustainability of a transportation project can go far beyond transport itself.

Creating a safe neighborhood is also a step towards a more sustainable tomorrow. Considering principles of public safety when designing stations and spaces, such as adding visibility, avoiding dead end zones or areas that lend themselves to wrongful uses and so on, are critical to prevent crime itself, but also to prevent the association of public transportation with crime and unsafety, hence helping nurture a more transit friendly society.

Sustainability is primarily about what we do today to help create a better future, in every possible way, and clean public transport has a massive role to play.

2.3 Operations

For the purpose of this guidance document, the term ‘Operations Concept’ is used to imply a strategic level document which is developed and used at the feasibility, design development and build stages of the project.

Brief details of the contents of the operation concept document are presented below.

Monorail operations and maintenance (O&M) is the sum total of all processes and organization dedicated to delivery of the transport services and customer service and efficient management of all the assets. It involves managing interfaces between the eight subsystems as shown below.



Figure 95: Railway Subsystems

Source: Illustration by IMA

2.3.1 Operating Concept

Operating concept (OC) is aimed to provide designers and stakeholders an understanding of what services are expected to operate, when, where, and who will do what over the operations and maintenance stage.

2.3.2 Links to Other Key Documents

The operating concept document draws from the travel demand forecasts and from the feasibility studies. It supports and enhances the business case for monorail.

2.3.3 Parties Involved

The development of OC is led by a small team of operations and maintenance professionals. They are supported by the system's designers and, where possible, by the vendors of the monorail

systems. Key inputs are provided by the Public Transport Authority / Agency (PTA) who are responsible for setting the broad performance objectives from the transit system. There is a close working with Architects and other Engineering team for the finalization of the OC.

2.3.4 Stages of Operating Concept

The operating concept document evolves over time, with the project lifecycle. As more information becomes available, more details are added to the document about the system operations and the interfaces. The following graph illustrates the evolution from the Feasibility Study phase to the Testing and Commissioning (T&C) phase:



Figure 96: Stages of operating concept

2.3.5 Objectives of the Operations Concept Document

Main objectives of the operations concept document are as follows

1. To explain the various monorail systems (stations, depots/OMSF, train control, communication, power, services, operations control center etc.) and explain how they work together to develop the transit system.
2. To manage risks As Low As Reasonably Practicable (ALARP).
3. To be able to control change in a manageable way over time.
4. To ensure that planners can identify missing or conflicting requirements.
5. To describe outline maintenance concepts, principles and organization.
6. To Describe Operator and Maintainer roles and responsibilities.
7. To describe the key operational and maintenance activities during normal, degraded and emergency situations.

2.3.6 Typical Contents of OC

Topic	Contents
System description	Functional level description to be included in this section. Details of the systems are typically provided in Basis of Design and other Engineering documents. However, the OC includes a high-level description of the monorail system with main focus on their functions so that stakeholders can understand the system and the constituent elements that together constitute the whole transit system.
Train service planning	Generally, the public authority will specify the service levels it wants to procure in a project. Train service plan is usually expressed as <ul style="list-style-type: none"> - Hourly service for weekday, weekend, peak, off peak and night services This could provide sufficient information to calculate yearly train kilometers which would influence the maintenance costs as well traction power consumption. The train service plan has a direct correlation to the travel demand projections. The capacity required to meet the demand is usually determined by the transit authority which is reflected in the service plan. Therefore, the seating and standing capacity of the vehicles and the maximum passenger density per square meter are important factors to determine the train service plan. The train service plan should be consistent with other transit lines, so that waiting time is minimized for passengers who are required to interchange to other lines / modes.
Operation control center (OCC)	Monorail are driverless systems usually operated without any staff member on board the train. As a result, the OCC assumes a very important role in the traffic management but also in safety of the system. This section describes the role of the OCC and its general arrangement. For some public authorities who have existing transit lines, there could be strategic objective to co-locate all OCC functions under one management.
Station management	Monorail stations can be either staffed or remotely managed with the help of the OCC and mobile unit. This section should describe the strategy that is adopted for the specific project. The strategy should be aligned with the systems design to support it.
Operation, Maintenance, Storage Facility (OMSF) and depots	There could be one or more OMSF which includes stabling, train washing and cleaning, maintenance and storage depots. In addition, it is common for OMSF site to include OCC and Admin facilities for the management of the transit. The OMSF plan is based on the long-term requirements and is future proofed. This section should describe the high-level functions that will be performed at OMSF along with staffing strategy.
Service operations	Monorail systems are usually operated at Grade of automation level 4 (GoA4) which equates to unattended train operations. This section should explain how the critical safety functions are performed at this level of automation, and how the risks are mitigated.
Detrainment and evacuation	Monorail systems are predominantly built on elevated corridors. This presents the operators with a unique risk of passenger detrainment and evacuation specifically between station. This section should describe the strategy that is adopted for the specific project with respect mitigation of this risk and the associated solutions. These require close coordination between the design team, the O&M team and the safety regulators.
Maintenance	This section should be focused on the running maintenance which includes preventative and corrective maintenance of all monorail assets. In specific cases, where the life cycle responsibility is also handed over to the O&M agency, this section should outline the asset replacement strategy and whole life cycle approach to assets. OEMs have an important input to provide with respect to the maintainability of the assets; this section could use some of the material provided by them. section on maintenance could include approach to automation and application of latest trends in predictive and risk-based maintenance.

Topic	Contents
Customer experience	This section should outline the approach, principles and organization for customer service. The wider context could be provided by the public transit agency including multimode integration, fare and revenue collection systems etc. In general monorail systems are designed bearing in mind a fairly autonomous customer who is able to navigate through the system without aid and assistance. However, the principles of customer service are more relevant when there is a breakdown and equipment degradation.
Performance management	Performance targets are specified by the public authorities and very often contractually binding between them and the operator. This section should outline how the operator proposes to meet the performance targets. It should identify some high-level risks associated with performance and suggest some mitigation measures.

2.3.7 Operations Plan

A high-level operations (and maintenance) plan follows the OC. The plans are developed when the monorail system design and construction are complete, and the transit system is ready for hand over to operations.

Further risks and hazard analysis helps develop operating procedures which are step-by-step guidance to operate the systems. Rules and processes are built on the principles developed by OC document.

2.3.7.1 Dimensioning the Project

It is expected from the O&M to help to dimension the project using the optimized train service plan. The operations concept / plan determines the fleet size and other systems that go with it; OMSF, Traction power system and station footprint. Therefore, the OC (or Plan) is an important input in the project's planning and development stage.

Operations planner or engineers work with designers of the systems to determine the end to run time, dwell time, turn back time and the necessary margins for performance management. This is required to calculate the fleet size as below

Total trains = total round-trip time / headways

Therefore, for example, if the total round-trip time is 60 mins, and the headway is 5 mins, the total fleet needed will be 12. There is a need to add operations and maintenance reserve to this number to get to a final estimate of the number of trains. The reserve train sets provide the maintenance organization to plan for major overhauls without affecting the passenger service.

The number of cars for each train is derived from the passenger demand that needs to be met and is generally expressed at passengers per hour per direction (pphpd). For example, if the required pphpd is 12,000, and we have 12 trains in the peak, each train should have sufficient cars to carry 1,000 passengers.

Sometimes with projects which have multiple routes and lines, there is a sequence for commissioning the system. This needs to be highlighted and will have bearing on the fleet requirement over time.

2.3.7.2 Typical Content of Operation Plan

Part 1 – System Descriptions

Topic	Contents	
Introduction	State the purpose of the document and its intended use. Ideally, we should mention the responsibility, accountability etc. for the document – RACI matrix. Introduce the fact that the document will evolve over a period of time as the design development progresses or the requirements undergo any changes.	
Purpose		
Responsibility for Operations Planning		
Updates and Changes to the Operations Plan		
Reference Documents	Mention all the other documents that are linked or have an input – output relationship with the Operations Plan	
Standards	Make a list of all the national, and international standards that will apply to the operations and Maintenance management of the monorail system	
Definitions and Acronyms		
Network Description	This must be consistent with the design documents and updated every time there are changes to the alignment or the network. Network description mainly includes the civil infrastructure such alignment, station locations, track layouts including terminal station, location of switches and crossings. Schematic drawings can be used where available for illustration. Interchange with other transit lines can be shown (or with mainline services).	
Overview		
Infrastructure		
Alignment		
Tracks and Structures		
Crossovers between Lines		
Operations Planning – travel time simulation	This is covered in paragraph 2.3.6.1 above. It is a critical input for planners and designers. The starting point is a detailed assessment of the travel demand forecasts. In most projects (if not all), the travel demand projections are given for each section for each hour, along with station wise boarding and alighting. This gives the basis for devising the hourly train service plan. Travel time (includes turn back operations for calculation of round-trip time) is calculated with the help of OEMs and the transit authority. It is usually the public transit authority (PTA) that sets the performance requirements at the O&M stage. These need to be supported by the OEMs through their work on RAMS. In almost all cases, the key performance indicators associated with system performance are put in the contract for O&M services.	
Passenger Demand Forecast		
Capacity Planning		
Operational Headway		
Fleet sizing		
Travel Times		
Turn back operation during Normal Operation		
System Performance Requirements		
Grade of Automation		Monorail systems are generally designed for unattended train operations (UTO), or grade of automation level 4 (GoA4 – see UITP for definitions). Selection of the grade of automation has a direct bearing on staffing and plans and on future proofing of the system. In addition, the Operations Plan document should briefly touch on the OCC and the stations' performance monitoring strategy. The document should list the hourly service plan and explain how the transition takes place between operations and maintenance hours.
Future Proofing		
Performance Monitoring		
System Capability		
Hours of Operation		
Peak Hours		
Operation Hours, Maintenance Hours & Transition Time		
First and Last Trains		

Topic	Contents
Level of Service	
System Availability	
Operations and Maintenance Organization	Even the highest level of automation requires staff presence for oversight and for dealing with perturbations and unexpected events. The project should describe its approach to management of the transit at the O&M stage, the staffing levels for different functions and the organization required to operate the services.
Management Philosophy	
Training	
Management and Administration Center	
Operations Control Philosophy	OCC plays a very crucial role in GoA 4 level operations. This is why a section should be dedicated to the OCC working. It should include the key functions to be performed from the OCC and the staffing of the facility. Every transit should have a backup control center for resilience and business continuity. Attached to the main OCC, there needs to be a crisis room for senior managers to deal with emergencies. However, some transit authorities may have a unified crisis center to have a holistic response.
Automation Philosophy	
Operations Control Center (OCC)	
Emergency Control Center (ECC) Emergency and Crisis Room	
Functionality during Testing and Commissioning	This section is not about testing and commissioning but about the role of the OCC and the station control during the T&C. It is possible that the transit is operated under a set of safety rules and procedures that are prepared by the construction organization.
Station Control Room	If the stations are equipped with a local control center equipment for managing issues at the station, these need to be summarized in this section.
Modes of Train Operation	Please refer to the OEM manual for a description of these modes of operation as the terms may differ between manufacturers. The expected mode of operation is fully automatic mode, but there are other modes possible associated with equipment degradation. Operational procedures, which are based on risk and hazard assessment provide additional safety for the system.
- Automatic Mode (AM)	
- Manual Mode with ATP support (MATP)	
- Washing Mode (WM)	
- Sleep Mode	
- Depot Shunting Mode	
- Restricted Manual Mode	
Depots and Stabling Areas	This section is dedicated to describing the OMSF and all the associated functions and activities at the O&M stage. These have a direct bearing for the planning and design team at the development stage of the project. The OMSF has stabling lines to park the trains during off peak and non-revenue hours; workshop to maintain trains, wash plants and other maintenance related facilities. It has a test track to test the trains and on-board equipment for commissioning of new trains and after major overhauls. Usually, a depot control center is provided for managing interface between the depot / workshop and the OCC. Sometimes the depot controller is located within the OCC area. Safety aspects associated with depot (OMSF) working needs to be described in this section.
Depots (OMSF)	
Depot Control	
Designation of Areas and Tracks	
Train and Maintenance Vehicle Movements within the Depot	
Train and Maintenance Vehicle Launch and Reception	
Train Cleaning	
Depot Degraded Mode Operations	
Depot Emergency Preparedness Measures	

Topic	Contents
Stabling Areas	
Test Track	
Rolling Stock	<p>This section is dedicated to the fleet that will be used for transporting passengers once the transit system is commissioned and brought into revenue service.</p> <p>The chapter describes the trains at a functional level rather than technical. All aspects are orientated towards operability and traffic transportation outputs.</p> <p>Safety features and passenger interfaces and touch points are included in this section. Passenger handling during abnormal events is briefly described without getting to the level of details contained in procedures.</p> <p>Safety equipment such as smoke detectors, CCTV, passenger information and announcements systems are described. There is reference to the role of different O&M staff with respect to the management of incidences.</p> <p>The section should be closely aligned with the design offered by the OEMS so that there is consistency across different project documents.</p>
Train Specifications	
Multiple Unit Operation	
Coupling and Uncoupling	
Doors, Evacuation and Access	
Management of Rolling Stock	
Train Capacity	
Train Orientation	
Train Stopping Position	
Diagnostic and Status Monitoring Facilities	
Maintenance Vehicles	
Train Door Operation	
Communication Systems	
Emergency Facilities	
Identification System	
Energy Systems SCADA	<p>This chapter describes the energy (traction power) system which includes the current collection system and traction substation. The traction system is managed from the OCC through SCADA system which has ability for remote switching (so that maintenance personnel can carry out work on the section).</p> <p>Also, there should be a separate section with a high-level function description of the train control and signaling system. Most of the modern monorail system may go for communications-based train control system (CBTC) because of its many advantages.</p>
Third Rail System	
Signaling and Train Control System	
Communications management and systems	<p>Communication systems are provided at stations, OCC, depot, Admin centers etc., to be able to communicate urgent, necessary and required messages to passengers and stakeholders. There are a number of different communication tools ranging from dedicated radio, bespoke emergency communication systems and normal telephones.</p> <p>Communication can be vocal or written; they can be displayed publicly and can be automated with the possibility of manual override.</p> <p>The systems being provided for the project along with the different forms of communication as described in this chapter.</p>
- Verbal Communication	
- Written Communication	
- Communications Systems	
- Digital Transmission System	
- Time Distribution and Clock System	
- Telephone System	
- Voice and Data Radio	
- Emergency Call System	
- Public Address System	
- Passenger Information Systems	
CCTV System	

Topic	Contents
Access Control System	The CCTV, Access Control and intrusion detection systems are sometime bespoke to the project. They should be described in this section with support from preferred vendors.
Intrusion Detection System	
Signage	Architects are responsible for developing the signages for the benefit of customers and staff.
General	
Trackside Signage Fare Collection Station Equipment	Fare collection systems include the approach for vending of tickets and their validation. There are extraneous factors which may influence the choice for fare collection system such as multi modal integration, consistency with other transit lines in the city, open v close stations et.

Part 2 – The approach to operate and maintain the monorail system

This part describes how the O&M team plans to operate the monorail under normal, perturbed and emergency situations. As stated earlier, this is a high-level strategic document which contains the principles and the approach rather than the detailed step by step procedure for operations and maintenance.

Topic	Contents
Normal Operation	The section under normal operation presents how the system is made ready to launch the services in the morning and goes through the different stages that are typically expected in an automated monorail operation. At the start of the day, there is transition from maintenance to operations with the necessary safety protocols; in the night it is the converse. Different projects apply a range of tools to manage the tasks and risks associated with the daily normal operations. After the advertized revenue service hours, the stations are closed for public access. The trains are stabled (mostly) at the OMSF so that they can be cleaned, and light maintenance can be performed where required.
- Revenue Operation	
- Timetable Loading	
- Transition from Maintenance to Revenue Operations Time	
- Train wake up and launching	
- Station Opening	
- Sweep Operations	
- Revenue Operations and Management of Perturbations	
- Stabling of Trains	
- Station Closure	
- Transition from Revenue Operations to Maintenance Operation	
Event Operation	The O&M team should anticipate special events which would require a different level of service, organization, coordination and delivery than the normal operations described above. A different transportation capacity is needed for special events. This requires a higher level of mobilization of resources including trains and staff. Expected number of passengers need to be ascertained to plan the event carefully.
- Crowd Management	
- Potentially Crowded Stations	
- Event Stations	
- Event Operation Boarding	
- Event Plans	
Engineering Work	
- Maintenance of infrastructure	

Topic	Contents
- The Safe Conduct of Maintenance Activities	<p>This section should briefly describe how maintenance activities will be carried out in a safe and economic manner. It will include when the maintenance activities will be undertaken.</p> <p>Principles of preventative and corrective maintenance will be highlighted to state the objectives for the different types of maintenance interventions.</p> <p>Maintenance organization can be described in this section, along with the facilities, tools and equipment that will be provided to carry out the maintenance obligations.</p> <p>There are several maintenance related performance indicators that need to be agreed between the transit agency and the O&M organization. These can be listed here.</p> <p>Most O&M organizations rely upon Computerized Asset Management Systems (CAMS). There are advances in Remote Condition Monitoring (RCM) which can be applied. These are included in the maintenance chapters.</p>
- Maintenance during Maintenance Hours	
- Maintenance Considerations	
- Maintenance Metrics	
- Maintainability Benefits and Features	
- Maintenance Planning	
- Control of Access for Maintenance	
- Maintenance Vehicle Operations	
- Worksite Protection Systems	
- Conclusion of Maintenance Period	
Degraded Operation	<p>There are situations under which equipment degradation affects the normal operation. These may not be life threatening to the passengers or to the staff but require urgent attention to restore the system back to normalcy, as they may have impact on the system safety.</p> <p>This chapter should define (identify) some of these degraded conditions and the strategy to respond to these conditions. Once again, this description is not to the level of detail of Standard Operating Procedure (SOP) but kept at a high level.</p> <p>This chapter can elaborate the strategy for single line working, short loop or short termination, using schematic diagrams to illustrate the strategy.</p>
- Communication of Failure	
- Reporting	
- Recording	
- Scenarios	
- Speed Restriction	
- Dwell Time Extension	
- Fall Back Operations	
- Single Line Operations	
- Headway during Single Line Operation	
- Loop Operations	
- Event Operations or Total Line Blockage	
- Replacement by Bus I Taxi	
- Recovery	
Recovery Scenarios	
- General	<p>This chapter also includes equipment degradation which can cause inconvenience to passengers or delays to the system.</p> <p>For all the scenarios included in the list, the operational response, mobilization of staff and adjustment to the services should be described.</p>
- Train Door not closing/ failure	
- Turnout failure	
- Train can be reset and is able to continue journey	
- Train cannot be reset and needs to be rescued; automatic coupling	

Topic	Contents
- Train cannot be reset and need to be rescued; manual coupling	
- System wide Scenarios	
- Total Loss of Power	
- Partial Loss of Power	
- Total Loss of CBTC	
- Partial loss of onboard CBTC	
- Partial loss of wayside CBTC	
Emergency Operation	Emergency operation occurs where operation is stopped due to an emergency situation. The line (or the relevant section of the line) cannot be operated in normal mode or in degraded mode. In the emergency situations, operation shall be stopped, and passenger safety shall be ensured. The passengers are removed to a place of safety and response is initiated as per the established procedures.
- Response	
- Safety Measures	
- Incident Manager (IM)	
- Rescue and Recovery Team	
- Facilities	
- Rescue Equipment	
- First Aid Equipment	
- Fire Fighting Equipment	
Evacuation	There could be emergency situations when it becomes necessary to evacuate passengers from the train
- Controlled Evacuation	
- Emergency Evacuation	If the train cannot be rescued (it has failed between stations) -
- Facilities Supporting Emergencies	In extreme situations, and the passengers have to be evacuated, a rescue train (potentially operating on battery) can be used to transfer passengers. There could be other options to transfer passengers between trains
- System Operation In Case of Emergency	For non-urgent evacuation, the passengers could be guided by OCC and supported by staff who will reach the site by the quickest possible means (next train on adjacent line for example)
Interfaces to Operation	This section briefly describes the different interfaces and interdependencies between operations and other key functions within the monorail organization.
- Safety	
- Rail Safety Policy	
- Safety Management System	
- Safety Critical Position	
- Security	
- Incident Management	

2.3.8 Health and Safety

Health & Safety is monorail project's number one priority. Starting with the opening of the transit for passengers, the monorail O&M organization should foster a culture of personal accountability,

in which all employees are motivated to be focused on health and safety outcomes when making decisions.

The monorail should always achieve compliance with all relevant Health & Safety legislation. The O&M safety team should identify Health & Safety hazards and adopt a risk-based approach to managing the risk from all hazards. They should encourage all staff to seek a better way of working which improves safety and eliminates risk.

The safety management system must contain and apply plans to monitor compliance with the pre-defined processes and ensure continual improvements through regular audits and control verifications.

The most common standard is ISO 45001, which although not transport-specific, is widely used in industry. The application of this standard offers an expedient enhancement to the laws.

O&M safety team should have a single Safety Policy and develop a common and positive safety culture that encourages all its employees, contractor and subcontractor employees to engage and manage both health and safety in the workplace and the health and safety of all persons exposed to the operation of the railway.

2.3.9 Total Cost of Ownership Models

Introduction

Total Cost of Ownership models (TCO) in this guidance document is used loosely to mean Whole Life Cycle Costs (WLCC) of the assets, even though the two terms are different. Broadly speaking, assets are created by the construction team and handed over to the O&M. The amount spent in the creation of the assets at the point of handover represents the capital expenditure (Capex). The assets are then put to use to transport passengers and generate income for the transit authority. In this process there is wear and tear which needs regular attention. Some of the assets / systems undergo technological obsolescence because of advancement of technology and other factors. Sometimes, there are incidents which result in damages to the assets and needs repair. Finally, over a period of time, some assets, or their critical parts reach the end of their useable life and need renewals, replacement or life extension. Life extension, renewals or replacement costs are generally accounted for as Capex for obvious reasons, rest of the interventions are classified as operating expenditure (Opex) and include preventative and corrective maintenance.

There are many factors that affect the overall costs involved in operating a system. While some of these factors are out of the operator's control, many can be influenced and should therefore be monitored continually.

An effective way of achieving an end-to-end approach to total cost of ownership is to be involved in designing the system and the building in the initial phases. In many cases, an initial capital expenditure or a decision on the installation design can help to minimize long term the resources required for operation (such as staff, tools, materials). These decisions can have far-reaching implications for the total cost of ownership.

The main parameters influencing the total costs of a system are

- the location of the system and its surroundings,
- the configuration of the technical components,
- the number of stations,
- the number of operating hours,
- the operating speed, and
- the energy costs.

TCO models

TCO models guide transit authorities to effectively manage the assets, costs, risks and performance. They provide good practice investment decision making, including the impact of constraints such as funding. These models are developed to help the authorities or the operators to respond quickly with agility and efficiently so that the right decisions are taken with respect to the interventions with the assets. The main objectives for these models are as follows:

- Help to develop long term asset management plans
- Reduce costs and risks over a period of time
- Develop efficient strategies by capturing the asset condition and behavior under use
- Test different options for interventions under a range of funding scenarios
- Develop strategies to deal with obsolescence

Initial investment is a key driver to the whole life cost; other significant factors are usage and technology.

The development of TCO models is a specialist topic which requires multi-disciplinary team. Normally these are outsourced to external consultants with a heavy participation of internal teams.

Whole life costs are broader than TCO of assets, as they include system expansion, additional fleet to cater to increased demand etc.

2.4 Investment and Funding

2.4.1 Monorail System Procurement and Finance Models

Once the Monorail system has been properly defined and a final check on feasibility has been performed, the resulting project is ready to be procured. In this chapter, post-planning procurement activities are described. For each step, there are decisions about options within the project's procurement, implementation, and operations phases.

This chapter defines the typical standard procurement contracting approaches and procurement processes.

The contracting approach is the way the work is divided into packages (contracts) that best suit the nature of the project and the parties expected to carry it out. The procurement methodology is the procedure used to select the team that will do the work defined in the contract approach. *TCRP Report 131: A Guide- book for the Evaluation of Project Delivery Methods* is an excellent resource on this topic.



The contracting approach is the way the work is packaged in contracts that best suit the nature of the project and the parties expected to carry it out. The work of a Monorail project can best be divided into two general areas:

Operating system—The operating system includes all of the mechanical and electrical equipment that make up the Monorail system (vehicles, automatic train control system, communications systems, power distribution system, station equipment, guideway equipment, safety equipment, other equipment, and the maintenance equipment and tools).

Fixed facilities—Fixed facilities are the buildings, spaces within buildings, building mechanical and electrical systems, guideway structures, stations, power substations, and other structures and civil works associated with and in support of the Monorail.

Assigning the work should be based on ‘who does what the best’ and ‘who can best control the risks’ of that part of the project.

The operating systems of Monorails are typically proprietary, often with patented designs, and are usually available only as unique complete packages. Therefore, it is best that at least the operating system be delivered through a single contract with a qualified supplier.

Minimizing interfaces, conflicts, and contractor dependencies should be among the deciding factors in assigning the work of the fixed facilities. Facility work that is not involved with other construction (such as commercial spaces, landscaping, or other disconnected builds) and that is related only to the Monorail can be packaged with the operating system or designed and built separately. Having different contractors working in the same spaces can create conflicts. Where there are interfaces between the work of separate contractors, they will be dependent on each other for the correctness of the interfaces and the schedule. Such conflicts, disagreements over interfaces, and schedule delays can lead to claims being filed by the contractors and an increase in costs. More contracts mean more coordination and management effort and increased risks associated with managing and controlling the interfaces.

Typically, the Monorail system supplier is not familiar with or qualified to design and construct the other Monorail facilities, although the supplier must provide system–facility interface information during both the design and construction phases. Some Monorail system stations are integrated into other commercial buildings or transportation hubs and other facilities.

This will affect the approach taken to procure and implement the Monorail. Often the project is separated into two or more contracts: one for the operating system and one or more for the facilities (which may be part of larger facility projects).

The infrastructure owners rarely want to operate and maintain an actual train system, unless they have experience operating and maintaining a train system. However, many times, the Monorail system supplier is perceived as the organization that best knows the system, including its O&M and the owning entity usually wants to ensure that the system operates as required for a significant period of time, particularly as it is proprietary and the detailed design and implementation is usually done by the supplier, with any problems being solved by the supplier. Finally, if the procurement process includes pricing an O&M period, the owning entity can receive a competitive package for the system and its O&M.

Thus, it is frequent that clients will opt to have the system supplier perform all O&M services for at least several years. Three to 5 years is typical, and usually the contract is renewable for at least one more term at the owner’s option. Subsequent periods are often negotiated, but occasionally

they are competed among the supplier and third parties. Variations on this include the public transportation operator staff overseeing the operations and the supplier performing maintenance. A few owning entities do both or have contracted with a third party for both or for maintenance, usually after an initial period undertaken by the supplier.

2.4.2 Procurement Methodology

Many procurement methodologies can be used for Monorail systems. Typical procurement alternatives include:

- Design-bid-build
- Limited design-build
- Split design-build
- Design build
- Design-build-operate-maintain

These broad categories are discussed in the subsequent sub-sections. There can be variations to each approach; only the basic procurement concept is discussed in these subsections.

Conventional Design-Bid-Build (DBB)

DBB is the conventional project procurement approach under which the owning entity contracts separately with a designer(s) and construction contractor(s). The design entity provides detailed, prescriptive design (plans and specifications) documents. The owning entity subsequently solicits fixed price bids from construction contractors to perform the work provided in the design documents. The contractor is usually selected on the basis of the lowest price. The owning entity and design entities may separate the project design documents into multiple specialty contracts.

This approach requires the owning entity to award and administer separate contracts to each contractor. This alternative allows the owning entity to retain maximum design control, but also carries the responsibility and risk for designs, contractor coordination, integration, and scheduling. The owning entity would need a large staff or set of consultants for detailed design, contract administration, and project/construction management to assume the responsibility for these multiple contracts. It would be responsible for the cost, schedule, and technical risks of the project and the integration and interfaces among the many contracts. With such a separation of project aspects, the owning entity usually undertakes the O&M functions as well.

This approach is often followed for urban rail transit projects.

Limited Design-Build

With a limited design-build (sometimes called limited turnkey) project approach, the owning entity and its system consultant develop performance specifications for the system elements, usually as a complete system. The owning entity and its architectural and engineering consultants develop detailed design plans and specifications for the facilities. The owning entity then contracts with a single entity to perform all Monorail operating system design, manufacture, implementation, and tests under a single design-build contract. The facilities are each designed, procured, and built separately using the conventional design-bid-build method.

This alternative allows the owning entity to retain facility design control, but transfers most of the system integration responsibility to the Monorail contractor, except possibly for the interfaces

among the operating system and facilities. Interfaces can be led by the owning entity and its system and project management consultants, or this responsibility can be assigned contractually to the system contractor.

Split Design-Build

The split design-build (sometimes called split turnkey) approach is the same as the limited turnkey alternative with respect to the operating system. However, with this approach, all the Monorail facilities are contracted to a single entity that will perform all final design and construction under a second design-build contract. This consolidates all facilities' design and construction into a single point of contact.

These alternative transfers most of the integration to the contractors and limits much of the owning entity's risk. The owning entity can retain the responsibility for integration of the operating system and facilities, which are usually done with the assistance of its system and project management consultants, or the responsibility can be assigned to the system or facilities contractor.

Design-Build

The DB approach, sometimes called a turnkey approach, allows the owning entity the maximum opportunity to reduce costs and schedule risks by contracting with a single entity for design and construction of the entire project, for both system and facilities. With this alternative, the contractor assumes responsibility for all the detailed design, construction, integration, schedule, and cost risks, and the owning entity has one organization to go to.

The single procurement and internalized project integration can result in a shorter overall schedule. The owning entity has a large, consolidated package for procurement. The owning entity and its system and facility design team take the design to about the 30% level, enough to define the project thoroughly and obtain valid prices. The owning entity subsequently loses some control of the detailed design and construction packaging and implementation. It will want to retain some design and schedule control over the project due to specific operational needs; this is possible with proper use of design reviews and payment milestones and the use of an overall project management team.

Because no single contractor has all the needed expertise in Monorail systems and facilities, the owning entity selects a team with all the requisite capabilities. Particularly if a low-bid process is used, the winning team might not include the best Monorail technology, the best designers and the best construction contractors. To obtain the best of each category, the owning entity could procure each major contractor separately and then require that the separate winning contractors form a team. This approach has the potential problem of contractors that are not compatible, and thus increases the owning entity's risks and integration responsibilities, partly negating the possible advantages of having a single team. With this approach, the contractor team leader is often the construction contractor because it has bonding and management capabilities. The owning entity or a third party would have O&M responsibilities. Construction and design contractors typically want to do their work, be paid, and move on; they do not want to retain longer-term responsibilities such as for O&M. If the system is supplied by a Monorail supplier, it could be retained to provide O&M services.

Design-Build-Operate-Maintain (DBOM)

The DBOM (sometimes called super turnkey) approach transfers the operations and maintenance of the system to the contractor in addition to the design and construction of the operating system and facilities.

The advantage to the owning entity is that the contractor will be responsible for all aspects of the Monorail design and construction, as well as the operations and maintenance of the system. Typically, however, the O&M contract will be with the system supplier and not the entire contractor team.

A possible advantage of this approach is that the schedule for procurement and construction might be reduced.

The owning entity gives up considerable control of all aspects of the project. This makes the contractual and procurement documents and phases critical to the success of the project.

A variation of the DBOM approach is where the owning entity operates the Monorail system while the contractor maintains the system. This approach is abbreviated as DB-M.

Public-Private Partnership (PPP)

In the past several years, this approach, also called P3 (or in FTA parlance, Penta-P), has become more prevalent in the United States. This approach is similar to the DBOM/super turnkey approach but with a mix of public and private funding. The public agencies control the project in terms of procurement, general design (approximately 30%), environmental clearances, jurisdictional coordination, project oversight, and considerable percentage of the construction cost. Private funding is used to cover the remaining construction cost and repayments are usually made via operating budget.

This approach may be considered for other Monorail projects if the required funding is not initially available and other conditions are conducive. It is, however, only an alternate funding mechanism.

2.4.3 Procurement Process Alternatives

This section discusses two procurement process alternatives: sole source and competitive.

Sole Source Procurement

In a non-competitive, sole-source procurement, the owning entity determines that only one supplier is capable of or is strongly preferred for the delivery of the Monorail system. State and local statutes/ordinances usually permit agencies to make this determination if they can demonstrate that a sole-source procurement is in the best interest of the project (due to existing conditions, budget, and/or schedule) and that a competitive procurement process would not yield any greater benefits. In such a case, the owning entity enters into negotiations with the selected supplier, and when the contractual terms, scope of work, and price are agreed, a contract is awarded. Usually this is used for an extension to an existing system that the selected supplier installed initially, and due to the proprietary nature of the technology, no other supplier can do the work.

In almost all cases when the Monorail will be newly built and is not an expansion or addition to an existing system, there are multiple technologies that can provide the required service. Thus, a

sole-source procurement is not justified, and a competitive procurement approach should be pursued.

Competitive Procurement

Many different competitive procurement processes have been used successfully for public procurements of transit systems. Three basic types are:

- Competitive one-step
- Competitive two-step (low bid)
- Competitive negotiated procurement (best value)

These types are explained in the following subsections. There are many variations involving these approaches. The exact procedure should be developed in compliance with the owning entity's customary contracting and procurement procedures and applicable laws and regulations.

In all of these, an owning entity can first use a request for information/interest (RFI) to determine the potential suppliers that might participate in the procurement.

Typically, the RFI will include a summary description of the project (initial and ultimate), and a list of information requested, such as general information about the supplier's technology(ies), specific technical solutions with the supplier's technology for the project, experience with similar projects, financial capabilities and strengths, project management approaches and tools, and the like.

This can be the initial formal step of a procurement or an informal seeking of information. As part of the formal process, there will also be information about screening criteria to select a shorter list for the next step in the process. In this case, some suppliers that express interest might be removed from consideration, either because they and/or their technology did not meet project requirements, or they did not respond to the RFI.

The RFI should be sent to all known suppliers and advertised in trade journals and other media that will reach the widest audience. Typically, this is a two- to three-month-long step, depending on the administrative and legal requirements of the owning entity.

The next step (or possibly first step) in the process can be a request for qualifications (RFQ).

This is always a part of the formal procurement process. It is used to pre-screen potential proposers and technologies to focus the list to a set of well-qualified ones.

The RFQ contains the same sort of information and response requirements as an RFI. This formal pre-qualification process can save the owning entity the time and expense of evaluating proposals from unqualified proposers/technologies, as well as saving prospective proposers who are not qualified the cost of preparing a proposal. Because the RFQ is an additional step, it normally extends the length of the procurement process by several months. Alternately, the owning entity can go directly to the proposal stage without any such screening.

If an RFI or RFQ is not used, then the owning entity should notify all known suppliers and give the RFP extensive advertising/publicity.

Competitive One-Step

The competitive one-step procurement approach is characterized by a solicitation by the owning entity to which potential contractors submit their qualifications (if no RFQ) and technical, management, commercial, and price proposals all at one time. The RFP is developed in detail by the owning entity and its consultant. This package includes everything the proposers need to submit a complete and responsive proposal:

- The instructions to proposers (which includes summary evaluation criteria as well as a list of everything required to be included in the proposal),
- A detailed description of the project (plans and drawings to the 30% design level):
 1. The contract:
 - General terms and conditions [often standard for the owning entity, but modified for a design-build type (DB, DB-M, DBOM, etc.) contract],
 2. Special (management) provisions.
 - Technical provisions (performance specifications),
 3. O&M provisions (often a separate O&M contract), and
 4. Project reference drawings.

The RFP specifies precisely the information required in the proposal. Typically, these instructions and the format are detailed so that the owning entity can clearly compare and evaluate each proposal against the criteria and against other proposals.

The owning entity evaluates the responses using a detailed evaluation plan, which is important in order to avoid or defend against challenges to the selection. The evaluation plan includes detailed evaluation criteria (and weightings as appropriate) and is established in advance. The criteria normally include such items as demonstrated successful experience in designing, implementing, and operating systems similar to the project; evidence that equipment is technically mature and capable of satisfying the availability and other performance requirements; compliance with provisions in the contract; corporate resources sufficient to back up performance guarantees and warranties; demonstrated ability to complete projects of similar size and complexity on time and within budget; experience and capabilities of key personnel; aesthetic compatibility and physical and structural fit of the system in the provided facilities; and ability to accomplish future expansion.

Based on the evaluation and comparison of proposals, the owning entity makes a determination on responsibility and responsiveness and then selects the lowest price or best value.

At any point in any of these processes, the owning entity may decide to award the contract, cancel the procurement, or re-advertise the procurement.

Competitive Two-Step

The competitive two-step procurement approach can be used when the potential suppliers or their products or services being solicited might not be considered equal in terms of technical merit, quality, or price.

Step one. This step consists of a partial RFP being sent to the list of potential proposers. The partial RFP includes all aspects of a full RFP except for pricing. (Any pricing data will typically disqualify a proposal in step one). The technical, management, and qualifications information are then evaluated in accordance with the evaluation plan to determine the acceptability and ranking

of the proposers. There can be one or more iterations for clarification questions, with updated proposals being submitted by each proposer. Addendums to the RFP can be issued; final, conformed proposals are submitted and evaluated. The final, complete proposal must be in conformance with the RFP, including all clarifications and addenda. Final non-priced proposals are categorized as either qualified or not qualified for price proposals.

At the end of this (single or iterative) step, proposers deemed by the owning entity to be qualified for the project are invited to participate in step two. Those proposers found to be not qualified will be notified of the reason(s) for this determination and will not be permitted to proceed further.

Step two. Upon successful completion of step one, an invitation to submit price proposals will be issued to those firms whose step one proposals have been qualified (the competitive range). This could be all or a few of the step one proposals. Typically, two or three proposals are wanted in the competitive range.

The owning entity then evaluates the price proposals, again based on the evaluation plan, which includes reasonableness. If a low-price approach is used and the competitive range has been judged in step one to be essentially equal, then the owning entity selects the proposer submitting the lowest total fixed-price bid for the Monorail procurement and the Monorail O&M contract. If there are options included in the RFP, the prices for these options can also be included, but the selected options should be determined in advance.

If a best-value approach is used, then the weighted scores from step one and the step two proposals are summed and the proposer with the highest score is selected. The best-value approach considers price and other factors to arrive at the proposer that offers the best overall value to the owning entity. The evaluation criteria must be clear, as must the process to arrive at the final score. There are multiple ways of doing this given in the literature. One that has been used successfully in several transit procurements is based on a numerical approach. Each evaluation criterion is disaggregated into a number of specific categories or requirements. Each is weighted. Numerical ratings are given to each proposer on each item (typically a 5-scale: 0, 1, 2, 3, 4), depending on whether and how well the item is met. The ratings and weightings are applied to technical, management, qualification, and price aspects of the proposal. The sum of these ratings and weightings is then used to select the best value proposal.

Again, at any point in the process, the owning entity may decide to award the contract, cancel the procurement, or re-advertise the procurement.

Competitive Negotiated Procurement

The competitive negotiated procurement approach is a method whereby the contract award is made based on price and other evaluation factors considered in the best interest of the owning entity. The owning entity has the ability to negotiate with multiple proposers at the same time in strict confidence on all matters in the proposals.

In the approach, the owning entity solicits proposals via the RFP process. The respondents are required to submit their qualifications and technical, management, and price proposals at the same time but in separate envelopes. No cost, price, or financial information is to be included in the technical or management proposals. Initial evaluations of these proposals are completed without knowledge of price and financial data in order to ensure that such evaluations are

objective and free from any low-price bias. Proposers and proposals are rated and ranked based on these non-price proposals, by either a quantitative or qualitative procedure.

After opening the price proposals, in confidence, the owning entity evaluates them; then, in conjunction with the technical, management, and qualifications parts of the proposals, it determines the competitive range. The owning entity can then conduct separate negotiations on technical, management, pricing, and other matters, in strict confidence with each of the suppliers with proposals found to be in the competitive range.

Upon completion of negotiations, the owning entity requests best and final offers (BAFOs). The BAFO follows the same format as the initial proposals and can include updates on any or all aspects of the proposal requested by the owning entity. BAFOs are evaluated in accordance with the same criteria and procedures as the initial proposal. The best-value award is made on the basis of price and other evaluation factors that are considered to be in the best interest of the owning entity. As with the other approaches, at any point in the process, the owning entity may decide to award the contract, cancel the procurement, or re-advertise the procurement, including using a different approach.

The term ‘bid’ is not used in the competitive negotiated procurement method. The acceptability and quality of a proposal is assessed in terms of a set of requirements and evaluation criteria. Most competitive negotiated procurements score the qualifications of the suppliers as part of the basis for the award. Even with a best-value approach, price is usually considered the key evaluation factor because it is the determinant of project affordability and proposal value.

Before soliciting proposals, the owning entity must determine whether to evaluate the responsive proposals on the basis of the lowest price or to score them using predetermined criteria to identify the best overall value to the owning entity. The best value may be based on a predetermined weighted combination of the price, technical merit, management, qualifications, and/or commercial scores or a ranking.

2.4.4 PPP Models

Public-Private Partnerships (PPP) are collaborative agreements between government entities and private sector companies to finance, build, and operate mass transit projects. These partnerships leverage the strengths of both sectors to deliver efficient and effective transit solutions. Here are some concise PPP models commonly used in mass transit:

Build-Operate-Transfer (BOT)

Description: The private sector designs, finances, builds, and operates the transit system for a specified period. After the contract ends, ownership is transferred to the public sector.

Example: A private company constructs a new monorail line and operates it for 20 years before handing it over to the city government.

Build-Own-Operate (BOO)

Description: The private entity designs, builds, owns, and operates the transit system indefinitely. The government might regulate service standards and fares.

Example: A private firm develops and runs a monorail system, retaining ownership and operation rights.

Design-Build-Finance-Operate (DBFO)

Description: The private sector is responsible for designing, building, financing, and operating the project. The public sector retains ownership and may provide payments based on performance.

Example: A consortium constructs a monorail system, operates it, and receives payments tied to service quality and ridership levels.

Concession Agreement

Description: The government grants a private company the right to operate and maintain an existing transit system, usually involving significant upgrades and expansions.

Example: A private operator takes over a city's aging metro system, invests in modernization, and manages operations under a long-term concession.

Lease-Develop-Operate (LDO)

Description: The public sector leases existing infrastructure to a private company, which then develops and operates the system.

Example: A private entity leases a monorail line, upgrades it, and runs passenger services, sharing revenue with the government.

Joint Venture

Description: Both public and private sectors jointly invest, develop, and manage the transit project, sharing risks and rewards.

Example: A city government and a private company co-invest in a monorail project, jointly managing construction and operations.

Benefits of PPP Models

- **Efficiency:** Leveraging private sector expertise can lead to more efficient project delivery and operations.
- **Risk Sharing:** Risks are distributed between public and private partners, reducing the financial burden on the public sector.
- **Innovation:** Private companies often bring innovative solutions and technologies to transit projects.
- **Financing:** Access to private capital can accelerate project timelines and reduce the need for public funding.

Conclusion

PPP models in mass transit offer a variety of structures to suit different project needs and contexts. By combining public oversight with private sector efficiency, these models aim to deliver high-quality transit solutions that are sustainable and responsive to public needs.

2.5 Future Expansion Consideration

Effective expansion of mass transit systems requires analyzing population growth and economic trends, incorporating green technologies, and planning for equitable access. In this way, incorporating future transit projects allows expansions to meet rising demands while reducing environmental impact and enhancing community satisfaction. This multifaceted approach ensures that the transit systems remain efficient, adaptable, and sustainable in the face of evolving urban needs.

2.5.1 Key Considerations for System Expansion

Performance of the Existing Fleet: Evaluating the current fleet's performance is crucial in deciding when to expand the system. The factors driving the need for expansion or extension are similar to those for establishing a new system.

Fleet Expansion and Increased Passenger Demand: Fleet expansion becomes necessary when passenger demand exceeds the current system capacity. To increase capacity, the system can:

- Increase the frequency of trains (reduce headway).
- Increase the length of trains (add more vehicles per train).
- Implement a combination of both strategies.

When operating at maximum capacity, these changes will require a larger fleet and potentially more maintenance resources, which may also necessitate an expansion of the Maintenance and Storage Facility (MSF).

System Extension and Adding New Stations: System extensions involve expanding the guideway to serve additional stations. This process includes:

- Installing new guideway and associated equipment (e.g., power rails, control elements, switches).
- Equipping new stations with necessary infrastructure.

Fleet Considerations: Extending the system may require additional vehicles, although sometimes the existing fleet may be sufficient. If more vehicles are needed, they must be procured. Additionally, the MSF may need to be expanded or relocated depending on the extension details.

Process for Reviewing and Selecting Expansion Options

When considering either fleet expansion or system extension, a thorough multi-step process is essential to review options and select the best approach. The steps in this process are as follows:

1. **Assess Current System Performance:** Evaluate the existing fleet and system capabilities.
2. **Identify Demand and Capacity Needs:** Analyze passenger demand and determine necessary capacity increases.

3. **Develop Expansion Plans:** Create detailed plans for either fleet expansion or system extension.
4. **Evaluate Infrastructure Requirements:** Assess the need for additional guideway, equipment, and station infrastructure.
5. **Cost-Benefit Analysis:** Conduct a comprehensive analysis of costs and benefits for each option.
6. **Procure Additional Resources:** If needed, acquire additional vehicles and expand maintenance facilities.
7. **Implement Expansion:** Execute the chosen expansion strategy efficiently.
8. **Monitor and Adjust:** Continuously monitor system performance and make necessary adjustments.

This structured approach ensures that any expansion or extension of the monorail system is thoroughly evaluated and effectively implemented, meeting the growing needs of the passenger demand.

Typical fields of investigation

Topic	Contents
Demand Forecasting	<ul style="list-style-type: none"> ▪ Analyze current and projected population growth, urbanization trends, and economic activity. ▪ Utilize data analytics and modelling to predict future ridership and transit needs.
Sustainability	<ul style="list-style-type: none"> ▪ Integrate green technologies such as electric or hydrogen-powered vehicles. ▪ Plan for reduced carbon emissions, energy efficiency, and environmental impact.
Funding and Financing	<ul style="list-style-type: none"> ▪ Explore diverse funding sources, including public funds, private investments, and international grants. ▪ Implement innovative financing mechanisms like value capture and congestion pricing.
Technology Integration	<ul style="list-style-type: none"> ▪ Incorporate smart technologies for real-time tracking, fare collection, and passenger information systems. ▪ Plan for autonomous vehicles and other emerging transit technologies.
Infrastructure Scalability	<ul style="list-style-type: none"> ▪ Design adaptable and modular infrastructure that can be expanded or upgraded with minimal disruption. ▪ Ensure that new transit lines are compatible with existing systems.
Community Impact	<ul style="list-style-type: none"> ▪ Engage with local communities to address concerns and incorporate feedback. ▪ Plan for equitable access, considering underserved and low-income areas.

Intermodal Connectivity	<ul style="list-style-type: none"> ▪ Enhance connections between different modes of transport (e.g., buses, trains, bikes, and pedestrian pathways). ▪ Develop integrated ticketing and seamless transfer systems.
Regulatory and Policy Framework	<ul style="list-style-type: none"> ▪ Update regulations to accommodate new technologies and operational models. ▪ Ensure policies support long-term transit development and operational efficiency.
Risk Management	<ul style="list-style-type: none"> ▪ Identify and mitigate potential risks, including financial, operational, and environmental risks. ▪ Develop contingency plans for unexpected challenges.
Operational Efficiency	<ul style="list-style-type: none"> ▪ Optimize route planning, scheduling, and resource allocation. ▪ Implement maintenance strategies to ensure reliability and longevity of transit assets.

By considering these factors, mass transit systems can be effectively expanded to meet future demands, ensuring sustainability, efficiency, and community satisfaction.

2.5.2 Strategies for Fleet Expansion vs. Longer Trains

In the context of urban rail transit systems, expanding capacity to accommodate growing passenger demand is a critical challenge. Two primary strategies for fleet expansion are commonly considered: operating shorter trains at higher frequencies or using longer trains at the same frequency. Each approach has distinct advantages and considerations from the perspectives of passengers, operators, and system owners.

Shorter Trains with Higher Frequency

Passenger Point of View:

1. **Reduced Wait Times:** Increasing the frequency of shorter trains means passengers spend less time waiting at stations. This can significantly improve the overall journey experience.
2. **Flexibility:** More frequent trains can provide greater flexibility for passengers, allowing them to plan their travel more conveniently and reducing the impact of missed connections.
3. **Perceived Reliability:** Frequent service often translates into a perception of higher reliability and efficiency, which can boost passenger satisfaction and encourage public transit use.

Owner Point of View:

1. **Asset Utilization:** Operating more frequent trains might require a higher number of trains in service, increasing initial capital expenditure on rolling stock. However, this can lead to better utilization of infrastructure and rolling stock.
2. **Operational Costs:** Increased frequency may result in higher operational costs, including staffing, maintenance, and energy consumption. Careful calculation and planning are needed to balance these costs with expected revenue from increased ridership.

Operator Point of View:

1. **Operational Flexibility:** Shorter, more frequent trains provide greater operational flexibility to respond to varying demand throughout the day, such as peak and off-peak periods.
2. **Signaling and Scheduling:** Implementing higher frequency services requires robust signaling systems and precise scheduling to ensure trains run smoothly without delays. This can necessitate investment in advanced train control systems.

Infrastructure Considerations:

1. **Platform Availability:** Stations must be capable of handling the increased frequency of trains, including sufficient platform space and facilities to manage passenger flow.
2. **Signaling Impacts:** Enhanced systems are required to safely manage shorter headways between trains, ensuring safe and efficient operations.

Case Study: Okinawa

The Okinawa Urban Monorail system initially operated 2-car trains but expanded with additional 3-car trains to meet the rising demand. Alongside the increase in train length, service frequency was also enhanced, providing a dual approach to capacity expansion.

Longer Trains with the Same Frequency

Passenger Point of View:

1. **Capacity:** Longer trains can carry more passengers per trip, reducing overcrowding, especially during peak hours.
2. **Consistency:** Maintaining the same frequency ensures that passengers can rely on a consistent schedule, which can be crucial for daily commuters.

Owner Point of View:

1. **Capital Investment:** Extending train length typically requires substantial investment in purchasing additional vehicles and potentially upgrading existing infrastructure, such as platforms and maintenance facilities.
2. **Efficiency:** While longer trains can carry more passengers per trip, this approach might optimize the use of existing infrastructure without necessitating a significant increase in the number of trains.

Operator Point of View:

1. **Operational Consistency:** Running longer trains with the same frequency can simplify scheduling and reduce the complexity of operations, as the headway between trains remains unchanged.
2. **Maintenance and Energy Efficiency:** Longer trains might lead to higher individual train maintenance costs but can be more energy-efficient on a per-passenger basis compared to more frequent, shorter trains.

Infrastructure Considerations:

1. **Platform Extensions:** Stations need to have platforms long enough to accommodate longer trains, which may require upgrades and investment.
2. **Capacity Utilization:** The effectiveness of longer trains depends on high occupancy rates; underutilized long trains can lead to inefficient operations and higher per-passenger costs.

Case Study: Cairo

The Cairo Metro started with 4-car trains and expanded to 8-car trains as demand increased. This strategy allowed the system to significantly boost capacity without altering the frequency of service, leveraging existing infrastructure and scheduling frameworks.

Custom-Based Solutions

The choice between shorter, more frequent trains and longer trains at the same frequency is not one-size-fits-all and must be tailored to the specific needs of the transit system, passenger demand, and operational capabilities. Factors such as platform length, signaling system capabilities, ridership patterns, and financial resources all play a role in determining the most appropriate strategy. The ultimate goal is to balance capacity enhancements with cost-efficiency, operational flexibility, and passenger satisfaction, ensuring that the chosen approach aligns with the long-term vision and growth of the transit system.

3 Urban Transit Technology Selection

When an owner/operator plans a transit line there are many urban transit technologies to choose from including bus, tram or LRV, APM, Monorail, light metro (LRT), and heavy metro (MRT) for mass transit applications. Each technology offers a range of system capacity and operating speeds, and each has advantages and disadvantages in terms of capital cost, operation and maintenance cost, and so on. Often more than one technology may be suitable for a particular application, and the process of selecting the right technology is complex and time consuming.

This chapter (Urban Transit Technology Selection) discusses each of the technologies; their target application, cost impact, quality of service impact and so on. Guidelines for selecting a technology are provided; for example, under what conditions an owner/operator or application user should select monorail as the best fit technology for their requirements.

It is important to make a technology selection in the early stages of a project to avoid wasting resources in evaluating clearly sub-optimum solutions. The ideal process is for an owner/operator to select the technology that meets its needs and preferences, and then optimize that technology for the application. Early selection of the right technology will make a city's project more viable in planning, more successful in implementation, and less expensive for the total turnkey system.

3.1 Introduction

The purpose of this chapter is to offer guidelines on urban transit technology selection. The selection process should occur in the earliest stages of urban transit system planning, providing guidance for a more successful transit project implementation. This will encourage more buy-in from public and political parties and attract funding. The benefits of early technology selection include:

- Early planning of marketing and communications for the transit project,
- Better acceptance by politicians, the public and potential special groups (e.g. minorities),
- Lower cost through early focus on the most efficient technology for the application,
- Better integration with the existing transit network and city infrastructure, resulting in better connectivity and less travel time for commuters,
- Early investigation of needs and sources of funds, with potential for early funding.

Table 3: Key characteristics of transportation modes comparison

Item	Autonomous GRT ¹ Repurposed Street	Bus/BRT Shared Street	LRV / Tram Shared Street	Monorail Primarily Elevated	APM Elevated & Tunnel	Light Metro Elevated & Tunnel	Metro At Grade & Tunnel
System Capacity [PPHPD]	< 500 typical < 1,500 per berth	< 2,000	< 5,500	2,500 < 25,000	2,500 < 25,000	8,000 < 40,000	30,000 < 100,000
Construction Cost	Very Low	Very Low	Low	Medium	Medium	Medium	High
Construction Schedule	Very Short (repurpose street)	Very Short (Existing street)	Medium (utilities relocation)	Short (Light precast beam)	Medium (Elevated Deck)	Medium (Elevated Deck)	Long (Tunneling)
Commercial Speed	10 < 15 km/h mixed <20+ km/h exclusive	Typically below 20 km/h	Typically below 20 km/h	Typically from 30 to 40 km/h	Typically from 25 to 40 km/h	Typically from 30 to 40 km/h	Typically from 30 to 40 km/h
Headway Typical / minimum	Typical 2-5 minutes minimum 30-60 sec	Typ.10 minutes min. 5 minutes	Typ10 minutes min. 5 minutes	Typ 2-5 minutes min. 90 sec	Typ 2-5 minutes min. 90 sec	Typ 2-5 minutes min. 90 sec	Typ 3-5 minutes min. 120 sec
Urban Fit	Follows Street Winter limitation	Follows Street Winter limitation	25 m curves 6% grades (sand)	46 m curve 6% grades	22 m curves 6% grades	140 m / 4% (Rotary) 35 m / 6% (LIM) ²	140 m curves 4% grades
Relief of Traffic Congestion	Limited - adds congestion	Limited - adds congestion	Limited - adds congestion	Excellent - Elevated	Excellent - Elevated	Excellent - Elevated	Excellent - Underground
Noise and Vibration	Low - Electric	High - Diesel Low - Electric	High - steel rail & at grade	Low - rubber tire & elevated	Low - rubber tire & elevated	Medium (conventional) Low (steered LIM bogie) ²	Medium (non-steered bogie)
Energy Consumption	Medium to High (weight/pass space, tires)	Medium to High (weight/pass space, tires)	Medium (weight/pass space)	Low (weight/pass space)	Low (weight/pass space)	Low (weight/pass space)	Medium (weight/pass space)
Safety	Limited - SIL2 / SIL3 Speed limitations	Accidents common. Fatalities occur	Accidents common. Fatalities occur	SIL4 - Very safe. Segregated & ATO	SIL4 - Very safe. Segregated & ATO	SIL4 - Very safe. Segregated & ATO	SIL 4 - Very safe. Segregated & ATO
Life Cycle Costs Per passenger	Medium to High - (Tires, batteries, design life)	High - (Driver, tires, diesel, design life)	Medium to High - (driver, conventional bogie, track)	Medium to High (Driverless, tires)	Medium to High (Driverless, tires)	Medium (Conventional) LOW (driverless, steered LIM bogie) ²	Medium - (Driverless, conventional bogie)

FAIR

BETTER

BEST

1: Autonomous GRT is a developing technology

2: LIM - Linear Induction Motor powered light metro with steered bogie technology

Source: International Monorail Association 2015 Monorailex Conference, Las Vegas
Urban Transit Technology Selection
Tim Zhang¹, Peter Timanz², Régis Grattard³

The table explains the different modes of transportation for mass transit and provides a relative comparison of key performance characteristics. One of the leading criteria is the passenger capacity as it defines the lead input measure for further evaluation. This measure will focus quickly on the system that will make sense for a particular application. One further important characteristic is the total life cycle cost as it impacts long-term aspects. Other characteristics may be weighted different depending on specific priorities.

Comparison of Technology

Table 3 compares the technologies mentioned, in terms of the major features that can help a customer decide which technology is optimal for its applications.

Major Criteria of Technology Selection

There are many factors that affect technology selection, including:

- System design capacity,
- Capital cost,
- Urban fits or alignment limitation (curve, grade, availability of space, etc.),
- Type of line (number of stations, distance and time between 2 stations...),
- Construction time,
- Aesthetics,
- Service quality (travel time, headway, connectivity),
- Owner/operator preference,
- Safety and driverless consideration,
- Passenger acceptance,
- Operation and maintenance cost,
- Funding availability.

Urban Fit and Alignment Limitations

Elevated intermediate capacity transit technologies, such as APM, monorail and light metro, offer economical mass transit solutions for cities that cannot afford a heavy metro system. They are also sustainable solutions for cities with lower ridership demand than heavy metro.

The benefit of small curve and steep grade capabilities is that a transit line can be planned around existing buildings or along existing streets, resulting in low land acquisition and relocation costs. These features of elevated technology should be considered when planning a transit system.

Other Factors

Other important factors include a city's, or its residents', preferences, acceptance and service quality requirements.

The following section of this chapter offers an evaluation matrix to take into consideration those factors or any other factors an owner/operator may wish to include.

3.2 Process of Technology Selection

The planning process of urban transportation can be described in a stepwise approach:

- Identify key principles in your urban planning policy that would be enabled by the proposed project
- Identify key parameters from the planning policy that the project will need to address
- Consider what a successful complete mobility solution might look like
- Evaluate present and potential movement of goods and services in the intended corridor
- Prepare transportation studies to identify high level requirements for technology selection process including inter connectivity with other modes of transportation.

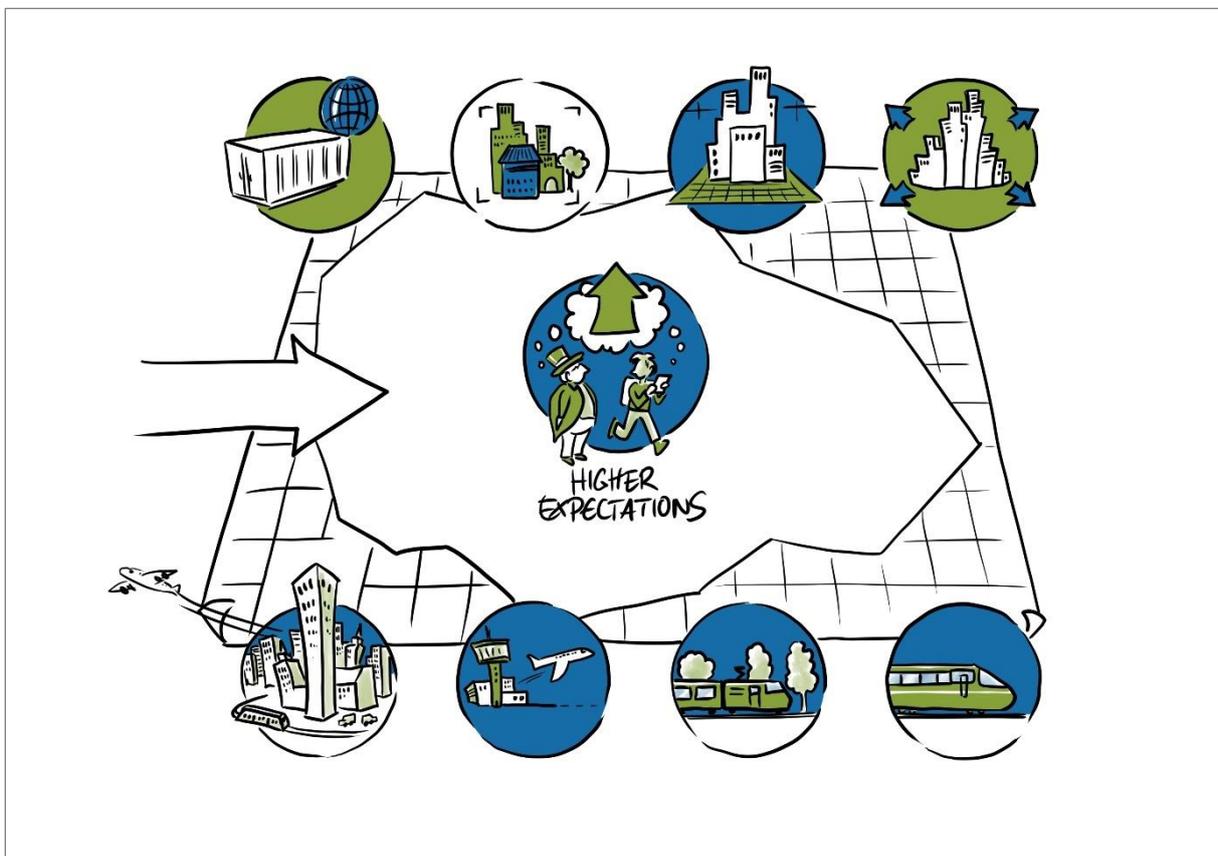


Figure 97: Requirements environment for mobility solutions

Source: Bombardier Transportation, illustration by IMA

3.2.1 Technology Selection - Step 1 Functional Requirements

Core or must-have functional requirements.

The following table identifies essential system parameters required to ensure a successful project.

The hypothetical project data is shown as an example, however for each specific application the system requirements might be different.

Hypothetical Project

System Parameter	System Requirement	Comments
System Capacity	Ultimate 15,000 [PPHPD]	Initial 5,000 [PPHPD]
System Length	20 km	Dual Lane
System Capital Budget	400 MUSD, Initial System	20 MUSD/km,
RFP Key Parameters	Life Cycle Cost	30-year system planning life
System Safety	GAO4 ATO	Service Proven History
System Route	Existing Urban Core	Dense, extensive utilities
Grades at surface	Up to 6%	Hilly terrain
Curve Radii	50 meter in key locations	Avoid infrastructure destruction
Aesthetics	Critical Aesthetics	Sensitive cultural infrastructure
Climate	5 C to 40 C	Temperate
Other Key Parameters...		

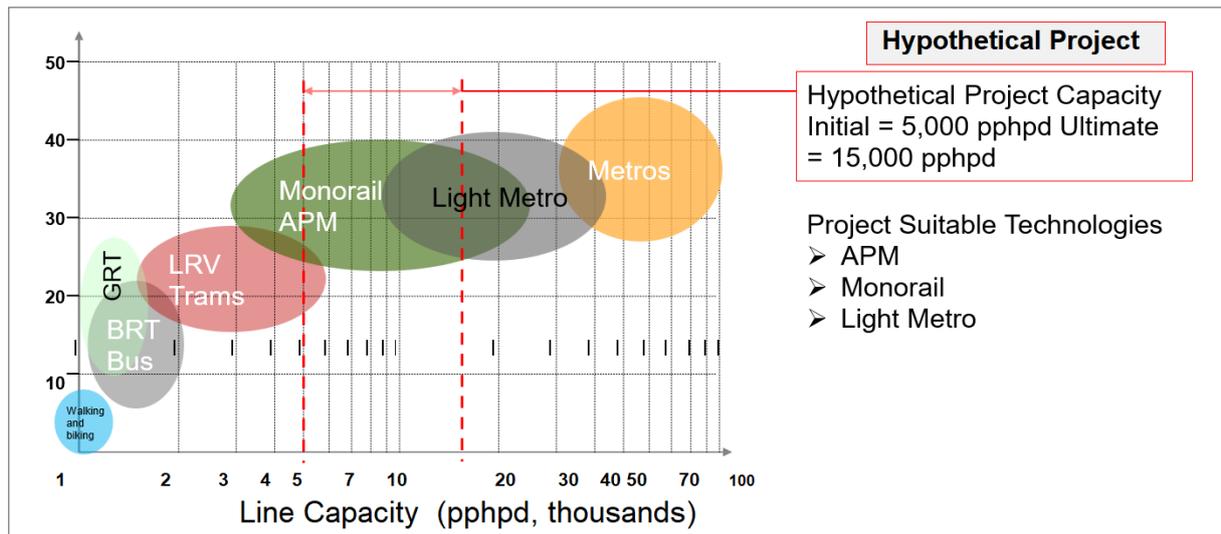
Other key parameters might be system availability or combined functionalities such steep grade with capacity.

In addition, a key consideration might be service frequency particularly when inter-connecting with other lines.

3.2.2 Technology Selection – Step 2 Limit Potential Technologies Based on Capacity

Determine required system initial and ultimate capacity [pphd] (maximum capacity between any two points)

Focus on those technologies that can best accommodate projected capacity requirements.



[pphd]¹: Passengers Per Hour Per Direction

Commercial speed²: average round trip time (including station dwell, charging time, travel time) divided by distance for a typical route

Figure 98: Capacity and commercial speed of transit technologies

Source: International Monorail Association, Monorailex Conference 2015, Las Vegas
Urban Transit Technology Selection

Capacity

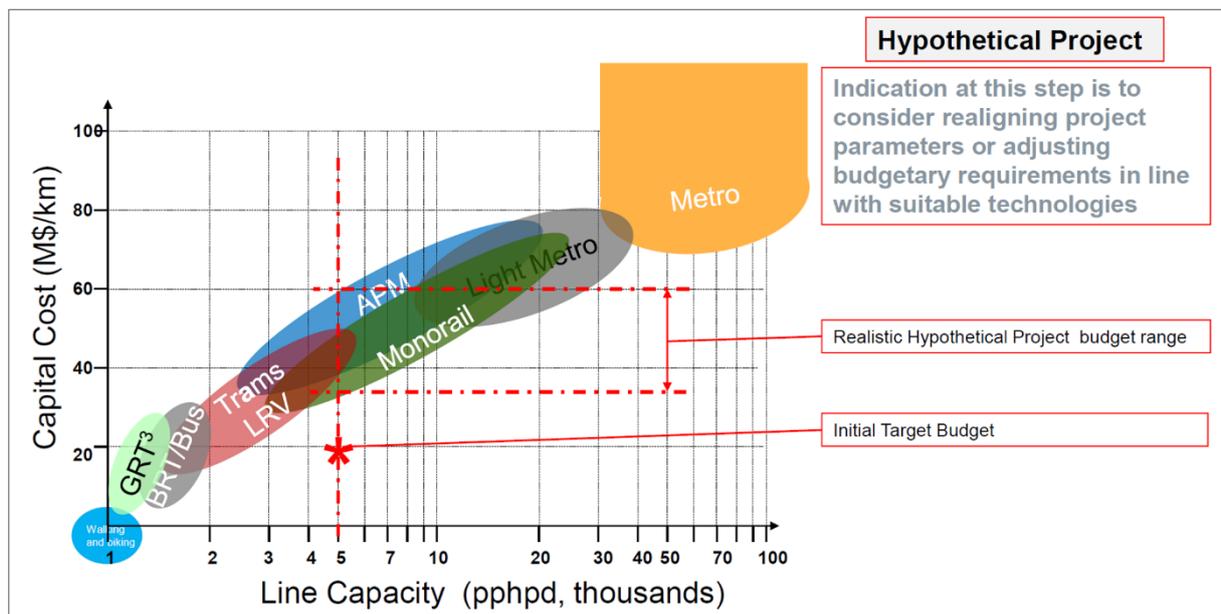
System design capacity should be the first factor to consider when selecting a transit technology. Typically, if the system capacity required is over 40,000 pphpd it is economical to consider heavy metro from the beginning. Unless there are issues such as construction time or geotechnical limitations, other technologies may not even need to be considered. The previous chart (Figure 98) offers a general guideline on how to select technology based on capacity. The capacity range here is a typical optimum range for each technology, but there may be exceptions.

3.2.3 Technology Selection – Step 3 Confirm Selected Technology Options are Affordable

Align technology options with local affordability.

Differentiation can be made between initial cost and total life cycle cost.

Establish appropriate budgetary planning and financing.



[pphd]¹ : Passengers Per Hour Per Direction

Commercial speed² : average round trip time (including station dwell, charging time, travel time) divided by distance for a typical route

Figure 99: Capital Cost of Technologies

Source: International Monorail Association, Monorailex Conference 2015, Las Vegas
Urban Transit Technology Selection

This data shows previous typical project costs and is appropriate to compare relative costs. However, absolute values need to be adjusted to reflect present day and regional condition.

Based on these cost ranges an owner/operator can decide what is affordable or seek more funding if the transit need is urgent.

3.2.4 Technology Selection – Step 4 Consider ‘Firm’ System Requirements Using a Decision Tree

This step can be used to identify the range of potential technologies for further evaluation.

This decision tree allows a more detailed assessment if multiple technologies can be considered.

Multiple Technologies Comparison Process

Urban fit means considering what could be possible in an application to best meet the requirement to minimize disruption of existing infrastructure and services.

Urban Fit – At Grade, Elevated, Underground – Gradient, Curve Radii

Environment – Winter Operation, Noise, Safety, Automated Operation

Hypothetical Project – Ultimate Capacity 15,000 pphpd

		System Design Capacity [pphpd]										
Requirement	Capacity	< 5,500					2,500 - 40,000				30,000 - 100,000	
	Typical Capacity	< 500	< 2,000	< 1,500	< 1,500	< 5,500	2,500 < 20,000	2,500 < 20,000	5,000 < 40,000	10,000 < 40,000		
Decision	Type of alignment	At-grade					Elevated				Underground	
Factors	Grade	12%	12%	12%	6%	6%	< 6%				< 3-4%	
Factors	Curve (metre)	N/A	N/A	N/A	25	25	30	50	40	120	150	
Decision	Type of technology	Bus	BRT	GRT	Tram	LRV	APM	Monorail	LIM	Light Metro	Heavy Metro	
Factors	Winter operation	adhesion mitigation	adhesion mitigation	adhesion mitigation	adhesion mitigation	adhesion mitigation	adhesion independent	adhesion independent	% Grade	adhesion	N/A	
Factors	Noise	diesel mitigation	diesel mitigation	Electric	conventional steel wheel	conventional steel wheel	Rubber tires	True radial steered bogie	conventional mitigation	conventional mitigation req'd		
Factors	Safety	fatalities occur	fatalities occur	Speed mitigation	mitigation req'd	mitigation req'd	GOA4 Safe Operations Preferred		Can be GOA4	Can be GOA4	Can be GOA4	
Factors	Manual operation / ATO	manual	manual	Limited ATO	manual	manual	30+ years history GOA4 ATO Operation		Can be GOA4 ATO Operation	Can be GOA4 ATO Operation	Can be GOA4 ATO Operation	
Factors	Service Proven Technology	Many service proven	Many service proven	Developing Technology	Many service proven	Many service proven	Many service proven		Many service proven	Many service proven	Many service proven	
Decision	Potential Technologies	Bus	BRT	GRT*	Tram	LRV	APM	Monorail	LIM	Light Metro	Heavy Metro	

* Developing Technology

Potential Technologies

Figure 100: Exclusion procedure based on core requirements - sequence of decision for hypothetical project

Source: International Monorail Association, Monorailex Conference 2015, Las Vegas Urban Transit Technology Selection

The green marked areas highlight the technologies that meet the specific project requirements.

Figure 100 illustrates part of the technology selection process. The key factor to start with is capacity. If the required capacity is below 5,500 pphpd, an owner/operator should consider an ‘at-grade’ type alignment such as bus, BRT, tram or LRV. For capacities between 30,000 and 100,000 pphpd, an owner/operator can consider underground heavy metro. For capacity in the middle range, from 2,500 and 40,000 pphpd, an elevated alignment for technologies such as APM, monorail and light metro can all be suitable and other factors should be evaluated to differentiate between these three technologies. The table above suggests using grade as the next factor to filter the technology. If the grade is between 4% and 6%, the technology can be APM, monorail or LIM-powered light metro. Rotary-powered light metro should only be considered for systems with grades less than 4% for reliable operation.

The next factor is curving capability. APM, monorail, and LIM-powered light metro with steering bogies can all handle small radius curves (50 m). Conventional light metro can typically only



negotiate curves down to 120 m. It is possible for conventional steel-wheel rotary motor power technology to go around smaller curves, but the expectation is that you will have higher wear on rails, wheels and bogies, the noise level may be unacceptably high, and derailment risk in sharp curves may become a concern.

The table also lists other factors. The matrix in the next step can be used to rate those factors to evaluate which technology in the end is the best technology for a specific application.

3.2.5 Technology Selection - Step 5 Add 'Softer' Requirements Using Evaluation Matrix

The following weighted table provides a more objective approach to softer requirements.

This matrix is intended to be flexible - configured to fit the specific client and project key requirements including 'softer' requirements.

This 1, 3, 9 weighting method will quickly differentiate those technologies that are better fits for the specific project application

Other criteria that might be considered may be the following: Ability to attract investment, carbon footprint, air pollution, etc.

Table 4: Technology evaluation matrix of hypothetical project

Hypothetical Project – Medium Capacity Technologies							
Medium Capacity Technologies							
	Weight	APM		Monorail		Light Metro - LIM	
Factors	(0-100)	1, 3,9⁽¹⁾	weighted	1, 3, 9⁽¹⁾	weighted	1, 3, 9⁽¹⁾	weighted
Customer preference	15	9	135	9	135	3	45
Capital cost	25	9	225	9	225	9	225
Construction time	20	3	60	9	180	3	60
Aesthetics	10	3	30	9	90	3	30
Life cycle cost	20	3	60	3	60	9	180
Other	10	3	30	3	30	3	30
Total	100		540		720		570

Source: International Monorail Association, Monorailex Conference 2015, Las Vegas
Urban Transit Technology Selection

Many other factors are also important for transit technology selection such as feasibility, customer preference, public acceptance, capital and O&M costs, construction time, and so on. An owner/operator can have a rating system to evaluate which technology best fits its needs. The example in Other criteria that might be considered may be the following: Ability to attract investment, carbon footprint, air pollution, etc.

Table 4 uses a weighted rating system to compare the three medium capacity technologies. In this table, an imaginary project is assumed, and each technology is rated in each category assigning a 1, 3, or 9 based on 'not suitable', 'moderately suitable' and 'definitely suitable' respectively. This method allows the factors that are important to a particular customer to stand out in the overall evaluation. Customers may use these factors, or add others, and will have a different weighting priority depending on specific needs. The idea is that this table is flexible and is offered to provide a reasonably objective evaluation of the potential technologies according to

a particular customer's needs.

3.3 Key Project Success Factors is Turnkey Procurement Process

Use turnkey procurement including significant period of operations and maintenance.

One proven success factor for a project is the use of a turnkey system procurement approach as it is integrating all functions with less risk, optimized interfaces and cohesive supply for all elements of the civil, wayside, rolling stock, signalling, communication, power supply and distribution, central control, service and maintenance and operation.

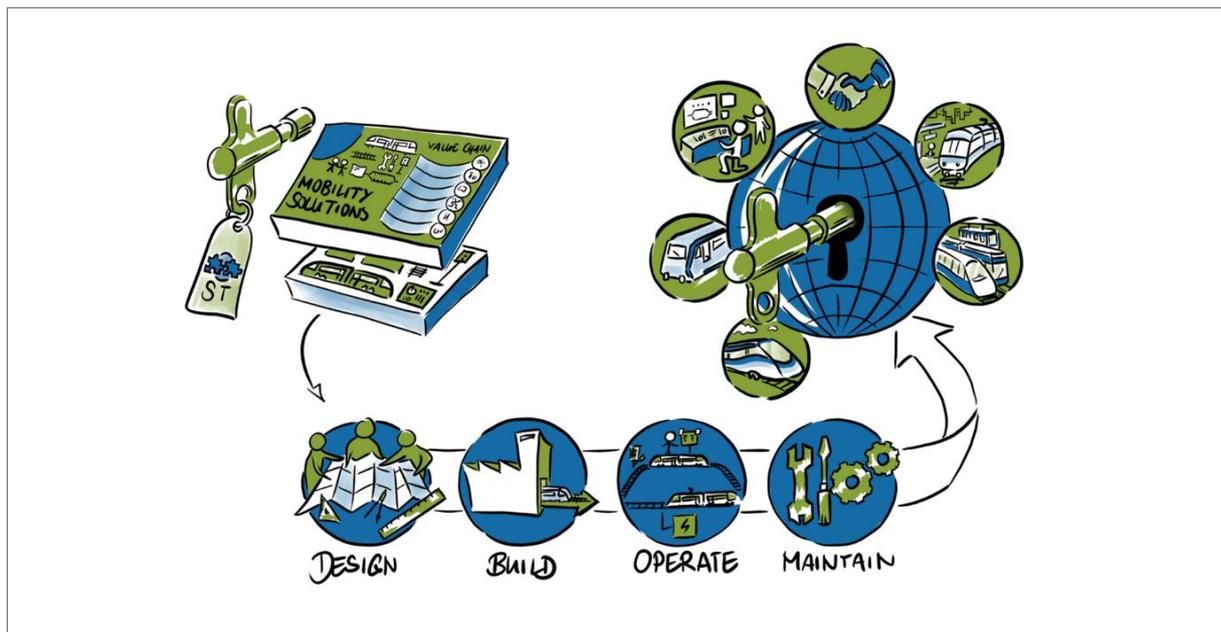


Figure 101: Turnkey procurement approach

Source: Illustration by IMA based on Bombardier Transportation

Include performance-based requirements and one single point of contact.

The turnkey procurement approach can be based on performance-based requirements in order to achieve the desired results and have the best system delivered. There are different types of procurement e.g. Design, Build, Operate and Maintain, but Finance could be added.

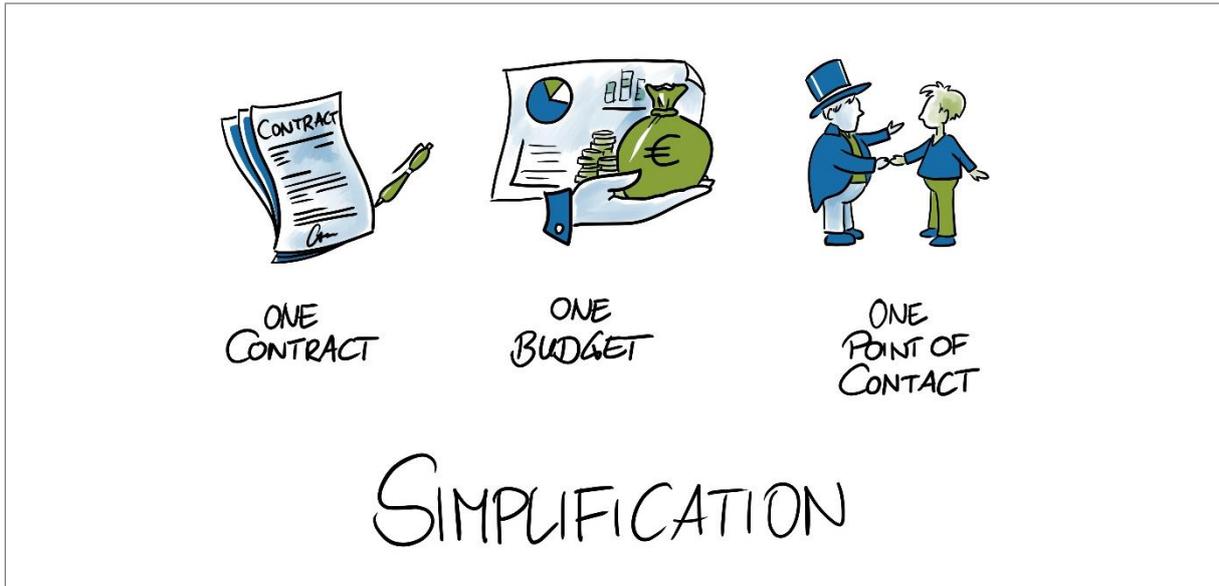


Figure 102: Simplification through turnkey procurement approach

Source: Illustration by IMA based on Bombardier Transportation

With this approach there is only the need of a single entity contract, which simplifies the whole process. This ensures a successful full mobility solution on time and on budget.

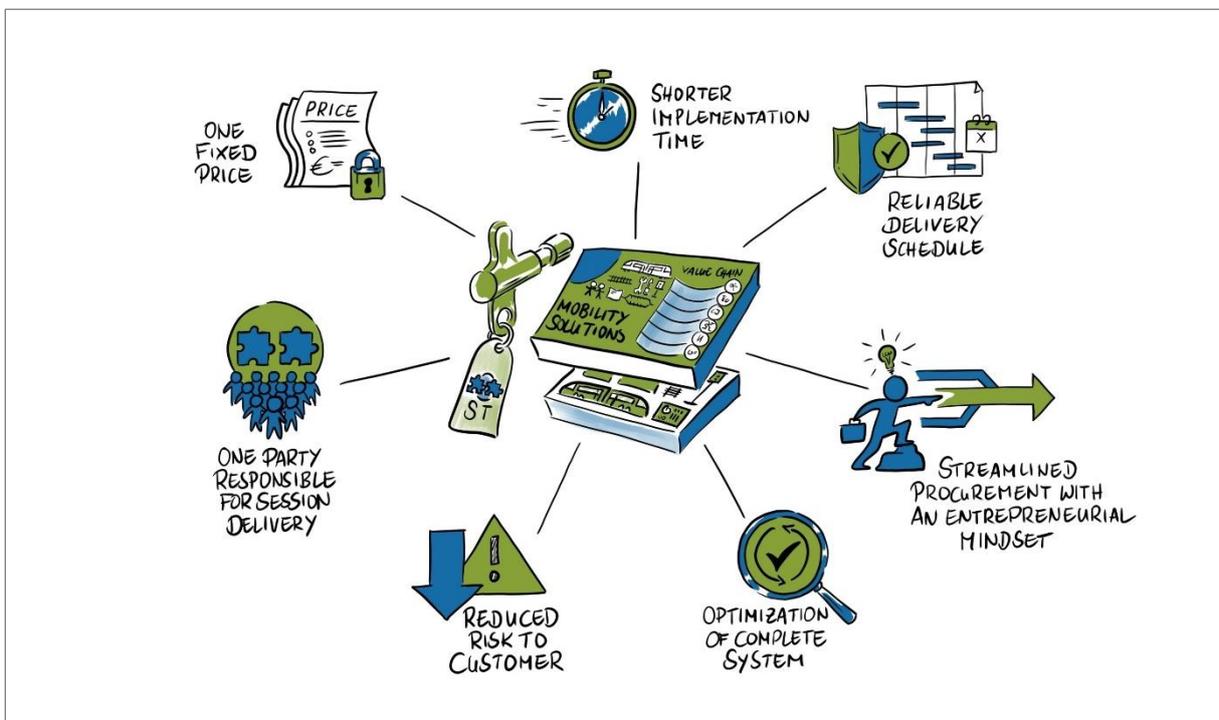


Figure 103: Advantages of turnkey procurement approach

Source: Illustration by IMA based on Bombardier Transportation

The advantages of this type of procurement are to have a fixed price, shorter implementation time, a reliable schedule, streamlined procurement with an entrepreneurial mindset, an optimized complete system, reduced risk and only one responsible party for the delivery session.

3.4 Driverless Technology and its Benefits

Fully automated driverless technology is widely used in urban rail transit systems, with the earliest driverless system starting operation on the small LRT in the 1967 for London’s Victoria Line.

The first commercial application of an APM started in Tampa in 1971 using APM technology. Light metro LIM technology started driverless operation in Vancouver in 1986. The first driverless rubber-tired metro started operation in Paris in 1998 (line 14). The first driverless heavy metro started operation in Singapore in 2003 (Northeast Line). Many transit authorities have now adopted driverless technology for new lines, and a number have converted their existing manually driven systems into driverless systems.

UITP (International Association of Public Transport) tracks driverless ‘metro’ system growth. Below is a chart from UITP that shows exponential growth of driverless urban transit systems. These fully automated and driverless systems include not only driverless metro, but also driverless urban monorail and APM systems.



Figure 104: Total growth in automated metros, measured as km in operation

Source: Illustration by IMA based on World Report on Metro Automation, UITP, 2018

There are significant benefits associated with driverless systems.

- Improved safety: Most train accidents are caused by human error.
- Shorter headway operation: Computerized, driverless trains do not require human intervention and are thus not reliant on the slower reaction times of human operators compared to those of a computer.
- Increased system efficiency: Shorter headways are possible resulting in improved ridership and increased revenues.
- Increased system capacity: Trains can be operated more frequently (i.e., at shorter headways) which allows the system to provide higher capacity with the existing infrastructure, in particular in the case of special events.

- Improved customer service quality: Shorter headways provide a more customer-friendly ride schedule for passengers.
- Fully automated systems provide higher commercial speed and thus permitting reduced fleet size to provide the same required capacity.

Reduced capital cost: Reduced headways permit shorter trains, resulting in shorter station platforms, and shorter maintenance workshops while offering the same, or better, system capacity than their longer counterparts. Shorter platforms also mean less station equipment (for example, a reduced platform screen door system). A shorter maintenance workshop means the maintenance facility and associated lifting and other equipment will be reduced. Fewer trains means that the overall maintenance facility size and scope can be reduced. Corrective and preventative maintenance can also be better planned due to the short trains.

Reduced operation and maintenance cost: Driverless trains do not require onboard personnel or personnel hosting trains on the storage lines. Removing personnel from the yard improves safety and efficiency and reduces costs.

Increased flexibility in operation: Without the need for drivers, the control center operator can change the number of operating trains based on passenger demand without the need to adjust staffing.

Reduced energy consumption: Driverless systems can optimize the travel time automatically by maintaining perfectly accurate acceleration, coasting, and braking while also regulating station dwell times to the exact preferred timing and performing turnback operations in the least amount of time. They can also incorporate scheduled make-up time in the speed profile which results in trains conserving energy while having the ability to respond to perturbations caused by passengers.

3.5 Rationale for Selecting each Technology

The following section discusses where each technology might best fit a particular application and technology limitations are explained.

Why Select Bus?

Bus and BRT are the lowest capital cost and lowest capacity public transit mode assuming the use of existing roads. They are ideal for small cities or low-capacity transit lines in big cities. BRT's system capacity is typically limited to a 2,000 pphpd range. It can be higher with double lanes and very low headway.

A double lane BRT would take significant road space away and increase congestion for other road traffic. Another reason that a lower headway is not practical is that each bus requires a driver, which is also the major component of operational costs.

Today, more and more buses operate with either batteries, hydrogen or biofuel. These buses are called 'clean buses' and they are used in many cities to address the pollution generated by traditional fossil fuel buses.

Why Select Tram/LRV?

Trams and LRVs are typically low-capacity rail transit systems. The design capacity is in the 5,000 pphpd range. A tram and LRV are an ideal solution for short frequent trips in a city core because

they operate on the surface. Construction cost is relatively low compared to elevated and underground systems. Trams only require simple, or no platforms, and passenger accessibility is most simplified. However, when planning for a tram or LRV project, it is important to know how much utilities relocation is needed. For some old cities there can be very significant relocation work, which will significantly drive up construction costs and delays.

Street level systems take already crucial lane space, have multiple traffic interactions, and can result in many accidents.

Why Select Monorail?

A monorail systems' ideal application is for capacity in the range of 2,000 - 25,000 pphpd. A monorail is capable of higher capacity because it uses a grade separated guideway and trains can be longer and the headway can be lower. There are cities that prefer to use monorails at the upper end of its capacity because of certain requirements that other technologies cannot meet. An example is São Paulo Line 15, in the east area of the city. A natural option would have been to extend the metro line, but the cost of construction of the underground tunnel would be too high to be viable and construction time would be too long. The monorail alignment follows the existing road using the median, thus saving significantly in land acquisition compared to other elevated or at-grade technologies.

Urban fit is another major reason for selecting monorail. Monorail systems can accommodate grades of up to 6% and curve radii down to 50 meters, permitting the guideway alignment to optimally follow existing rights of way such as roadways, and a system can be built without the need to tear down existing infrastructure. The line can also be placed close to buildings due to the low noise of monorail technology. The narrow guide beam provides minimum visual intrusion compared to other elevated technologies.

Adding a monorail in a town where little spare road space is available permits cars and vehicles to continue to use the existing road. The monorail line is built above the street along the exiting alignment, which generates extra transportation capacity and attracts new riders.

Another key reason for selecting monorail is tourism. With its very large windows and aerial image, monorail is known for its sleek and futuristic look and is often associated with amusement park attractions while still providing medium capacity mass transit. For cities where tourism is one of the major revenue sources, monorails can offer a good transit solution and at the same time attract more visitors to the city.

Why Select APM?

APM systems offer similar design capacity as monorail – ideally in the 2,500 to 25,000 pphpd range. APM has similar urban fit features as monorail including small curve, high grade and low noise, however APM requires larger elevated guideway structure than monorail.

APM is designed for reliable frequent operations such as airport and urban circulators. Today's APM technology is also designed for medium capacity urban applications.

Why Select Light Metro?

Light metro offers capacity higher than APM and Monorail but lower than heavy metro. Design capacity can be up to 40,000 pphpd. If an alignment is relatively straight and flat without sharp curves or steep grades, light metro may be the ideal solution.

Another advantage of light metro, especially light metro using linear induction motor (LIM) technology with steered steel-wheel bogies, is that it can operate reliably in sharp curves and

steep grades under snow and ice conditions without the need for guideway heating while minimizing wheel and rail wear. This adhesion independent technology guarantees schedules under any weather condition. For rubber-tired technology such as APM or monorail guideway heating or other means of mitigation would be needed for harsh winter operation.

Why Select Heavy Metro?

The primary consideration of heavy metro is system capacity. If an owner/operator's required capacity exceeds 40,000 pphpd, heavy metro should be the first option. Heavy metro does require higher investment and takes a long time to build, but it is the most efficient solution for high density cities. If the cost of a heavy metro system is impossible for an owner/operator to afford then it can consider an elevated light metro, APM or monorail in combination with other modes such as buses.

Discussion of Other Technologies

The technology selection discussion in this chapter does not address some other urban technologies such as urban Maglev, suspended monorail or PRT (Personal Rapid Transit). Some considerations of other technologies for urban transit application are as explained below.

Maglev

Capital cost and energy consumption are the two biggest hurdles for urban low speed maglev technology. The drive system of maglev can be very complicated which may result in very high costs. The levitation system consumes significant energy, which is not considered environmentally friendly when compared to other transit technologies.



Figure 105: Maglev in Nagoya, 2024

Source: Photo by Rodolfo Szmidke

Suspended Monorail

Suspended monorail uses vehicles hanging below a beam. The significant disadvantages are:

- Ride comfort may not be ideal because the monorail can swing as it travels, or even in stations when the train stops.
- Windy conditions can limit the operation.
- Not suitable for level boarding. Typically, vehicle floor height is above the platform to avoid collision between the vehicle and the platform due to the dynamic movements (swing) of the train.
- It is not possible to add an emergency walkway to the guideway, posing significant evacuation safety risk.



Figure 106: Suspended Monorail in Wuppertal, Germany

Source: Photo courtesy of WSW Mobil GmbH

PRT

PRT operates on its dedicated guideway with small capacity vehicles (2-4 passengers/car). System capacity is low due to the size of the vehicle. The investment in a guideway is not justified because of the low system capacity. Driverless automobiles under development, such as Google cars, offer much better economic solutions for low-capacity transit than PRT, because these cars use existing roads.



Figure 107: PRT System at Heathrow Airport, London, 2018

Source: Photo by Marko Kroenke

High Speed Metro

High speed metro is a heavy metro system that operates at higher maximum speed such as 100 km/h or 120 km/h. The application of this technology is for fast connection of major centers in the city, or extend the travel to suburban areas quickly. An owner/operator can consider this technology if it needs faster speed with longer station spacing (express type of service) and there is enough ridership to support the investment.



Figure 108: High Speed Metro in Germany, 2023

Source: Deutsche Bahn AG / Uwe Mieth

This chapter does not cover unproven transit technologies such straddling buses, which are in the early stage of development. It is not certain that they will become urban transit alternatives in the future.

Other Consideration

Operation and Maintenance

Operation and Maintenance (O&M) is a very important factor in transit technology selection. as the cost of O&M over a 20- or 30-year period is very significant. This paper does not expand on the details of O&M because it is a very complicated topic. This could be the subject of a future paper.

Open technology procurement

As mentioned in this paper, for certain capacity ranges and applications, there may be multiple suitable technologies, especially in the intermediate capacity range where a light metro, APM and monorail can all be possible solutions. An alternative to making technology selection before project implementation is to specify an elevated alignment and leave the bidders to offer their most efficient and low-cost technology solution. This would require a performance-based RFP allowing each technology to compete on an equal basis. Ideally the RFP should also include a long period of O&M (e.g. 20 or 30 years) to ensure that the proposed solution has the best life-cycle cost. The benefit of this procurement approach is that the owner/operator takes advantage of the lowest cost solution, including lifecycle costs, and minimizes overall project risk and potential for contract disputes.

3.6 Conclusion

It is important to make a technology selection in the early stages of defining the mobility needs. The ideal process is for an owner/operator to select the optimum technology, or range of technologies, to meet its needs and preferences. The right technology selection will make an owner/operator's project more viable in planning, and more successful in implementation.

This chapter outlines some guidelines on how to make a good technology selection. There are clear principles to follow in areas such as system design capacity, commercial speed and cost, as well as more subjective factors that would require qualitative analysis, such as the owner/operator's preferences and public acceptance.

This process will provide both an early detection of unsuitable technologies, and identify technologies that are a potential good fit including those technologies that may not have been considered. It's important to keep the process open and unbiased to the greatest extent possible. By allowing multiple technologies during the entire bidding process based on total turnkey performance-based specification the client will benefit from the best-fit solution for the application.

Ideally the bidding process will also include a significant period of operations and maintenance to ensure that total life cycle cost is considered in the final selection.

In order to minimize the risk for the owner/operator, it is recommended that the 'Request for Proposal' is extended to a single entity (which can be a consortium) for the complete turnkey



project, thus making the project easily accountable and avoiding errors in assigning responsibilities.

In summary:

- Perform robust transportation studies and urban planning activities to clearly define your project unique requirements
- Evaluate potential solutions early to understand best fit technology choices.
 - Follow clear principals such as capacity, affordability, topography, environment.
 - Consider subjective factors such as owner/operator preferences, aesthetics, and public acceptance.
 - Maintain a process which is open to multiple technology options.
- An objective technology selection process will enable an appropriate and viable solution
- Use a turnkey system procurement to ensure a best-fit successful project.
 - Single entity contract
 - Performance Based Specification
 - Cover the complete mobility solution
 - Design, Build, Operate, Maintain
 - Include a significant period of Operations and Maintenance to account for total system Life Cycle Cost

4 Success Stories about Monorails

4.1 Opportunities and Challenges

Monorails offer several opportunities and face various challenges in transportation and urban planning.

Opportunities

Urban Mobility Solutions: Monorails provide an efficient means of urban transportation, especially in densely populated areas where space is limited. They can ease congestion and offer an alternative to traditional modes of transportation like buses and trains. More recently, monorails have been used in projects with longer systems between urban centers. Monorails, being elevated, are not exposed to the disturbances of other systems that are at-grade, running on congested streets, or with the presence of animals or pedestrians. They are economical to build compared to heavier systems.

Environmental Benefits: Monorails are often seen as environmentally friendly due to their use of electricity and lack of direct emissions. They can contribute to reducing air pollution and dependence on fossil fuels in urban areas. They are the elevated system with the minimum use of concrete compared to other mass transit elevated systems.

Scenic Views: Elevated monorail mainline structures can offer passengers panoramic views of the cityscape, enhancing the overall travel experience and potentially attracting tourists. Examples of monorail scenic views are the Tama and Shonan monorails in Japan, where people can see the Fuji Mountain by the train.



Figure 109: Picture of Tama Monorail and Mt. Fuji at a station, 2024

Source: Photo by Rodolfo Szmidke

Integration with Existing Infrastructure: Monorail systems can be integrated with existing transportation networks, including metro lines and bus routes, providing seamless connections for commuters. Having a new mode in a metro ‘system’ might be considered a downfall for metro operating systems, however it is very rare to have metro systems with the same rolling stock supplier across lines, which exposes the operator to the same lack of uniformity. Monorails can be used as feeder lines to connect existing infrastructure or existing or future buildings or developments, in the same way the subways were used in London to extend the city into future developments away from the city core, in more affordable metropolitan areas.

Other integrations are with cable lines, airports and cycle paths that demonstrate the flexibility of the modal. A sample of integration is shown below with the Kitakyushu monorail, in Fukuoka Prefecture, Japan, which has part of the line and a station located under an elevated highway.

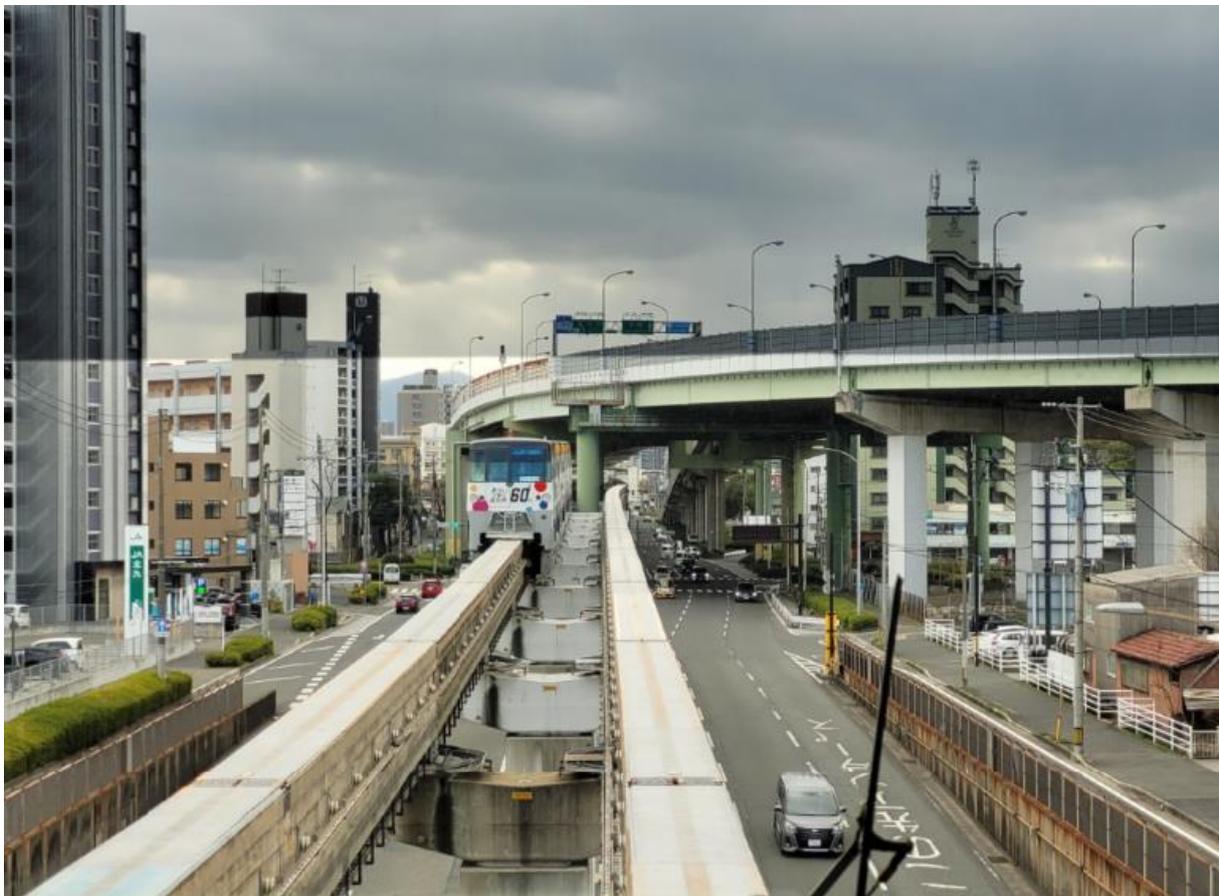


Figure 110: Kitakyushu monorail with an elevated highway, 2024

Source: Photo by Rodolfo Szmidke

Flexibility of Elevated Track Beams: Monorails are a lightweight transportation system compared to other elevated transportation systems. Monorails are composed of guideway beams typically supported on one column, which is then supported on a monopile in most places. This system results in many advantages:

- Monorails can be erected faster with less cost.
- Different types/shapes of columns can be used; rectangular, circular, etc.

- Reduced cost of construction by using a few types of molds for construction of supporting elements within most of the alignment.
- Monorail systems require a small area on the ground for columns only.
- High quality control is achievable due to using precast elements such as guideway beams.
- Monorails have strong grade capabilities and a small turning radius, providing adaptability to existing terrain.
- Monorails utilize 40 to 50% less concrete than any other elevated transportation system, thereby diminishing their environmental impact.

Therefore, monorail systems can play an important role in public transport in the future because of their unique advantages.

Capacity Flexibility: Monorails, like many transportation systems, can be designed and configured to accommodate varying levels of capacity based on factors such as train frequency, car design, and station layout. The capacity can range from 2,000 pphpd to systems like Line 15 in São Paulo and the planned Cairo monorails, both boasting capacities of more than 40,000 passengers per hour per direction (pphpd). This capacity demonstrates the potential of monorail systems to efficiently move varying volumes of passengers, contributing significantly to urban transportation networks. As urban populations continue to grow, and cities face increasing pressure to develop sustainable transportation solutions, the capacity of monorail systems can play a crucial role in meeting the mobility needs of residents while reducing congestion and environmental impact.

Development Opportunities: The construction of monorail systems can stimulate economic development along their routes, leading to increased property values and commercial activity in adjacent areas.

Challenges

Initial Costs: The construction of monorail infrastructure requires significant investment in terms of capital and resources over most at-grade systems, however it offers one of the smallest costs of development compared to other elevated and underground transportation systems depending on the application. Another advantage of elevated systems is that they provide natural isolation to the stray currents prevalent in at-grade systems.

Safety Concerns: Safety is a critical issue for monorail systems, especially in the event of accidents or technical failures. Ensuring the safety of passengers, personnel, and citizens and property below them requires rigorous maintenance and monitoring protocols and emergency walkways provide that assurance. Elevated structures provide the highest level of safety for vehicles and citizens compared to any at-grade system.

Perception and Acceptance: Some people perceive monorails as unconventional or impractical forms of transportation. Overcoming public skepticism and gaining acceptance for monorail projects may require extensive public outreach and education efforts. The labor of the International Monorail Association provides the industry a common platform to help overcome poor perception of the system.

Limited Flexibility: Like all rail-bound systems, monorails are difficult to relocate or modify, once the mainline structures are installed. This lack of flexibility can be problematic in dynamic urban environments where transportation needs may change over time.

Despite these challenges, monorails remain a viable option for improving urban transportation systems and addressing the mobility needs of growing cities. With careful planning, investment, and innovation, monorail projects can contribute to sustainable urban development and enhanced quality of life for residents.

4.2 World Market for Monorail Systems

Decisions in planning new or expanded transport systems are influenced by many economic, political, socio-cultural, ecological, and technical factors. The individual circumstances of each city pose a challenge in quantifying the potential for monorail systems. The International Monorail Association and SCI Verkehr (2022) performed a comprehensive world market study on monorail systems. Several factors were considered in this study such as: status quo of monorail systems worldwide, purpose of operation, and expected market growth.

A brief discussion of some of these factors is presented below and then, lessons obtained from this discussion are concluded.

4.2.1 World

Status Quo of Monorail System worldwide

The figure below shows the distribution of mass transit and theme park monorail systems in operation and in construction worldwide. Generally, they concentrated in Asia, Europe and North America.

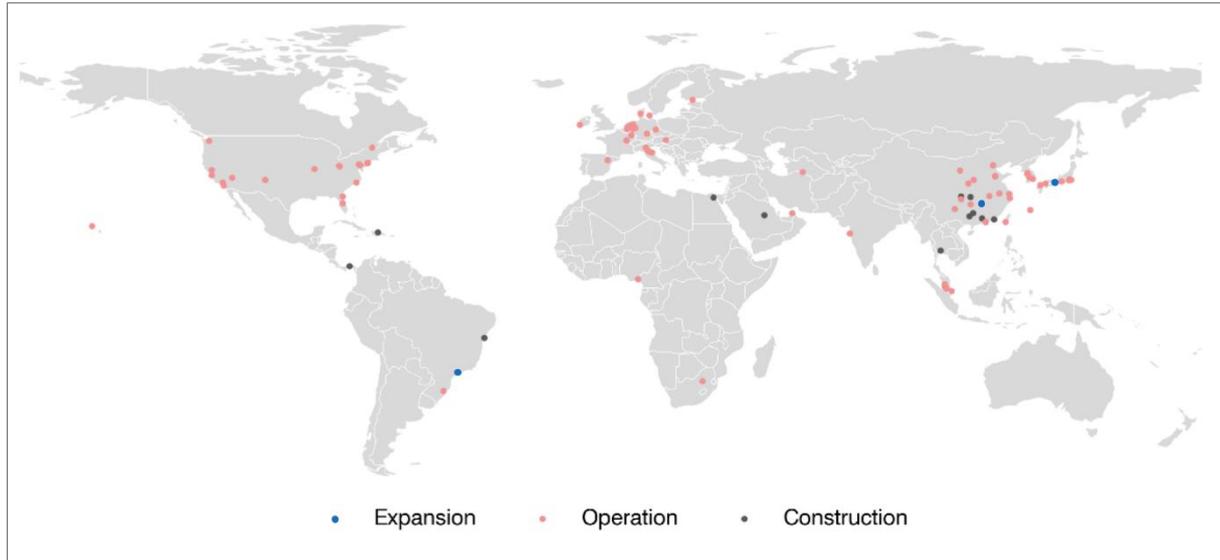


Figure 111: Monorail systems worldwide (by status)

Source: SCI Verkehr GmbH / International Monorail Association

Almost all new systems that are being constructed are in Asia and in emerging countries like Egypt (start of revenue service planned for October 2024) or Brazil, Panamá, Dominican Republic, or Mexico.

The following table summarizes the main information of monorail systems on the regional level, while the figure below shows the percentages of number of system and length relative to the total value.

Region	Number of systems		Length in km		Number of stations		average length (km)	
	A	B	A	B	A	B	A	B
Asia	36	10	511	394	366	259	14.19	39.40
Europe	23	0	46	0	61	0	2.00	0.00
North America	14	1	56	16	41	14	4.00	16.00
Other	7	3	35	145	37	72	5.00	48.33
Total	80	14	648	555	505	345	8.10	39.64

A= In operation, B= under construction

*Average length (km) = length/Number of systems

Source : <https://cms.uitp.org/wp/wp-content/uploads/2022/05/Statistics-Brief-Metro-Figures-2021-web.pdf>

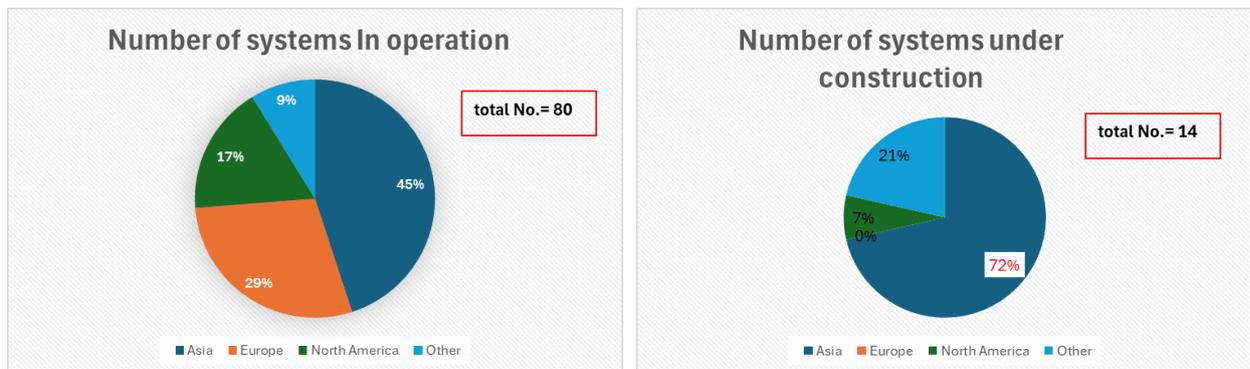


Figure 112: Regional shares worldwide (by number of systems)



Figure 113: Regional shares worldwide (by length of systems)

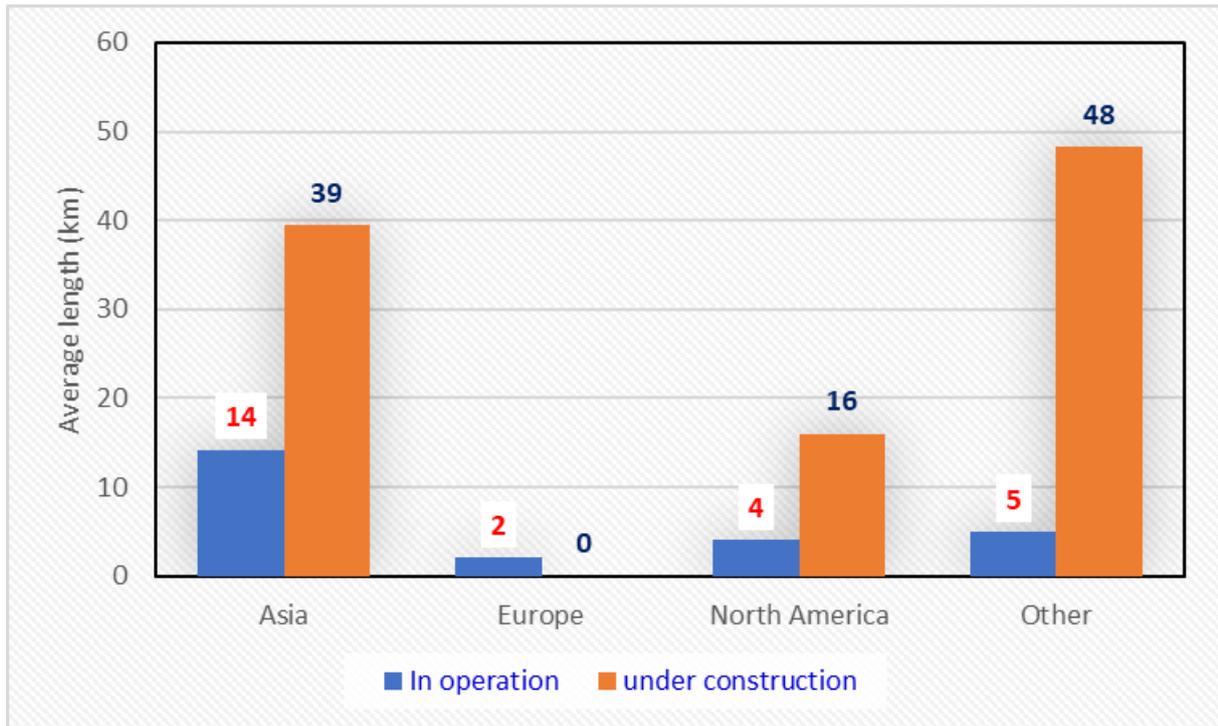


Figure 114: Average length of monorail system (km)= total length / number of systems

The average length of current systems is about only 7 km, while the systems under construction are on average 29 km long. A lower average length of systems indicates a larger number of systems with the purpose of the airport or theme park. Conversely, a higher average length suggests more usage in public transport. Hence, this signals a shift in the usage of monorails systems more towards public transport – which can be confirmed by current projects being under construction.

The average length of (in operation/under construction) systems is about (14/39) km in Asia, (2/0) km in Europe, (4/16) km in North America and (5/48) km in the other regions. This shows how much ahead Asia, and the other regions are in the application of monorails for public transport.

Purpose of operating lines worldwide (number of lines)

The general use of monorail can be classified into three categories:

- Public transport
- Passenger transportation in airports
- Amusement in theme parks and tourist areas.

The figure below shows the use of monorail system in different regions, while the following table shows the total length of each use worldwide. The following points can be clearly obtained from these figures:

- Asia is ahead of Europe and North America in terms of utilizing monorail systems in public transit.
- the prevailing significance of monorail systems is in public transport
- theme parks or tourism lines are mainly quite short.

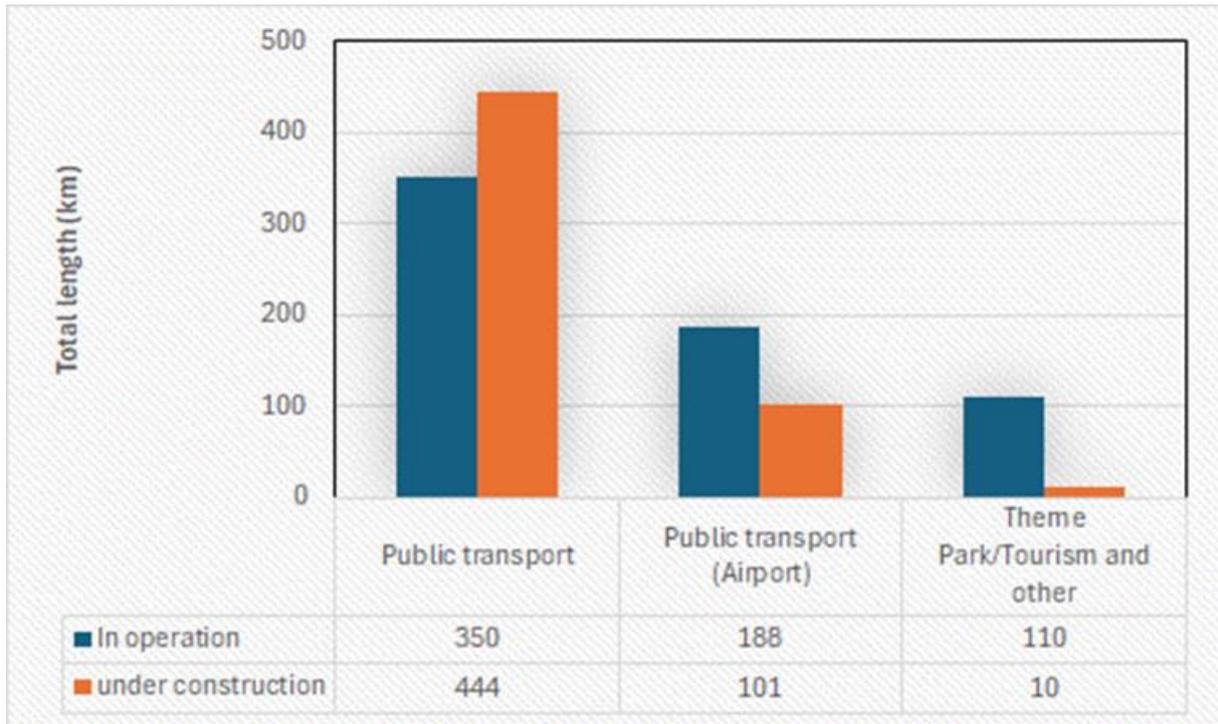


Figure 115: Total length of share of line Purpose worldwide

Table 5: Currently the top 10 longest monorail lines in operation worldwide (SCI Verkehr, 2022)

Rank	Country	City	Line	Length (in km)
1	China	Chongqing	Line 3	66
2	China	Chongqing	Line 2	31.36
3	China	Shanghai	Shanghai Maglev Train	30.5
4	China	Wuhu	Line 1	30.46
5	Japan	Osaka	Main Line	28
6	South Korea	Daegu	Line 3	23.95
7	USA	Bay Lake	Walt Disney World Monorail System	23.66
8	India	Mumbai	Mumbai Monorail	19.54
9	China	Changsha	Changsha Maglev Express	18.55
10	Japan	Tokyo	Tokyo Monorail Haneda Airport Line	17.8
Total				290

4.2.2 Regional Distribution of Monorail Systems

Asia

In Asia, 36 monorail systems are in operation with total length equals 512 km, and 10 system are in construction with total length 421 km, around 93% of them (in length) are for urban transit.

In Asia monorail systems are quite well-established as a public transport solution. Japan has the highest density of monorails in the world with eleven urban transit lines in eight different cities. China is the country with the most monorail lines in operation of which twelve are used for urban transit.

Europe

Monorail is not well-established as a public transport solution in Europe's urban areas, where light rail and metro transit prevail. Many European cities are historic with a view of the city that is considered a cultural heritage. This makes it harder for an elevated system, which monorails usually are, to gain acceptance as the impact on the aesthetics of the city is stronger compared to light rail or metro. 26 monorail systems are in operation in Europe with total length equals 54 km. About 73% of them are used in theme parks or for touristic purposes.

The shares of purposes weighted by line length reveal that public and airport transport in Europe still account for around 45% of the total usage.

North America

In North America, 14 monorail systems are in operation, one in Canada and 13 in the USA. In USA, five lines have an urban transit purpose, while the rest are used in theme parks or for touristic purposes.

Other Regions

Outside of the focus regions, seven monorail systems are in operation. Five of these are used for public transport. The largest one is Line 15 in São Paulo with a length of around 15 km which is currently being expanded. This line also has one of the largest capacities in the world designed for 48,000 pphpd with trains at 75 seconds headway which can keep up with the world's largest monorail system in Chongqing.

4.2.3 Monorail Projects in Planning Phase

Across the world several monorail projects are in a planning process or under discussion. The status varies and sometimes projects are stopped for economic or political reasons – on the other hand, new projects arise when the strengths of monorail systems cover the transport needs in a metropolitan area and are better suited in comparison to other modes of transport. SCI Verkehr expects 25 to 40 new systems to be implemented worldwide between 2025 and 2035. The largest share of this potential is attributed to China, rest of BRICS countries (Brazil and India) as well as in emerging markets.

4.2.4 Summary of Survey Results

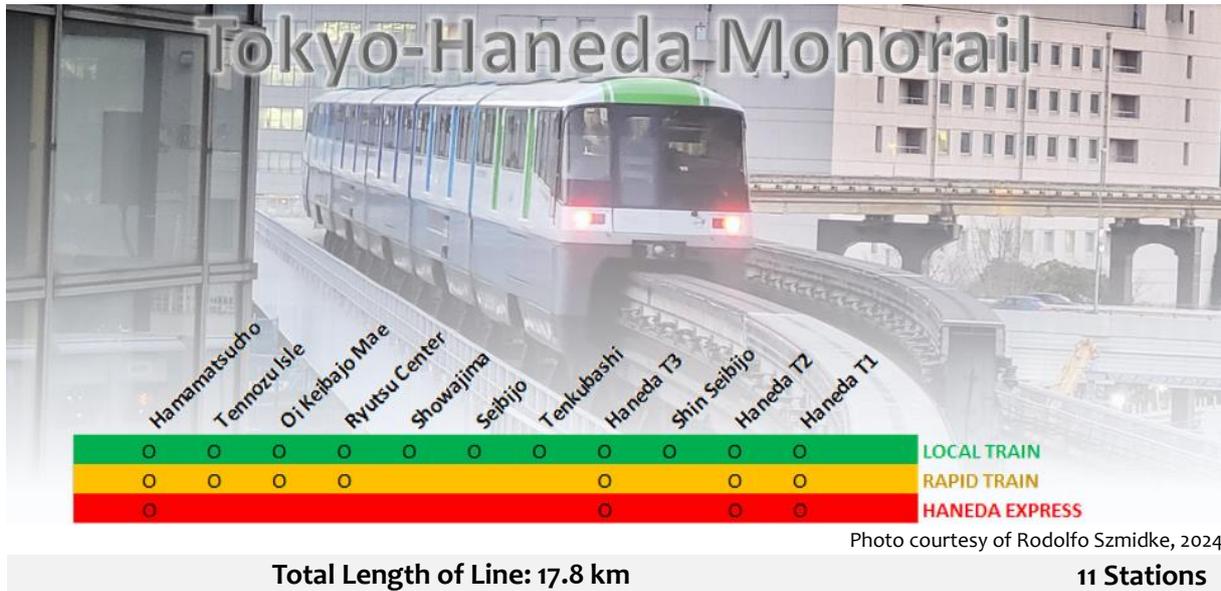
- Asia is leading the world in the use of monorail systems, and is ahead of Europe and North America in terms of utilizing them in public transit applications.
- In Europe, the use of monorail systems is mainly for touristic purposes and theme parks.
- With the trend moving towards more monorail lines for public transport, monorail use will become more widespread and is expected to become more evenly distributed around the globe. SCI Verkehr expects 25 to 40 new systems to be implemented worldwide between 2025 and 2035.



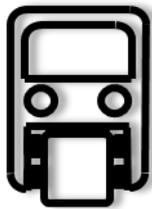
4.3 Description of Selected Implemented Systems

The following chapter presents cases where the monorail has been a success story in different places worldwide.

4.3.1 Tokyo-Haneda Monorail



City: Tokyo
Country: Japan 



Straddle Beam Type

1964
Start Operation

90,957 pass/day
(2022)

6 cars per train

1 depot



Figure 116: Tokyo Haneda Monorail, 2024
Source: Photo courtesy of Rodolfo Szmidke



Map of the line



- System configuration: pinched loop
- It was inaugurated to the Olympic Games in 1964
- First straddle beam type urban monorail in the world
- Has elevated and tunnel sections
- Connect the Haneda Airport to the railway system
- Completed 60 years of operation in 2024



Figure 117:Tokyo Haneda Station and Depot, 2024

Source: Photo courtesy of Rodolfo Szmidke

4.3.2 São Paulo, Line 15 Silver

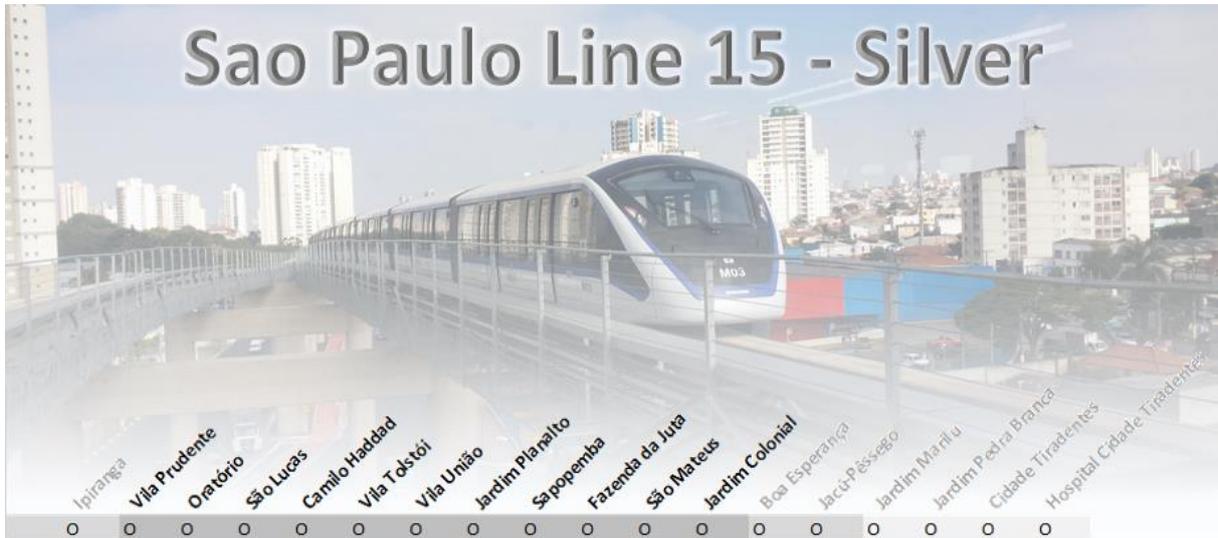
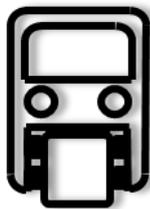


Photo courtesy of Rodolfo Szmidke, 2014

	In Operation: 15.236 km		11 Stations
2.163 km	Under Construction: 6.272 km	4.109 km	3 Stations
Total Length of Line: 26.632 km			18 Stations

City: São Paulo
Country: Brazil 



Straddle Beam Type

**2014
Start Operation**

**27 trains
7 cars per train**

**1 depot
(1 under construction)**

**500.000 pass/day
(project demand)**

**139.000 pass/day
(2024)**



Figure 118: Line 15 – Silver, 2014
Source: Photo courtesy of São Paulo Metro



Map of the line



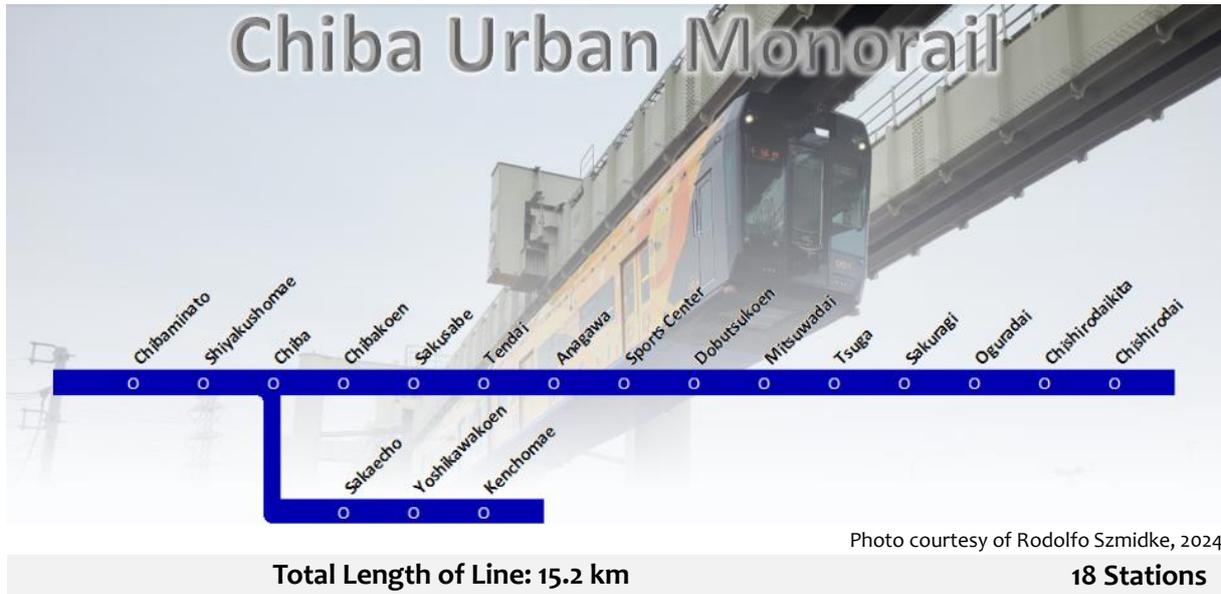
- **System configuration: pinched loop**
- **First mass transport monorail in Latin American**
- **Index of satisfaction above 78% from passengers**
- **Cycle path along the extension of the line**
- **Among all the lines in the São Paulo network system, this is the only one that has exceeded pre-pandemic demand levels**



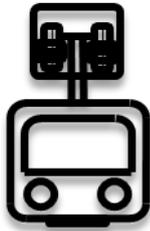
Figure 119: Line 15 station and depot 2024

Source: Photo courtesy of Rodolfo Szmidke

4.3.3 Chiba Urban Monorail



City: Chiba
Country: Japan 



Suspended SAFEGE Type

1988
Start Operation

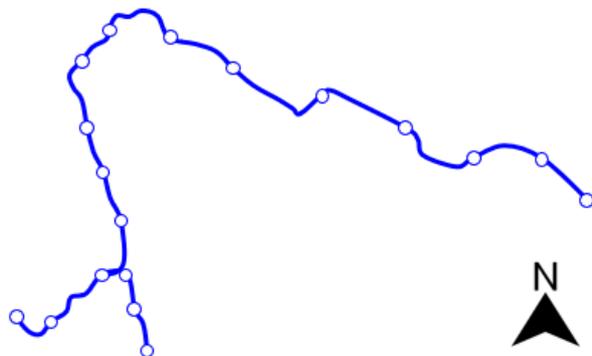
trains
2 cars per train

1 depot

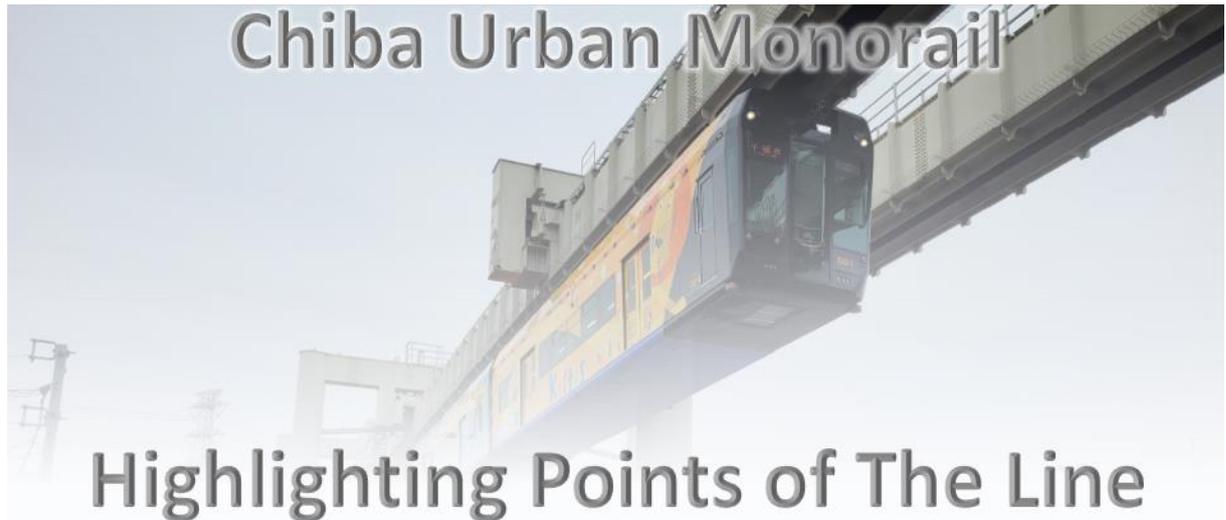
Over 48,000 pass/day



Figure 120: Chiba Monorail, 2024
Source: Photo courtesy of Rodolfo Szmidke



Map of the Line



- System configuration: pinched loop
- Biggest suspended monorail
- Has a main and a branch line
- Has new trains
- Transported 48.949 passengers per day in 2023 (largest number of passengers in the world of suspended monorail)
- Connect some train lines.



Figure 121: Station and Depot, 2024

Source: Photo courtesy of Rodolfo Szmidke

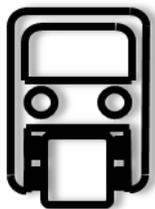
4.3.4 Osaka Monorail



Photo courtesy of Rodolfo Szmidke, 2024

In Operation: 21.2 km	15 Stations
Under Construction: 9km	4 Stations
Total Length of Line: 30.2 km	19 Stations

City: Osaka
Country: Japan 



Straddle Beam Type

**1988
Start Operation**

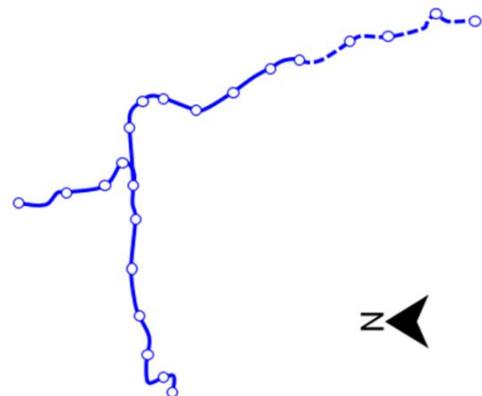
**trains
4 cars per train**

1 depot

Over 100,000 pass/day



Figure 122: Osaka Monorail, 2024
Source: Photo courtesies of Rodolfo Szmidke



Map of the Line



- **System configuration: pinched loop**
- **It was inaugurated for the 1970 Expo**
- **Has a connection to the airport and other subway and train lines**
- **Has a main and a branch line**
- **Very famous track switch at Kadoma-shi Station**
- **Nowadays in expansion**
- **Different type of structures along the line (bridges)**
- **Transported 121.441 passengers per day in 2023 (second largest number of passengers for monorails in Japan)**



Figure 123: Station and Depot, 2024

Source: Photo courtesy of Rodolfo Szmidke

4.3.5 Chongqing Monorail

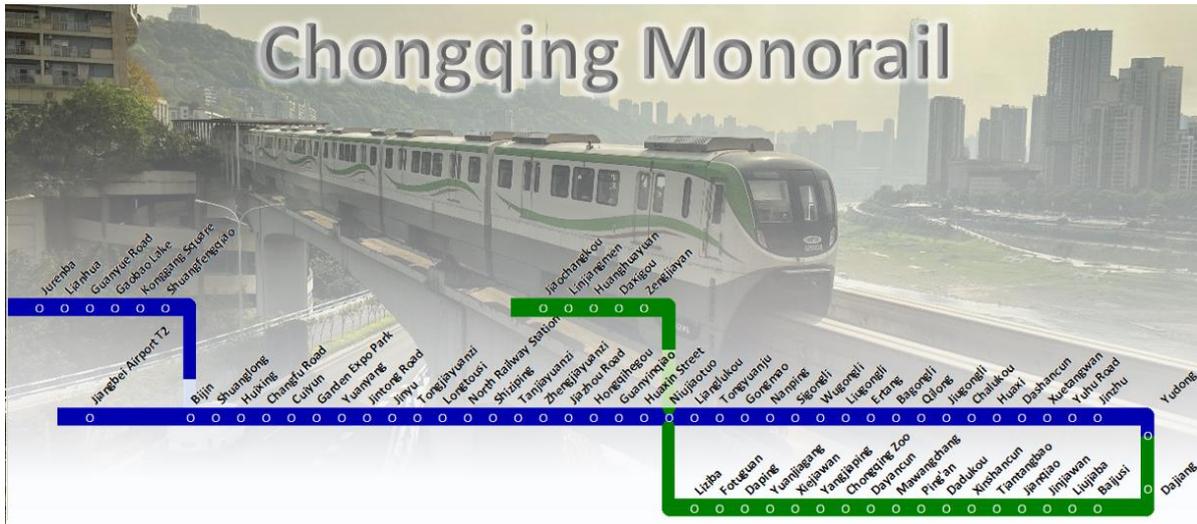
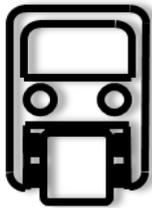


Photo courtesy of Paulo Meca, 2024

Extension of Line 2: 31.4 km	25 Stations
Extension of Line 3: 67.1 km	45 Stations
Total length of monorail network: 98.5 km	68 Stations

City: Chongqing
Country: China 



Straddle Beam Type

2005
Start Operation

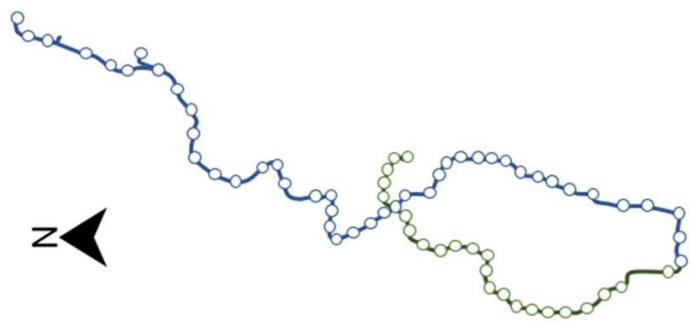
6 cars per train (Line 2)
4 cars per train (Line 3)

4 depots

1,075,000 pass/day



Figure 124: Chongqing Line 2, 2024
Source: Photo courtesy of Paulo Meca



Map of the line



- **System configuration: two lines, pinched loops**
- **Mainline with concrete and steel beams**
- **Line 2 has 400,000 passengers per day, Line 3 675,000 passengers per day (2023)**
- **Variety of features: station inside a building, tunnels, connection to airport**
- **Added new trains**
- **Useful in a mountainous urban environment**



Figure 125: View of station and track, 2024

Source: Photo courtesy of Paulo Meca

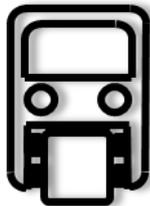
4.3.6 Walt Disney World Monorail System



Photo courtesy of Virginia Moura Clementino, 2023

Extension of Resort Line 2: 6,5 km	5 Stations
Extension of Epcot Line 3: 17,2 km	2 Stations
Total length of monorail network: 23.7 km	6 Stations

City: Orlando
Country: United States 



Straddle Beam Type

1971
Start Operation

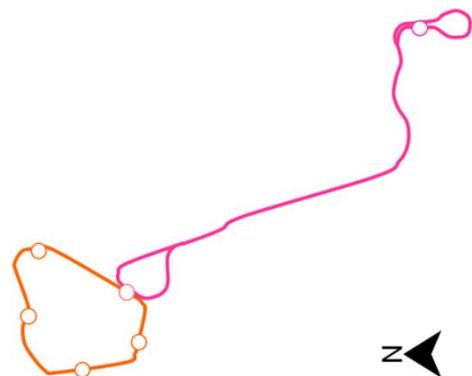
6 cars per train

1 depot

150.000 pass/day



Figure 126: Walt Disney World Monorail, 2023
Source: Photo courtesy of Virginia Clementino



Map of the line



- **System configuration: pinched loop and double loop**
- **Biggest monorail in an amusement park**
- **Three different lines: Magic Kingdom Express, Magic Kingdom Resort, EPCOT**
- **One of the few monorails in the USA**
- **Started operation in 1971 (more than 50 years ago)**
- **In 2021 was opened a new station in the middle of the line (Disney's Polynesian Village Resort)**



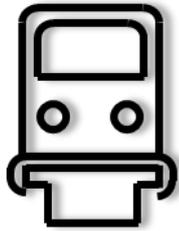
Figure 127: Walt Disney Monorail entrance and Column Detail, 2023

Source: Photo courtesy of Virginia Clementino / Carlos Banchik

4.3.7 Nagoya Linimo Line



City: Nagoya
Country: Japan 



Maglev Type

2005
Start Operation

3 cars per train

1 depot

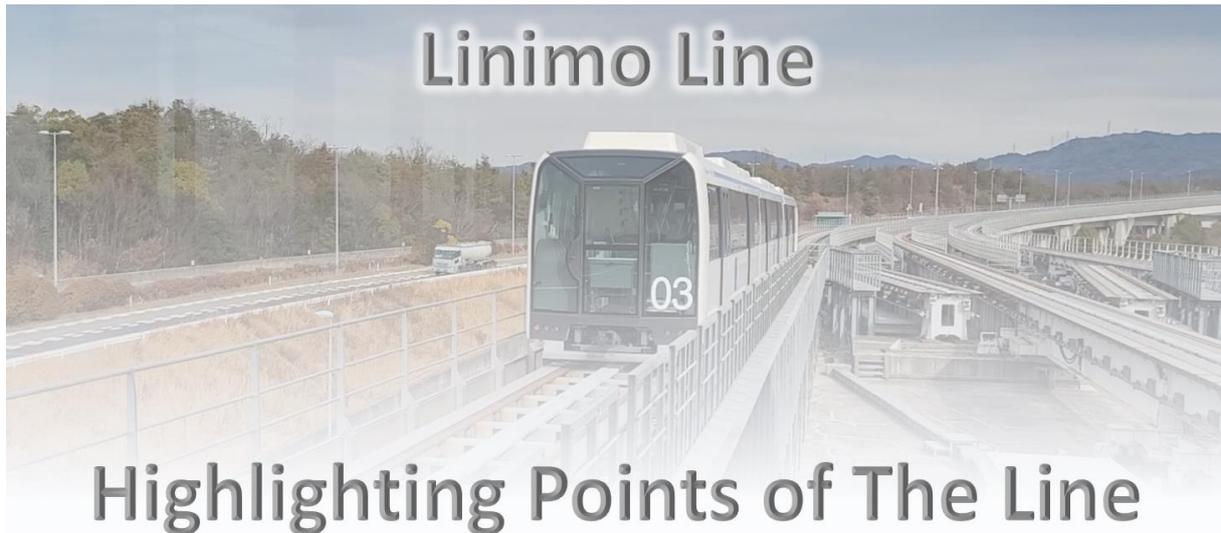
23.400 pass/day



Figure 128: Linimo Line, 2024
Source: Photo courtesy of Rodolfo Szmidke



Map of the line



- System configuration: pinched loop
- Top speed of 100 km/h
- Can accelerate 1.5 times faster than a bullet train
- Automatic operation without conductors
- Distance from the electromagnets and rail is maintained at a constant 8 mm



Figure 129: Linimo Line station, 2024



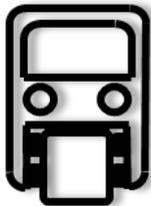
Source: Photo courtesy of Rodolfo Szmidke

4.4 Description of Selected Systems under Construction

4.4.1 Cairo, East of Nile (EoN) and West of Nile (WoN) Monorails



City: Cairo
Country: Egypt 



Straddle Beam Type

2024
Preview Start Operation

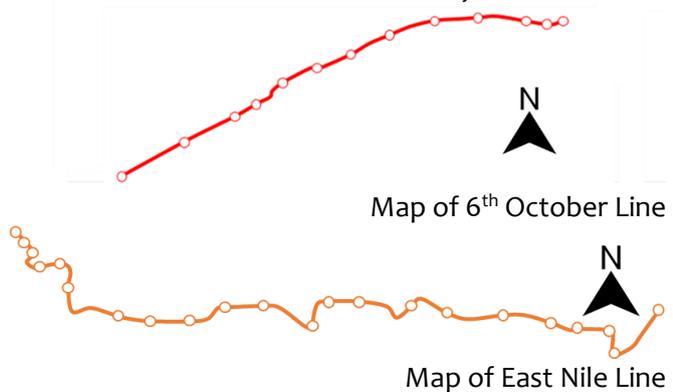
70 trains
4 cars per train

2 depots

45.000 pass/h
(project demand)



Figure 130: Cairo Monorail, 2022
Source: Photo courtesy of Maxim Weidner





- First mass transport monorail in Africa
- Maximum velocity of 80 Km/h
- 90 seconds frequency per train
- Each four-car train can carry up to 600 passengers



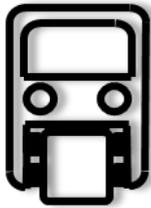
Figure 131: Cairo Monorail, 2022

Source: Photo courtesy by Maxim Weidner

4.4.2 Panama City Line 3



City: Panama City
Country: Panama 🇵🇲



Straddle Beam Type

2027
Preview Start Operation

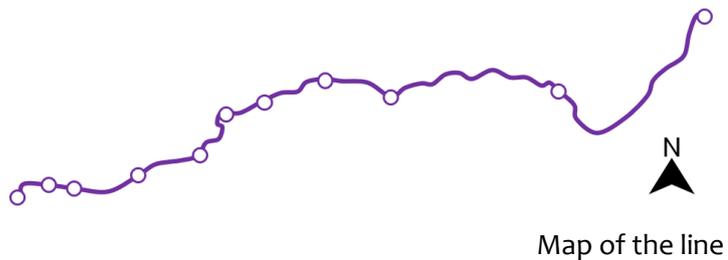
26 trains
6 cars per train

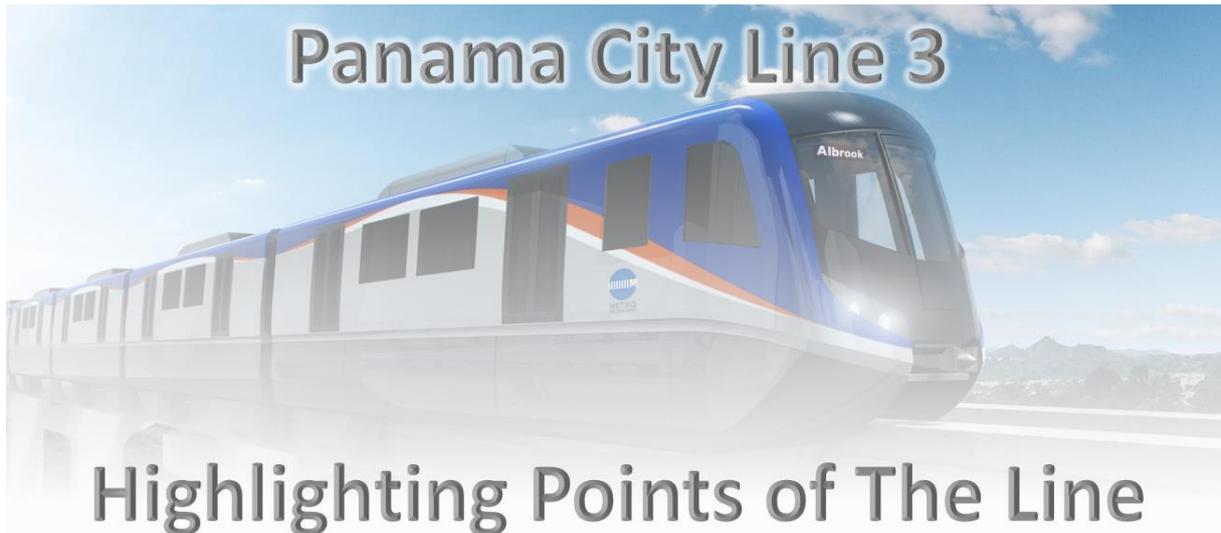
1 depot

20.000 pass/h
(project demand)



Figure 132: Panama City Monorail tunnel construction, 2024
Source: Photo courtesy of Metro de Panamá S.A.





- **First mass transport monorail in Central America**
- **20.000 passengers by hour on rush time**
- **200 seconds frequency per train**
- **160.000 passengers by day demand**
- **5.3 km of underground line under Panama Channel with 13m diameter tunnel**
- **Capacity of 1.000 passengers per train**



Figure 133: Panama City Line 3 Monorail Construction, 2024

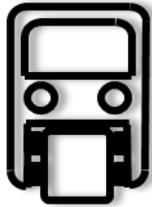
Source: photos courtesy of Metro de Panamá S.A.

4.4.3 Santiago de los Caballeros (SdC)



Photo courtesy of Lucas Bernardi, 2024

City: Santiago de Los Caballeros
 Country: Dominican Republic 



Straddle Beam Type

2025
 Preview Start Operation

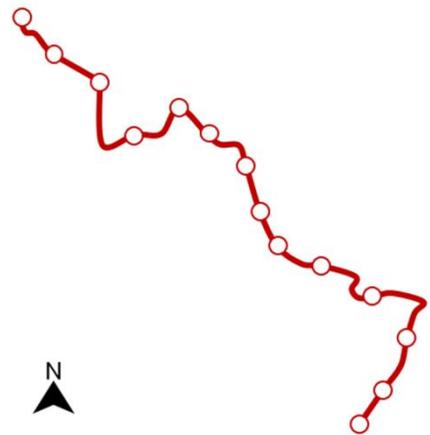
20 trains
 4 cars per train

1 depot

20.000 pass/h
 (project demand)



Figure 134: Santiago de Los Caballeros, 2023
 Source: Photo courtesy of Maikel Garcia



Map of the line



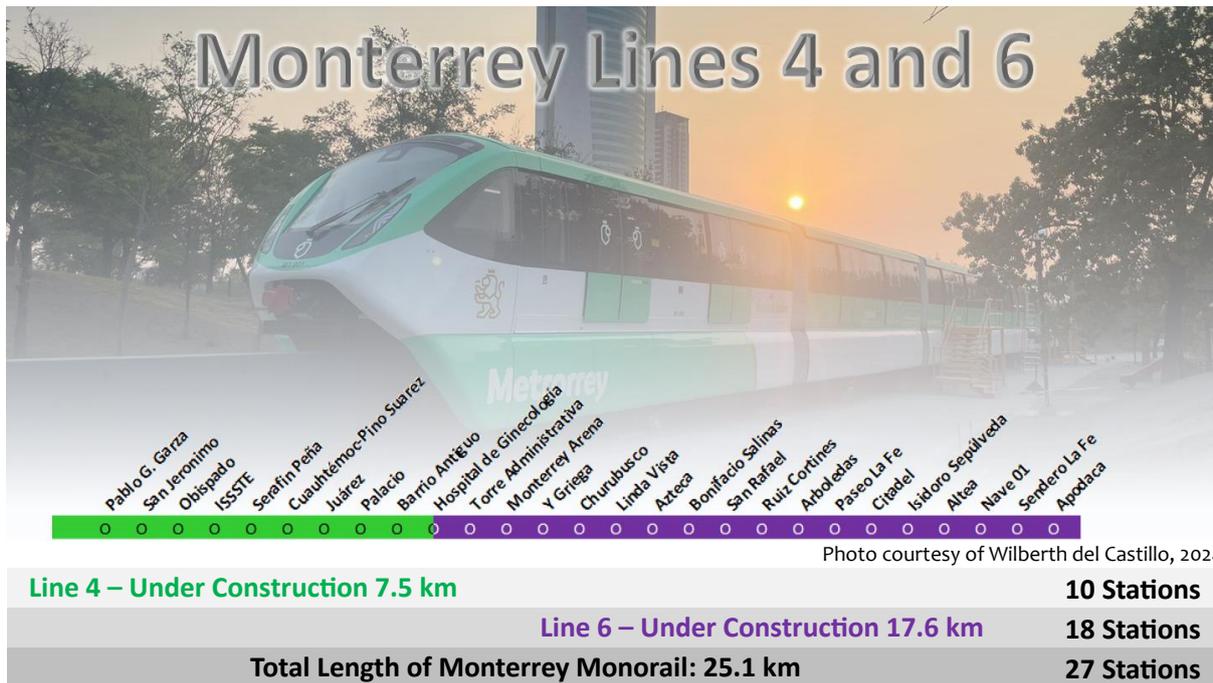
- First mass transport monorail in the Caribbean Islands
- Maximum velocity of 80 Km/h
- 90 seconds frequency per train
- Trains of 590 passengers of capacity
- Intermodal integration with cable cars, BRTs and cycle paths



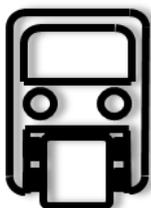
Figure 135: Santiago de Los Caballeros Monorail Construction, 2023

Source: Photos courtesy of Maikel Garcia

4.4.4 Monterrey Lines 4 and 6, Nuevo León, México



City: Monterrey
Country: Mexico 



Straddle Beam Type

2025
Preview Start Operation

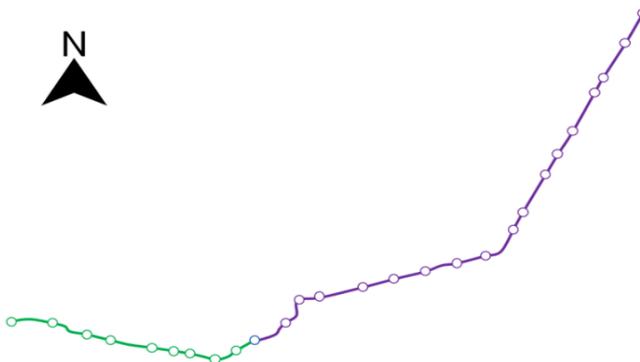
trains
6 cars per train

2 depots

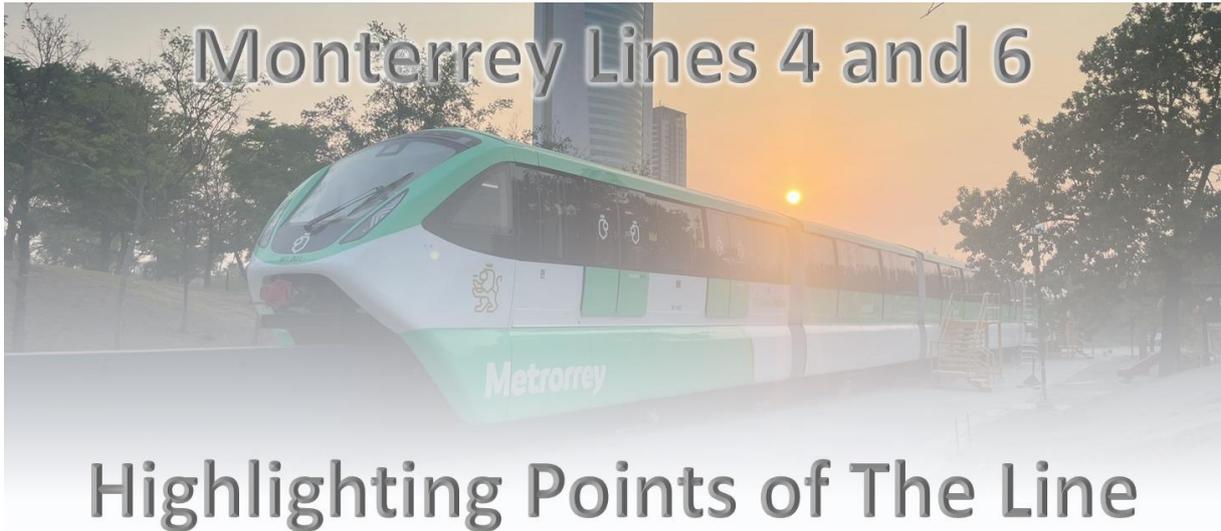
10,000 pass/h (L4)
15,000 pass/h (L6)
(project demand)



Figure 136: Monterrey Monorail, 2024
Source: Photo courtesy of AECOM



Map of the line



- First mass transport monorail in Mexico
- Maximum velocity of 80 Km/h
- More than 1,600 guideway beams
- Trains of 1,108 passengers of capacity
- Project using BIM 3D models



Figure 137: Monterrey Monorail Construction

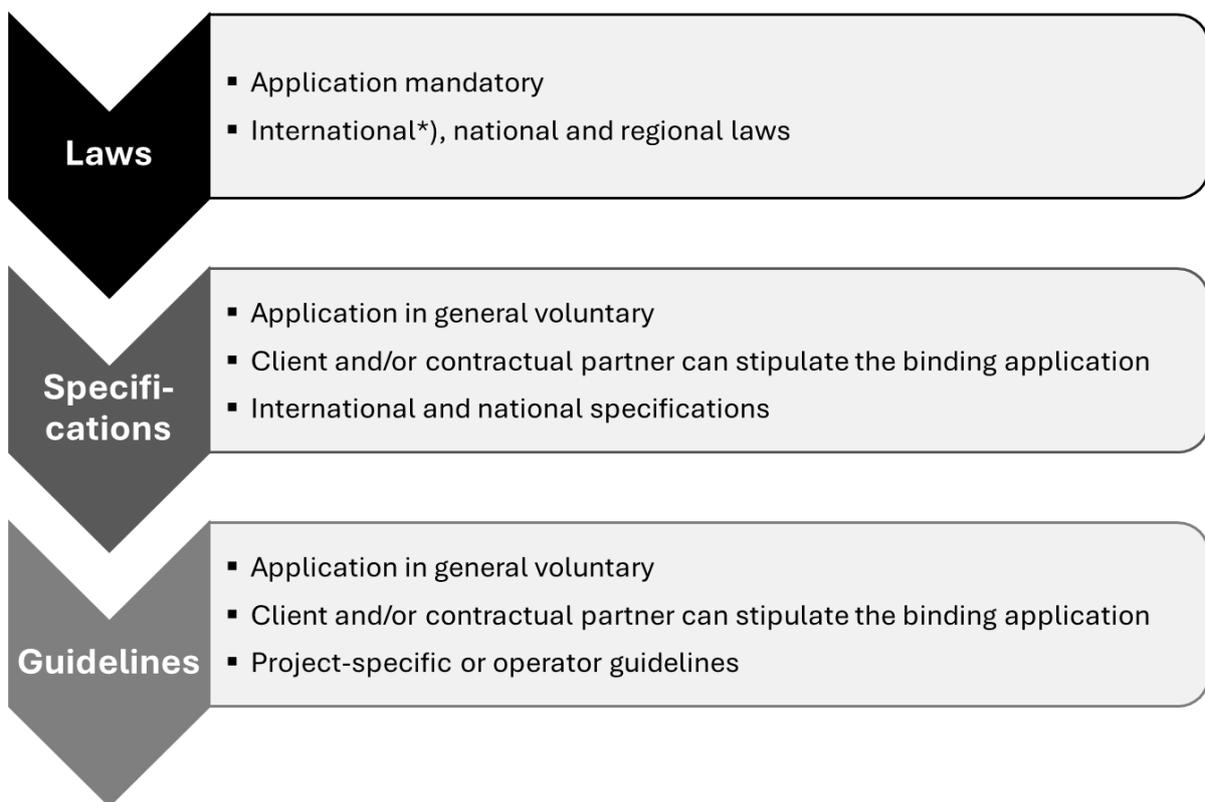
Source: Photos courtesy of AECOM

5 Certification of Monorail Projects

5.1 Regulatory Framework

5.1.1 Introduction

When developing a monorail project, the regulatory applicable framework should be known at a very early stage and continuously developed within the project's progress. The regulatory framework is in general specified by the national authorities and the owner/operator, and it is usually also part of the tender. Regulatory frameworks are legal mechanisms that exist on national and international levels. In general, the regulatory framework is distinguished between laws and standards. The application of standards is generally voluntary whereby the application of laws is mandatory. Standards are not binding but can become legally binding when laws or ordinances refer to them. In addition, the client and contractual partners can also stipulate the binding application of standards in agreements or provide project-specific or operational standards.



^{*)} As monorail systems generally do not cover two or more countries, there are currently no applicable international laws (such as e.g. the TSI in Europe)

5.1.2 Responsibilities of the National Authorities and the Client

In general, the national (urban) railway authority checks which laws must be applied for the commissioning of a Monorail and can also specify the applicable safety standards (e.g. EN 50126). The national authority is responsible for issuing the building permission and the final commissioning authorization. For this reason, the client must deliver all the

relevant documentation together with the request for approval to the national authority. The national authority checks the documentation - and may commission external verification services (third parties) - for checking compliance with the law and defined specifications.

The client applies to the national authorities for building permission and final commissioning and submits all the related documentation required for approval giving evidence that the valid laws and specifications are fulfilled. The client commissions also further parties (designer, manufacturer, internal verifier) who are involved in the project. It is also possible that the external verifier is commissioned by the client.

Note: Depending on the country in which a monorail is approved, there may be a deviation from the above-mentioned process.

5.1.3 Regulations for Monorails

The following table shows examples of the applicable laws for Monorail systems in the respective countries.

Table 6: Example of applicable laws for monorail system

Country	Applicable Laws for Monorails
Brazil	<ul style="list-style-type: none"> ▪ Law 14.273/2021 – New Legal Framework for Railways ▪ ABNT NBR 150309 – Measurement Methods for Building Setting Out and Dimensional Control of Underground Railway Works and Similarly Works - Procedure
Egypt	<ul style="list-style-type: none"> ▪ Law 152/80 ▪ Law 20/2018 is the updated version of law 152/80 <p><i>Note: The first monorail in Egypt is currently under construction in Cairo.</i></p>
Germany	<ul style="list-style-type: none"> ▪ BOStrab - Ordinance on the Construction and Operation of Street and Light Railway Regulations <p><i>Note: The BOStrab regulations apply not only to trams and elevated and underground railways, but also to monorails such as the Wuppertal suspension railway, automatic people movers such as the Dortmund H-Bahn or the SkyLine at Frankfurt Airport.</i></p>
India	<ul style="list-style-type: none"> ▪ Indian Railway Act 1989
Thailand	<ul style="list-style-type: none"> ▪ Thailand Railway Act <p><i>Note: The Thailand Railway Act is currently under review.</i></p>
United States	<p>There are several regulations for railways in the United States. The following link represent the official website of the US Department of Transportation:</p> <p>https://railroads.dot.gov/legislation-regulations/regulations-rulemaking/regulations-rulemaking</p>

5.1.4 Common Specifications for Monorails

The applicable standards and specifications are project specific and are in general hierarchically defined in the tender document from the owner/operator, also called ‘Operator Requirements’. In these requirements as well from the authority specified standards are included. For common applicable International Standards for Straddle-Beam Monorails see Appendix 1 of the IMA ‘Performance Specification for a Turnkey Mass Transit Monorail System’, First Edition 2022.

5.1.5 Required Documentation for Construction and Final Commissioning

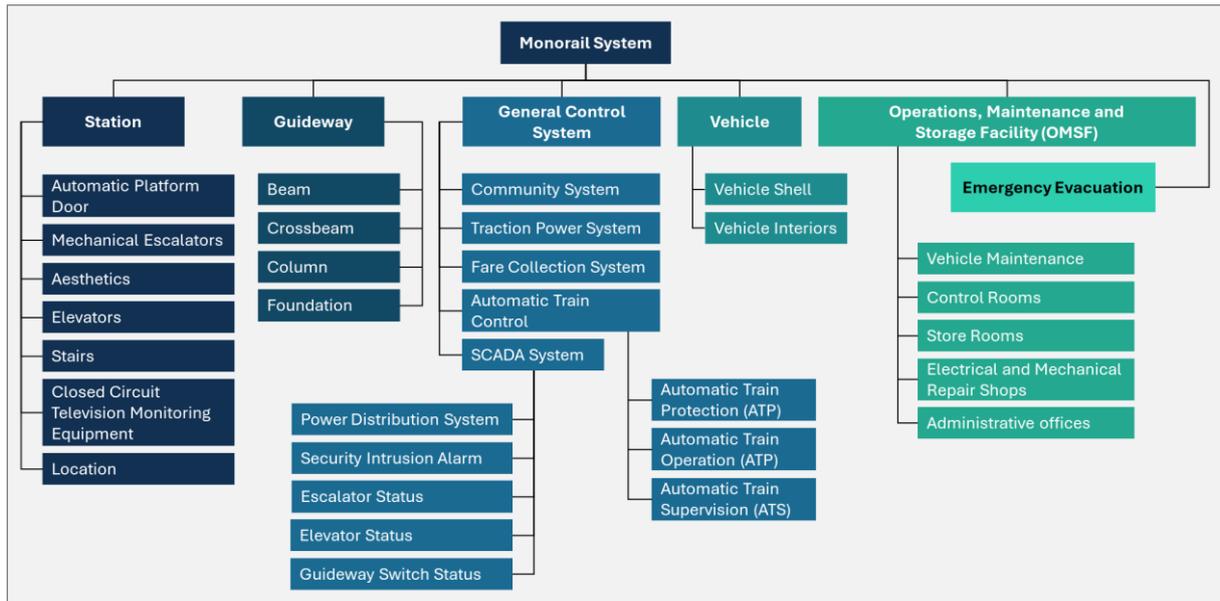


Figure 138: Documentation scheme for construction and final commissioning

Source: Illustration by IMA based on Constructability Analysis of Monorail Project, CIV. 1278 F, Prof. El-Diraby, March 24th, 2003, page 9

For all subsystems

General documents
General project description
Overview plans
Documents required for the RAMS assessment according EN 50126
Hazard log
Interface Management Plan
Design Safety Report
Safety Case

Station

Building permission	Final commissioning
Cross sections	Acceptance reports
Design Safety permission	As-built plans
Execution plans	Delivery notes of components
Safety plan preliminary design stage	Reports
Static calculations	
Technical reports	

Guideway

Building permission	Final commissioning
Cross sections	Acceptance report
Execution plans	As-built plans
Alignment plans	Delivery notes of components
Permissible speeds or design speeds	Reports
Static calculations	
Technical reports	

General Control System

Building permission	Final commissioning
Circuit diagram	Acceptance report (3.1 certificates)
Factory acceptance test	As-built plans
	Delivery notes of components
	Reports

Vehicle

There are no requirements for building permission.

Final commissioning	
Technical documents	Vehicle data sheet, vehicle overview drawing, bogie overview drawing
Test reports	For all relevant subsystems of the vehicle
Calculations	For all relevant subsystems of the vehicle
Design drawings	For all relevant subsystems of the vehicle
Cyber security plan	For all relevant subsystems of the vehicle
Fire safety and evacuation concept	For all relevant subsystems of the vehicle
Functional safety proof	For all relevant subsystems of the vehicle
PRM verification	Consideration of the issues of persons with reduced mobility
Acceptance report (3.1 certificates)	For all relevant subsystems of the vehicle
Delivery notes of components	For all relevant subsystems of the vehicle

Note: The following link: https://www.brd.nrw.de/system/files/media/document/2023-06/230601_2_25_OePNV_TAB_Checkliste_Fahrzeuginbetriebnahme_Version6.pdf represents the official site of the technical supervisory authority for the tram and trolleybus companies in North-Rhine Westphalia (Germany). The requirements for the final commissioning are shown in the table.

Operation, Maintenance and Storage Facility

Final commissioning
Maintenance Plan
Operating Instructions

Emergency Evacuation

Final commissioning
Passenger Emergency Evacuation Concept

5.2 Safety Regulations

5.2.1 Introduction

The realistic goal is to develop a monorail system with an acceptable accident risk profile. This is accomplished by seamlessly integrating the safety concept into the Monorail system life cycle which comprises the concept, design, manufacturing, testing and commissioning, operation and maintenance, and finally disposal of the Monorail system, subsystem and component.

Monorail Transit System Safety (MTSS) is a system attribute intentionally designed into the Monorail system including the product design and development, operation and maintenance procedures, emergency evacuation plan, etc.

A proactive preventive approach to safety during the system design and development is much more cost effective than attempting to add safety into a system after the occurrence of an accident or mishap. Therefore, MTSS is the initial investment that saves future losses that could result from potential mishaps.

MTSS is a systematic process to the mishap risk management which can be accomplished by eliminating or mitigating the hazards that can result in death, injury, system loss and damage to environment throughout the Monorail system life cycle.

There is no published safety standard particularly for the Monorail system. Although there are various safety standards published for the diverse industries and some of them are published in particular for railway applications. Nonetheless, some of these safety standards can be applied in the Monorail transit system. Among these safety standards, the US Department of Defense published MIL-STD-882, which is sometimes called the ‘mother’ of all safety management standards.

Another safety management standard utilized in military industries is DEF-STD-00-56 which was published by the UK Ministry of Defense. Both MIL-STD-882 and DEF-STD-00-56 were originally developed for military industries, then commonly utilized by other industries including railway and public transit industries.

In North American countries, MIL-STD-882 is still the commonly applied safety management standard for the railway and public transit systems which also include the Monorail transit system.

Further safety standards regarding infrastructure:

- EN 50126 - RAMS
- EN 60812 - Technical standard for Failure Mode and Effects Analysis
- MIL-STD-1629A – Another standard for Failure Mode, Effects and Criticality Analysis (FMECA)
- ASCE 21 - Automated People Mover
- NFPA - 130 - Standard for fixed Guideway Transit and Passenger Rail Systems
- DIN 5510 - Preventive protection on railway vehicle

5.2.2 Safety verification of the infrastructure

In order to show evidence that systems, subsystems or the individual single components fulfil the requirements specified in the tender, the following safety verifications are a helpful tool to increase the safety level of the infrastructure. In addition, an independent safety assessment for the infrastructure should also be conducted, see chapter 5.2.4.

5.2.2.1 Comparative calculations

For structural calculations, independent calculations should be conducted by an authority approved structural engineer. A recognized structural engineer checks the structural engineer's calculations on behalf of the responsible building supervisory authority or the building owner. In other words, independent checks are done by a structural engineer to avoid errors. The results are summarized in test reports.

Note: The decision as to whether tests reports are required is usually the responsibility of the authority and/or the client.

5.2.2.2 Certification of safety-relevant components

For safety-relevant components manufactured in the factory and installed on the construction site or vehicles, a certification should be conducted. Manufacturers can thus provide proof of fulfilment of the requirements of specified standards by an independent certification body (e.g. inspection body accredited by EN 17020). A certification of components ensures reliability, safety, quality and efficiency.

Note: The decision as to whether certificates are required is usually the responsibility of the authority and/or the client.

5.2.3 Safety verification of the vehicles

For new rolling stocks, an independent safety assessment (ISA) should be conducted, see chapter 5.2.4. The decision about the applicable standards and whether an ISA should be conducted is in general the responsibility of the national authority and/or the client.

5.2.4 Independent Safety Assessment

Like most industries, railway technologies have become increasingly complex over time. These developments have made railway safety assessments not only more necessary but more challenging. While this is generally true for all subsystems, it is particularly the case for large railway infrastructure projects. The complexity of a complete railway system makes it difficult to accurately analyse and ensure system safety. The risks resulting from this increase in complexity can be mitigated by an Independent Safety Assessment (ISA).

ISA is the formation of a judgement, separate and independent from any railway engineering design, development or operational personnel, that the safety requirements for the railway project are appropriate and adequate for the planned application and that all the systems and civil works assets as well as Operation and Maintenance (O&M) processes are compliant with those safety requirements.

The Independent Safety Assessor's role is to verify whether the relevant technical and operational risks have been reduced to an acceptable level.

Independent Safety Assessment helps suppliers, operators and system integrators prevent failures before they occur and ensure their systems comply with the safety requirements and global railway standards. An independent safety assessment ensures:

- Independent judgements and opinions are free from project constraints
- A completely independent final judgment based on the acceptability of the safety justification (including deviations) given by the project in the Safety Case. This includes checking that the required constraints are captured in safety-related application conditions and are sufficient to control the risk.
- Reduction of project risk due to competent third-party opinion
- Safety arguments as well as the treatment of railway hazards and risk have been appropriately and effectively addressed
- The project is delivered in compliance with international railway standards regarding safety targets
- Operators are given increased confidence independent from potential supplier constraints
- Technical and commercial stakeholders as well as regulatory bodies are assured that the project is being managed professionally and the safety targets are being met throughout the life cycle

According to cl. 6.8.1 of the EN 50126-1:2017:

'Independent safety assessment is an important means to provide additional confidence about the avoidance of systematic failures of the system under consideration which can adversely influence safety. Independent safety assessment includes an evaluation and judgement that specified aspects of the safety management process have been adequately undertaken and/or specific requirements

about the system or part of the system are fulfilled. Independent safety assessment is also based on the evaluation of the verification and validation already undertaken.'

Note: The decision as to whether an independent safety assessment is required is usually the responsibility of the authority.

The typical phases and stages of the project according to the EN 50126 are:

- Concept, System definition and operational context
- Risk analysis and evaluation
- Specification of system requirements
- Architecture and apportionment of system requirements
- Design and implementation
- Manufacture
- Integration
- System Validation
- System acceptance
- Operation, maintenance and performance monitoring
- Decommissioning

5.2.5 Proof Checking

Another tool used by the client to check that all the documentation issued by the designers is complete and fulfils the requirements of the specified standards from the tender is so called proof checking. Proof checking in general is conducted before the Independent Safety Assessment and is a very helpful tool for the client to save costs and time before the external (cost intensive) verification. The scope of Proof Checking is to conduct the assessment of the boundary conditions, fulfilment of requirements of applicable standards, correctness of reports, plans and calculations.

Note: The decision as to whether a proof check is required is usually the responsibility of the client and is in general conducted during the design phase.

List of Sources and Useful Literature

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