ISTANBUL TECHNICAL UNIVERSITY ★

GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

COMPARISON OF DISTURBANCE RESOLUTION BETWEEN TIMETABLE-BASED AND HEADWAY-BASED REGULATIONS: A CASE STUDY OF MARMARAY

M.Sc. THESIS

Anıl ATEŞ

Department of Railway Systems Engineering

Railway Systems Engineering Program

Thesis Advisor: Prof. Dr. M. Turan SÖYLEMEZ

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ZAMAN ÇİZELGESİ VE TRENLER ARASI SÜRE TABANLI DÜZENLEMELER ARASINDAKİ ARIZA ÇÖZÜMÜNÜN KARŞILAŞTIRMASI: MARMARAY ÖRNEĞİ

YÜKSEK LİSANS TEZİ

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HAZİRAN 2019

Anıl ATEŞ, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 526141003, successfully defended the thesis/dissertation entitled **"COMPARISON OF DISTURBANCE RESOLUTION BETWEEN TIMETABLE-BASED AND HEADWAY-BASED REGULATIONS: A CASE STUDY OF MARMARAY"**, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 03 May 2019
Date of Defense : 11 June 2019

In commemoration of Mustafa Kemal ATATÜRK and Nuri DEMİRAĞ
who have great contributions to the development of railway industry
in the early years of the Republic of Turkey,

FOREWORD

I would like to thank to Mehmet Ali DAĞLI, Electronic Communications Engineer and Lütfü AKÇİL, Electrical-Electronics Engineer Hüsnü Levent PANDÜL, Electric-Electronic Engineer from Metro Istanbul family who have a great place in my experience in railway vehicles and signaling areas so far.

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May 2019

Anıl ATEŞ

(Mechatronic Engineer)

TABLE OF CONTENTS

Page

ABBRIVIATIONS

AC	:	Alternative Current
AoC	:	Area of Controller
AP	:	Access Point
APR	:	Absolute Position Reference
ARS	:	Automatic Route Setting
ATC	:	Automatic Train Control
ATO	:	Automatic Train Operation
ATP	:	Automatic Train Protection
ATR	:	Automatic Train Routing
ATS	:	Automatic Train Supervision
BP	:	Block Processor
CBTC	:	Communication Based Train Control
CER	:	Community of European Railway and Infrastructure Companies
CI	:	Computer-Based Interlocking
CR	:	Commuter
CTC	:	Centralized Traffic Control
DC	:	Direct Current
DMI	:	Driver Machine Interface
ERTMS	:	European Railway Traffic Management System
ESP	:	Emergency Stop Button
ETCS	:	European Train Control System
GOA	:	Grade of Automation
GSM-R	:	Global System for Mobile Railway
HMI	:	Human Machine Interface
HSL	:	High-Speed Line
HST	:	High-Speed Train
HT	:	Headway Time
IC	:	Intercity
IEEE	:	The Institute of Electrical and Electronics Engineers
IMB	:	Inter Module Bus
IXL	:	Interlocking
LEU	:	Lineside Electronic Unit
LRT	:	Light Rail Transit
MA	:	Movement Authority
MAS	:	Maintenance Aid System
MENA	:	Middle East and North Africa
OCC	:	Operation Control Centre
OPC	:	Open Platform Communications
PA	:	Passenger Announcement
PID	:	Passenger Information Display

PIS : Passenger Information System
RBC : Radio Block Centre
SDH : Synchronous Digital Hierarchy
SIL : Safety Integration Level
TCP : Transmission Control Protocol
TCS : Traffic Control System
TSR : Temporary Speed Restriction
UDP : User Datagram Protocol
UIC : Union Internationale des Chemins de Fer
UITP : International Association of Public Transport
UTO : Unattended Train Operation

SYMBOLS

$\mathbf{SDT_{platform,\ train}}$	:	Station dwell time for the platform and train
$\mathbf{SDmin_{platfrom}}$	:	Station dwell time for platform
$\mathbf{TD_{train}}$	:	Train dwell time
t	:	Time
s	:	Second

LIST OF TABLES

Page

LIST OF FIGURES

Page

COMPARISON OF DISTURBANCE RESOLUTION BETWEEN TIMETABLE AND HEADWAY BASED REGULATIONS: A CASE STUDY OF MARMARAY

SUMMARY

The railway transportation system technologies that started to arise in the 1800s all over the globe has continuously been enhanced day by day. The crashes and incidents that been placed in this immature atmosphere have great supports to create modern techniques. Also, city congestion come up as one of the greatest problems for metropolitan communities with population growth of cities particularly in the 2000s.

However, countless studies have been conducted to decrease and maintain this traffic throughout the globe even today. Currently, public transportation usually comes first when considering metropolitan city problems where the railway system's transportation brings itself to the forefront. The demand for railway systems has increased and continues to grow based on factors such as punctuality, comfort, high capacity and safety.

Metro systems and high-speed trains are among the trends of today in urban transportation. Especially in the cities that have growing population like Istanbul, in order to meet passenger demand with city center metro, technology and its facilities operated in high-speed train systems used to connect them to other cities plays a very important role.

Although the investment costs of railway system projects are quite high, investment plans consider for 30 - 40 years old conjuncture for these projects. Completing the projects and delivering them on time is usually very troublesome since the systems have different disciplines should be used together in this period. The first feasibility of the Marmaray line, to be examined within the scope of this thesis, was made in 1987, and it was tendered in 1998, and its construction could even be started in 2004. In fact, it took about 15 years to complete the whole project, and the whole line was finally opened on March 12th , 2019.

In this thesis, the signaling infrastructure and operation processes of the Marmaray line were examined in detail. The European Railway Control System (ETCS) and the European Railway Traffic Management System (ERTMS) systems, which are offered by the European Union with the concept of international operability, with the Communication Based Train Control (CBTC) system, where demand is increasing day by day in urban systems, are used simultaneously in the line of Marmaray. The fact that such a signaling project was not carried out in the world before has brought some difficulties in the project's construction phase. The project connects Europe with Anatolia by railway and Marmaray has added to the geopolitical location advantages of Istanbul another aspect.

The signaling infrastructure of Marmaray continues to operate with CBTC grade of automation level 2 and ETCS level 1 systems. It consists of 3 lines except Marmaray tunnel area. Line 1 and line 2 are used for Marmaray vehicles except for tunnel area, line 1, line 2 and line 3 have infrastructure for use in high speed trains, conventional and freight trains. However, only the Marmaray vehicles can be moved unless there is an emergency in line 1 and in line 2 during operating hours. Trains from line 3 are routed to line 1 and line 2 according to the situations in the tunnel area.

Many control machines, dispatchers, supervisors and computers have passed with the increasing level of signaling technology used in railway systems. We can divide these control systems into 3 basic parts that can be summarized as the Vehicle Board System / on-board, Wayside System and Automatic Train Supervision system.

Within the scope of thesis, the most basic equipment's used in railway systems and some of its protection methods, fixed and moving block subjects that occur with the development of signalization, grade of automation and European Railway Control System / European Railway Traffic Management System signaling technologies used in the transportation of railway and intercity railway system and automatic train control systems that provide control in these systems are investigated in detail.

The ATS system is the administrator of the general system, everything that is on the platform and on the vehicle comes to the ATS as an information, the necessary commands are sent from the ATS and the system is routed accordingly. The regulation system which is the subsystem of the train supervision system is deeply investigated as a part of the thesis. The regulation system is timetable or headway based. While having two systems depend on a time-based and tariff-based, different research on which system is better or advantageous has been conducted.

The main aim of this study was to examine the advantages and disadvantages of the time-based and tariff-based studies. For this purpose, the Marmaray line in the SIMUX program and even the Hyundai Rotem operating vehicle were modeled. Simulation line 1 and line 2 have been realized since both time and tariff-based systems will be compared. Since the time-based regulation system does not support ETCS / ERTMS trains, conventional and high-speed trains are not included in the simulation.

Situations such as virtual track circuit occupation, pressing station emergency stop button, and non-removed route between Halkalı and Gebze terminal stations and their superiority against each other were investigated with also their sociological effects on passengers.

ZAMAN ÇİZELGESİ VE TRENLER ARASI SÜRE TABANLI DÜZENLEMELER ARASINDAKİ ARIZA ÇÖZÜMÜNÜN KARŞILAŞTIRMASI: MARMARAY ÖRNEĞİ

ÖZET

Dünyada 1800'lü yıllarda başlayan raylı sistem taşımacılığı her geçen gün kendini geliştirmiş, yaşanan olaylar ve kazalar yeni teknolojilerin gelişmesine yardımcı olmuştur. Özellikle 2000'li yıllarda artan kent nüfuslarının en büyük etkisi şehir trafiğine olmuştur. Bununla beraber bütün dünyada bu trafiği azaltmak için çeşitli çalışmalar yürütülmeye başlanmıştır ve bu çalışmalar günümüzde de devam etmektedir.

Günümüzde metropol şehirlerin trafik sorunlarını çözüm yöntemleri incelendiğinde ilk sırada genelde toplu taşıma geliyor, burada da raylı sistem taşımacılığı kendini ön plana çıkartıyor. Raylı sistemler teknolojik gelişmeler bağlı olarak sunduğu avantajlar nedeniyle toplu taşıma sistemlerinde ilk sırada tercih ediliyor. Diğer toplu ulaşım sistemleri ile karşılaştırıldığında sağladığı dakiklik, konfor, yüksek kapasite, güvenlik gibi etmenlerle her geçen gün raylı sistemlere talep artmış ve artmaya devam etmektedir.

2000'li yıllarda gelişmiş ülkeler hem şehir içi hem de şehirler arası trafik sorununa karşı kalıcı çözüm olarak raylı sistemlere yatırım yapmışlar, yapmaya da devam etmektedirler. Şehir içi ulaşımında metro sistemleri, şehirler arası ulaşımda ise hızlı trenler günümüzün trendleri arasında yer almaktadır. Özellikle İstanbul gibi nüfusu her geçen gün artan şehirlerde, yolcu talebi karşılayabilmek için şehir içinde kullanılan metro sistemlerinde, İstanbul'u diğer şehirlere bağlarken kullanılan hızlı tren sistemlerinde kullanılan teknoloji ve teknoloji altyapısı çok önemli bir rol oymaktadır.

Raylı sistem sektörlerinde yapılan yatırımların maliyetleri çok büyük olmakla beraber, 30-40 yıllık konjonktür düşünülerek bu yatırımların yapılmasına karar verilir. Bu sürede kullanılacak sistemler farklı disiplinleri bir arada bulundurmasından dolayı projeleri sonlandırmak ve zamanında teslim edebilmek oldukça zordur. Ayrıca Yap İşlet Devret modeline uygun bir yatırım aracı olmayan raylı sistemler çoğunlukla devlet finansmanı ile yapılmaktadırlar. Bununla beraber inşaat süreleri, saatleri ve maliyetleri beklenenden daha fazla olmaktadır.

Bu tez kapsamında incelenecek Marmaray hattını ilk olarak 1860'lı yıllarda Sultan Abdülmecid tarafından ortaya atılmıştır. Ardından 20. Yüzyılın başlarında Abdülhamit tarafından Amerikalı mühendislere ilk tasarımı yaptırılmıştır ve projenin ilk ismi ise Tünel-i Bahri olmuştur. Ardından uzun bir süre sonra, 1987 yılımda fizibilitesi yapılmış olup, 1998 yılında ihale edilmiş, inşaatına 2004 yılında başlanabilmiştir. Boğaz geçişi kısmı yani BC1 olarak adlandırılan bölüm 29 Ekim 2013 tarihinde açılmıştır. Kalan kısımlar ise CR3 yüklenicisi OHL – Siemens tarafından yapılmıştır. Maalesef hattın tamamının açılması yaklaşık 15 sene sürmüş, nihai olarak 12 Mart 2019 tarihinde açılabilmiştir.

Bu tezde Marmaray hattının sinyalizasyon altyapısı ve işleyiş süreçleri detaylı olarak incelenmiştir. Günümüzde şehir içi sistemlerinde her geçen gün talebin arttığı Sürekli Haberleşmeye Dayalı Tren Kontrol Sistemi (CBTC) ile Avrupa Birliği'nin uluslararası işletilebilirlik kavramıyla sunduğu Avrupa Tren Kontrol Sistemi (ETCS) ve Avrupa

Demiryolu Trafik Yönetim Sistemi (ERTMS) Marmaray hattında eş zamanlı olarak kullanılmaktadır.

Dünyada böyle bir sinyalizasyon projesinin daha önce yapılmamış olması, projenin yapılış aşamasında bazı zorluklar getirmiştir. Projenin Avrupa'yı ve Anadolu'yu demiryolu ile bağlaması ise İstanbul'un jeopolitik konum avantajlarına bir yenisini daha eklemiştir.

1800'lü yılların ortalarından günümüze kadar kullanılmakta olan sabit blok mantığındaki sinyalizasyon sistemleri, yolcu ve taşıma yoğunluğunun artması, trenler arası yolculuk sürelerinin her geçen gün daha da düşmesi sebebiyle özellikle şehir içi metro sistemlerinde Sürekli Haberleşmeye Dayalı Tren Kontrol Sistemi (CBTC) kullanılmaya başlanmıştır.

Sabit blok sinyalizasyon sistemlerinde ortaya çıkarılan çözüm ve önerilere ek olarak CBTC sistemlerinin en bilineni hareketli blok sistemlerinin temel bileşenleri ve mantığı bu tez kapsamında anlatılmıştır. Hareketli blok mantığında hareket eden trenlerin güvenli fren mesafesi, takip hızı gibi konulardan da bahsedilmiştir.

Marmaray sinyalizasyon altyapısı Sürekli Haberleşmeye Dayalı Tren Kontrol Sistemi (CBTC) GoA seviye 2, Avrupa Tren Kontrol Sistemi (ETCS) seviye 1 sistemleriyle işletmesini sürdürmektedir. Marmaray tünel bölgesi hariç 3 hattan oluşmaktadır. Tünel bölgesi dışında hat 1 ve hat 2 Marmaray araçları için, hat 1, hat 2 ve hat 3 ise hızlı tren, konvansiyonel ve yük trenleri için kullanım altyapısına sahiptir. Ancak işletme saatlerinde hat 1 ve hat 2'de acil bir durum olmadığı sürece sadece Marmaray araçları hareket edebiliyor. Tünel bölgesinde duruma göre hat 3'ten gelen trenler hat 1 ve hat 2'ye yönlendiriliyor.

Raylı sistemlerde kullanılan sinyalizasyon teknolojisinin seviyesinin artmasıyla beraber pek çok kontrol makinistlerden, dispeçerlerden, süpervizörlerden bilgisayarlara geçmiş durumdadır. Bu kontrolü sağlayan sistemleri 3 temel parçaya bölebiliriz. Araç üstü sistemi (on-board), hat kenarı sistemi ve otomatik tren denetleme, Otomatik Tren Süpervizyonu (ATS) sistemi olarak özetleyebiliriz.

Tez kapsamında raylı sistemlerde kullanılan en temel ekipmanlar beraber bazı koruma yöntemleri, sinyalizasyon gelişmesiyle beraber ortaya çıkan sabit ve hareketli blok konuları, şehir içinde ve şehirler arası raylı sistem taşımacılığında kullanılan GoA ve Avrupa Tren Kontrol Sistemi (ETCS) / Avrupa Demiryolu Trafik Yönetim Sistemi (ERTMS) sinyalizasyon teknolojileri ve bu sistemlerde kontrolü sağlayan otomatik tren kontrolü sistemleri detaylı olarak incelenmiştir.

Otomatik Tren Süpervizyonu (ATS) sistemi, genel sistemin yönetici konumundadır, sahada ve araç üstünde olan her şey ATS'ye bilgi olarak gelir, gerekli komutlar Otomatik Tren Süpervizyonu (ATS) tarafından gönderilir ve sistem yönlendirilir. Tez kapsamında çalışmaya yoğunlaşılan bölüm tren denetleme sisteminin alt sistemi olan düzenleme sistemidir.

Düzenleme sistemi trenler arası süre bazlı veya zaman çizelgesi bazlı çalışır. İşletme yapılırken sefer süresi bazlı ve tarife bazlı 2 sistem olması beraberinde hangisi sisteminin daha iyi veya avantajlı olduğu konularda çeşitli araştırmalar yapılmasını sağlamıştır.

Tez kapsamında yürütülen çalışmada trenler arası süre bazlı ve zaman çizelgesi bazlı çalışmaların birbirine karşı olan avantajları ve dezavantajlarını incelemek olmuştur. Bunun için SIMUX programında Marmaray hattı, hatta çalışan Hyundai Rotem aracı modellenmiştir.

Burada hem trenler arası süre hem de zaman çizelgesi bazlı sistem karşılaştırması yapılacağından dolayı simülasyon hat 1 ve hat 2'de gerçekleştirilmiştir. Trenler arası süre bazlı düzenleme sistemi Avrupa Tren Kontrol Sistemi (ETCS) / Avrupa Demiryolu

Trafik Yönetim Sistemi (ERTMS) trenlerini desteklemediği için konvansiyonel ve hızlı trenler simülasyona dahil edilmemiştir.

Halkalı – Gebze terminal istasyonları arasında oluşabilecek sanal ray devresi meşguliyeti, istasyon acil durdurma butonuna basılması ve silinmeyen rota gibi durumlar karşısında sistemlerin birbirlerine karşı üstünlükleri, arıza durumunda hangi sistemi kullanmanın daha avantajlı olduğu ve bunların yolcular üzerine etkisi incelenmiştir.

1. INTRODUCTION

Railway systems were first introduced in the United Kingdom in 1830. It has taken its place throughout the world since its first use as one of the most reliable and cost-effective systems for passenger and freight transport. Following the industrial revolution, an irreversible process of migration between countries has begun and the importance of urban, rural and interurban transport has increased as a result of the rapid population growth in some regions.

It is known that the most effective approach to fixing transportation issues is the development and dissemination of public transportation systems, where world population, industrialization and megacity density are increasing rapidly. Because of their advantages, railway systems are preferred in public transport systems. Investments in railway public transport systems are increasing day by day in developed countries in order to provide a permanent solution to traffic problems.

In railway system technology, the initial objective is to prevent accidents. Therefore, signaling systems were developed and that is why signaling systems are one of the railway system's most essential subsystem. The main theme of signaling systems is to provide railway safety as well as increasing line capacity and minimizing human error. On the other hand, the transportation demands of the passengers are met thanks to the signaling systems that provide safe, secure, comfortable, timely and fast operation.

The use of CBTC systems in the city has become widespread with the technological developments in the signaling system over the past 20 years. Although these systems ' initial investment costs are somewhat expensive, in the long term they become a cost-effective system. High-frequency train services can be provided in crowded cities to meet passenger demands.

Railway standards have been developed to provide these advantages through worldwide signaling. For instance, the ETCS / ERTMS system has been developed across Europe for inter-city transport. There is no need in the city to develop such a common language. To better understand and interpret these systems, IEEE 1474 1, 2, 3 and 4 and IEC 62290-1 and 2 standards are analyzed in this thesis. It will transmit the information obtained here as small notes.

1.1 Purpose of Thesis

The level of signaling technology is very important in the metro and commuter systems used in the city. GoA levels are of great importance to the operation and how they are applied in the systems used in urban areas. Within the scope of this thesis, the SIMUX simulation program analyzed the effect of the Marmaray project, which has a unique line architecture in the world, on the GoA level 2 used in the operation, and the effects of the timetable and headway regulations subsystems on the other trains in the operation.

The other aims of the thesis are to discuss signaling systems that are used both in the city and inter-city. Also, today, which system in Turkey to ensure level of implementation in acknowledgment of the possibility of being more accurate.

1.2 Planning of the Thesis

Six chapters were planned for the thesis. After a brief introduction and the purpose of the thesis, the vehicles type used in railway systems are mentioned in Chapter 2. In the next section, in section 3, the history of signaling in railway systems since its find out is described in the literature as basic elements of signaling systems, signaling systems used in urban and inter-city transport, and finally automatic train control systems. Furthermore, the basic operating principle is explained in Chapter 3 fixed block, moving block, grade of automation and level of ETCS. The main topics of the Chapter 4 chapter are the story of the Marmaray project, used systems, signalization architecture, ATS, headway, timetable and regulation, ATR and ARS systems.

2. CLASSIFICATION OF URBAN RAILWAY SYSTEM VEHICLES

2.1 Tram

Tram is a passenger carriage that travels in the city on special rails. The tram is a product of the industrial revolution that started to change the appearance of the world in the 1800s. In 1832, Harlem, New York, commissioned the first line of railway transport in urban passenger transport. The engine of the vehicle consisted of a few horses only. The engine of the vehicle consisted of a few horses only. The horses were picked from the vehicle's front at the last stop, so the vehicle could run in the opposite direction. The first European tramway line was opened in Paris in 1853. The rails provided up to thirty passengers per hour with a pair of horses.

An electric motor was displayed at the Berlin exhibition in 1879, capable of pulling three small cars at a speed of 12 km/h. But there was also a big drawback on this engine. The third rail with energy was needed to transmit the energy to the engine. This system's greatest disadvantage was the great danger to people walking on the road.

The third rail proposal found a subway area for its application. Another solution has been created for the trams. To avoid blocking other vehicles ' traffic, the two main rails were placed between the paving stones. The cables provide the electrical current. Cables have been stretched along the line at a height of 5 meters from the ground [1].

Trolleybus, then electric motors and trams started taking their places in the cities. Therefore, tram systems are generally built as level crossings. Because there is no need to build tram lines, large-scale excavation and construction works are not required and cost-effectively they are cheaper than other systems. In many cities around the world, the tram systems used use existing bus stops or similar simple facilities [2].

The width of the vehicle varies from 2,200 mm to 2,650 mm. Ri59 or Ri60 slotted rail types are commonly used. The catenary provides the energy supply on trams and is widely used at 750 VDC. Because of all these features, tram systems can be built at very low cost compared to other public railway transport systems. The tram's passenger capacity varies between 13,200-26,400 passengers/direction per hour [3].

2.2 Light Rail Transit

Among city railway transport systems, LRT has an important place. Higher travel capacity systems than tram systems. While these systems are preferred as the main transportation systems in transportation lines where travel demands are high, they can be built as supporting transportation systems that are integrated in very crowded cities with higher capacity systems. LRT lines are safe systems according to tram systems [4].

The width of the vehicle is generally 2650 mm. Catenary, rigid catenary or feeding systems from the 3rd rail can provide the energy requirement. It is usually preferred to have 750 VDC or 1500 VDC. The LRT's maximum travel capacity of 35000 passengers/ direction per hour [5].

2.3 Metro

The word Metro is the abbreviation of the metropolitan French word, which is the Greek word for metaphor and city. Underground electric trains are called metro to relieve heavy traffic in big cities. As can be easily understood, the main purpose of the metros is to reduce the ground's traffic density and transfer some underground traffic. Metros in big and crowded cities like New York, London, Paris, Moscow are too complicated to think through the tunnels, passages, parallel running lines that intersect. The system is still operating in a great order, though [1].

The metro's maximum travel capacity of 100,000 passengers/ direction per hour [5]. Metro systems are preferred in the cities where the highest travel requirements are determined in the big cities [6].

In the form of a catenary or rigid catenary, as well as in light rail systems as well as from the third line, the energy requirement can be made from the overhead feed line. It is possible to use 750 VDC, 1500 VDC or 3000 VDC voltage [3].

Recently, ATC systems are designed without drivers and as a result of successful applications are expected to be more demanding. Signaling architecture in Marmaray line will be examined in detail in this thesis.

3. HISTORY OF RAILWAY SIGNALING

Since the early days of railway transportation, trains were considered a fast means of transportation. Of course, in the early days on the lines rarely carried out and no train in front of the train assuming that there was a comfortable ride. However, as the day approached, the increasing trains, weights, accidents with rising speed limits forced the railway system authorities to take measures, bring new rules and even develop new systems [7].

In the course of time, the manually used signal systems started to leave themselves to the electronic systems with the developing technology. Finally, the development of a modern signaling system used in railway systems has been instrumental. Figure 3.1 shows the historical development of the signaling system.

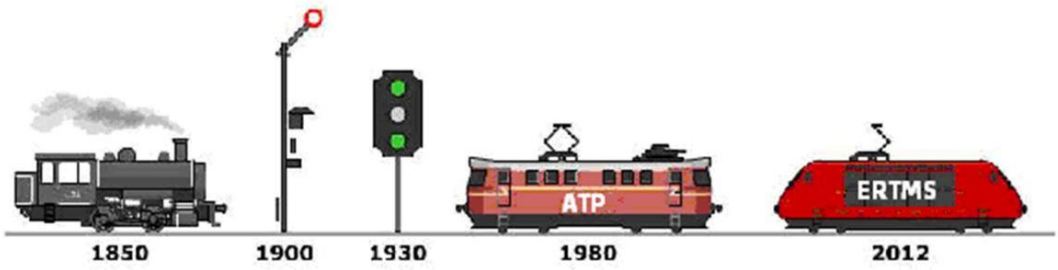


Figure 3.1 : History of signaling systems [8].

Thanks to modern signaling systems, speed, timing, passenger safety and safety of the system have become very important in railway transportation. Systems that meet these demands are developed day by day and faster, more comfortable and safer systems are designed. Most of the advantages of signaling system are listed below.

- It is inevitable that modern signaling systems should be used in urban or conventional lines where there is high demand for railway system.
- Advantages of signaling systems;
- Reduces travel time,
- Reduces the time between the two trains.
- Increases operating capacity by operating more trains,
- Reduces commitment to personnel and manpower,
- Minimizes system safety by minimizing human errors,
- The number of possible accidents is minimized.

3.1 Basic Elements in Railway Signaling

In this section, the terms and components of the railway system which should be known in the thesis will be discussed. Respectively signal, track circuits, points, interlocking, protection methods, dwell time and more.

3.1.1 Signals

Signals are visual equipment used to inform railway drivers. Although the signals vary from country to country, they differ from project to project. The signals have lost the ability to be the first security measure with the increase of automatic and driverless operating systems. Although it is used in open lines today, it is used for degraded level mode in order to continue operation in automatic systems.

Signal types vary from project to project, from station to station. The signal colors can be different depending on the content of the project. Unlike the commonly used two aspects, high three aspects, dwarf three aspects, high four aspects signals, five aspects signals lamps can also be used. In addition, day and night mode options are used to balance the visibility and power optimization of the signals.

According to the structure, there are 7 types of signal used in the Marmaray project.

3.1.1.1 High three aspect signals

High three signals are located on the main lines. The color of the high three signals are sorted from top to bottom in yellow, green and red. Table 3.1 describes the meaning of signal colors in high three aspect signals.

Table 3.1 : High three aspect signals.

Signals Aspects	
	Proceed, expect Stop in next signal
	Proceed, next signal shows Proceed
	Stop
	Proceed for shunting movements Stop

3.1.1.2 Dwarf three aspect signals

Dwarf signals are positioned on the siding roads. The color of the dwarf three signals is ordered from top to bottom in red, green and yellow.

3.1.1.3 High four aspect signals without CBTC

In Marmaray project, 2 of the 3 lines are used as commuter train, while all 3 lines are used as conventional and high-speed train lines. The color of the high four signals without CBTC is ordered from top to bottom in yellow red, green and yellow. Table 3.2 describes the meaning of signal colors in high four aspect signals without CBTC.

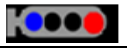
Table 3.2 : High four aspect signals without CBTC.

Signals Aspects	
	Proceed, expect Stop in next signal
	Proceed, expect Stop in next signal. Point in reverse before next signal
	Stop
	Proceed, next signal shows Proceed
	Proceed, speed limitation ahead
	Proceed for shunting movements Stop

3.1.1.4 Dwarf four aspect signals with CBTC

As mentioned above, dwarf signals with CBTC are being used on siding lines. The signals used here indicate whether the CBTC is moving from the siding line to the main line. The color of the dwarf four signals with CBTC is ordered from top to bottom in red, green, yellow and blue. Table 3.3 describes the meaning of signal colors in dwarf four aspect signals with CBTC.

Table 3.3 : Dwarf four aspect signals with CBTC.

Signals Aspects	
	Proceed, expect Stop in next signal
	Stop
	Proceed, next signal shows Proceed
	Proceed, speed limitation ahead
	Proceed for shunting movements
	Proceed into a section with track circuit occupied or non-signaled track
	Proceed for CBTC movements

3.1.1.5 High four aspect signal with CBTC

These signals are only located on line 1 and line 2 in the Marmaray project. The color of the high four signals with CBTC is ordered from top to bottom in blue, yellow green and red.

3.1.1.6 Two aspect signals

These signals are used at the end of the line. Red over red signal means stop.

3.1.1.7 Five aspect signals

These signals are only located on line 1 and line 2 in this project. The signal indicates whether the blue color is CBTC. The color of the five signals is ordered from top to bottom in blue, yellow, green, red and yellow. Table 3.4 describes the meaning of signal colors in five aspect signals.

Table 3.4 : Five aspect signals.

Signals Aspects	
	Proceed, expect Stop in next signal
	Proceed, expect STOP in next signal. Point in reverse before next signal
	Stop
	Proceed, next signal shows Proceed
	Proceed, speed limitation ahead
	Proceed for shunting movements
	Proceed into a section with track circuit
	Proceed for CBTC movements

3.1.2 Points

One track, two or more different paths developed to connect the railway system element is called point. The points are the equipment that makes the moving railroads move from the existing road to different lines. Control of the points is controlled by electric motors nowadays. In order to control the points especially used in high-speed train lines, multiple point motors are used.

After the points movement, information about the position of the point is sent to the system. This information can be classified as PM reverse position, PM normal position and PM fault. After setting the route, the point must be locked.

If the point in the route is not locked, the signal that protects the point falls red. When the train on the route approaches the scissor, it is stopped before the signal.

3.1.3 Track circuits

In railway systems, the correct detection of the train position is very important for safety. For this reason, the role of the track circuits, the correct location of the train is to transfer the system. With correct position information, the operation of the line can be sustained without a problem. Another task of the track circuit is to detect the rail crack. Figure 3.2 shows the track circuit occupancy status.

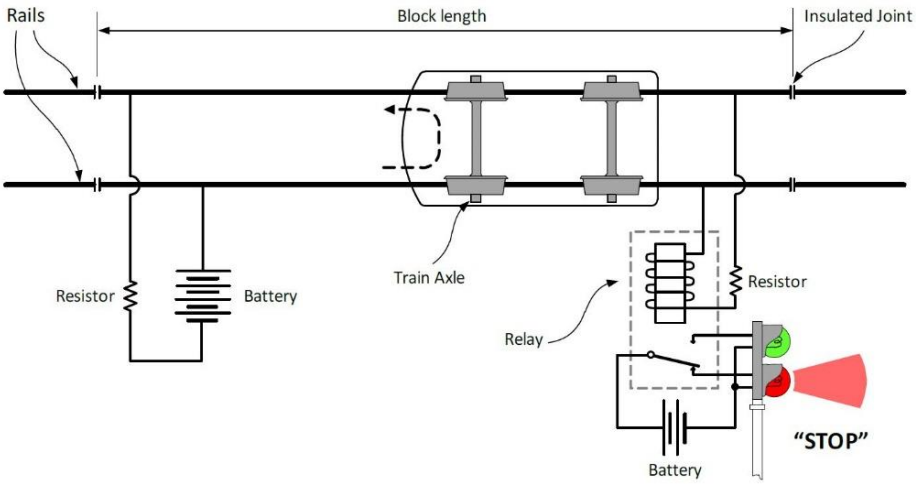


Figure 3.2 : Track circuit - block occupied [8].

When the track circuits are first introduced, the structure is the rail is divided into isolated zones. The rail is supplied with a current source and sensor. If there is no train, the circuit is open, the current does not flow, the relay does not move.

When the zone is short-circuited by a train, a current flow through the wheel and the axle and the relay pulls. It is normally called Open Track Circuit. This system does not have a fail-safe structure. However, the above structure is both primitive and costly and does not create a safe environment for train movement. Figure 3.3 shows the track circuit occupancy status.

Therefore, modern track circuits are used to determine the train location by keeping the electrical circuits at different frequencies separate from each other. This resulted in a less costly and more stable system.

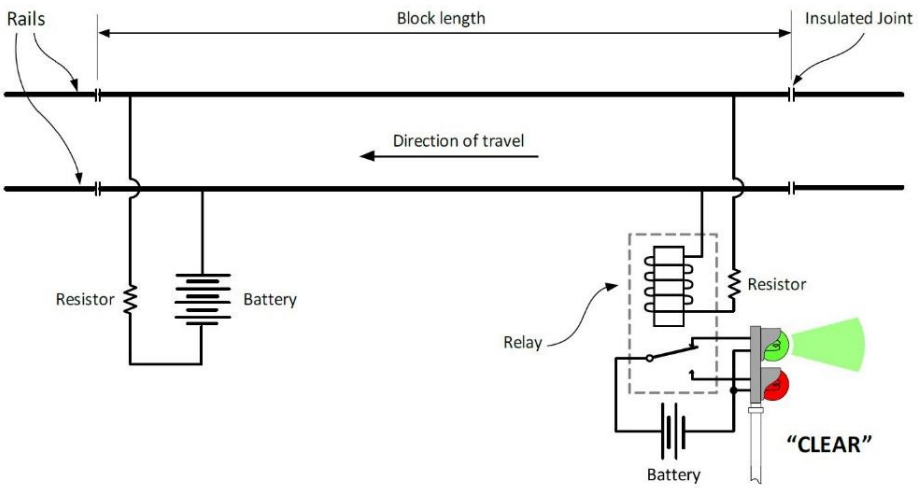


Figure 3.3 : Track circuit - block unoccupied [8].

3.1.4 Interlocking

Railway interlock system is a system that controls the traffic between a station and adjacent stations. This control carries out the train routes, the arrangement of the point movement and all other railway system vehicles to the rules of the railway. The term interlocking logic refers to the logical relationship between the physical units used in the field, such as points, signals and track circuits in railway systems.

The first interlocking in the history has been designed in mechanical structure and then the relays have been used. Nowadays, electronic based interlocking is used, and it is used in railway systems with faster and higher reliability rates with electronic interlocking.

3.1.5 Block

Railways need to have enough space between trains to ensure that a following train stops before it comes forward. This allows you to position the signal at certain intervals. This is achieved only by dividing the line into specific blocks. Each block is protected by a signal positioned in front of it. If a train has entered the block and the train needs to stop, the signal will appear red. If the block is clear, the signal appears green. Figure 3.4 shows simple block signaling.

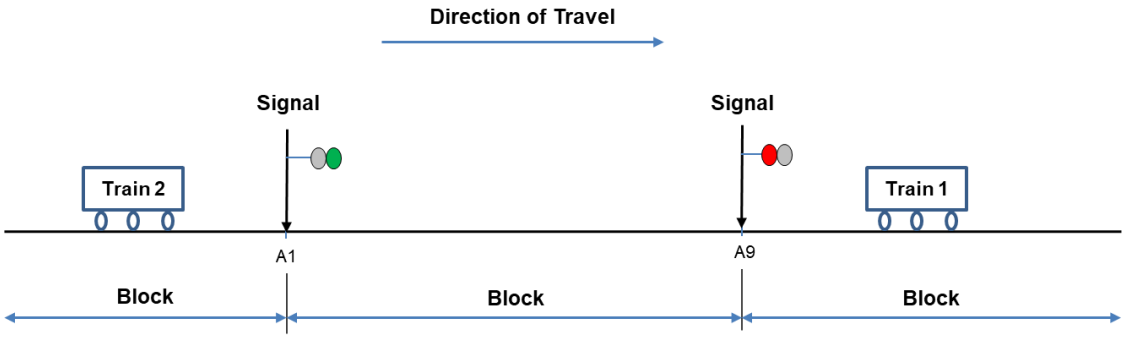


Figure 3.4 : Blocks arrangement of simple block signaling.

3.1.6 Route

When all the moving elements on the line take a suitable position for the moving of a train, a path is occurred on the line. A route with a specific start and end point and technically protected is called a route. All signals and points on the route are associated with each other. The system makes all the checks that the route is empty and then will be empty before allowing any movement.

The purpose of this approach is to ensure that the distance between the leading train's tail position and the train's nose position is greater than or equal to the safe breaking distance. With the signaling system “moving block” two consecutive trains move by the safe distance value of braking this leads to train lines operate quick and accurate way [9].

3.1.7 Overlap

If the control area of a signal is greater than the block length, overlap occurs between the signal control areas. Overlaps are used by most railways in the world and provide additional protection against any failure of the drive at the target braking distance. It is a distance that protects the driver in case of bad weather like foggy weather passing the signal. Especially, it is a technique used especially in Europe to increase the use of lines economically. For instance, it is 180-190 meters on British railways [10].

3.1.8 Flank protection

Most railways in the world provide flank protection at least for train routes. The signals are locked in the stop position. To ensure full protection, the red signal lamp must be proven alight. With reduced safety, few of railway operator, train drivers must accept this signal as almost unused. They consider this stopping as flank protection.

Risks to a route are explained below:

- Movements in overlapping paths are generally blocked by interlocking.

- Maneuvers can be made without the route.
- It may cause unintentional movement of parked vehicles.

3.1.9 Front protection

The railways can be used in different applications for locking elements in the overlap area. If an unauthorized train from the opposite direction enters the overlap area, the danger can be avoided by turning the oncoming train in a different direction. Therefore, some of the railways in the intermediate area some points are left unlocked so that they can be pre-protected in an emergency. In some countries for instance England, the points in the overlap area can be locked as a priority protection.

3.1.10 Safe braking distance

In the moving block signaling system, the movement of the trains depends on the safe braking distance. Thanks to this approach method, the distance between virtual occupation rear of the train moving in front and the virtual occupation front of the train moving in the rear cannot be smaller than the safe braking distance when the two trains move in a same line and same direction [9].

It must be greater than or equal to this distance. In this way, while the train operations are carried out quickly, the location information of the trains is determined exactly. Figure 3.5 shows IEEE provides a graphical illustration of a typical safe braking model.

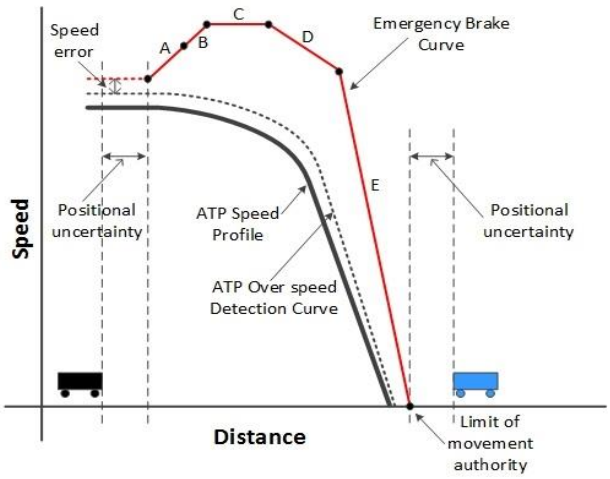


Figure 3.5 : Signaling safety distance [11].

3.1.11 Movement authority

Thanks to the CBTC system, the train's distance information can be moved by mean side equipment to the train when the train is on the move. This information is called the movement authority. This function is achieved by the wayside system or ATS. The

track, speed and distance information are transmitted to the points in front of the roadside via the central control system. Figure 3.6 shows train movement authority.

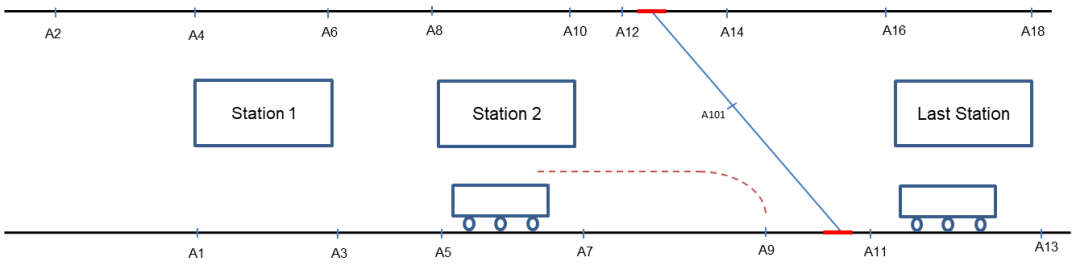


Figure 3.6 : Movement authority.

The CBTC system is a secure system that allows trains to move location from the starting point to the stopping. This location calculations are made accurately from point to point. The approximate error in position calculations is about 5 to 10 m considering the train is in moving. However, if the stopping position of the train is at the station, this error is reduced by 30 centimeters.

The track, speed and distance information are transmitted from the on-board system to the wayside system. This information is developed according to the runway conditions and is moving authority. In this way, the train moves in the braking distance without braking and conflict.

3.1.12 Timetable

In a railway system, the timetable is a list of times when trains should departure or arrive at a specified location. The timetable is a table that the operator gives to passengers, when and where trains need to departure or arrive. Table 3.5 shows example timetable of Marmaray Halkalı - Gebze.

Table 3.5 : Halkalı – Florya Akvaryum timetable.

Journey Number	10001	
Station	Arrival Times	Departure Times
Halkalı	-	06:00:10
Mustafa Kemal	06:03:45	06:04:15
Küçükçekmece	06:07:02	06:07:32
Florya	06:09:18	06:09:48
Florya Akvaryum	06:11:05	06:11:35

3.1.13 Headway

During the movement of the train, the time between two trains is called the headway. Shortening of headway time increases the capacity of the line and increases the rate of regenerative energy of consecutive trains.

3.1.14 Line capacity

The capacity means the maximum number of trains that can be operated within a certain period under defined operating conditions and infrastructure.

3.1.15 Dwell time

The waiting time of a train at the station is called dwell time.

3.1.16 Trip time

The moving time of train from a station to the next station is called trip time.

3.2 Railway System Signaling Technologies

In the recent railway signaling system, with the emergence of communication signaling, a great transformation has started all over the world. Besides in metros, which are used as urban transportation systems, the communication-based train control system is now being used. Especially the budgets allocated to the railway system throughout Europe are increasing every year. For example, in 2017, a budget of € 170 Billion was allocated. In addition, the communication-based train control system was only 188.9 km between 2001 and 2010, while the targeted distance between 2011 and 2021 was 1077.8 km. Based on communication systems are now being used in metros, which are used as urban transportation systems.

The conventional signaling system, which is still being used for almost half a century, is made by track circuits, axle counters and traffic lights. Today, modern signaling systems have emerged due to the development of communication technology. Thanks to the communication-based train control technology, real-time train control can be controlled. It also decreases the headway time by reducing the safe braking distance. This increases the capacity of the line and reduces the number of equipment to be used on the line.

However, it is not generally the industry-leading universities because private companies do not share information. On the contrary, those who develop and advance the sector are the private sector.

It is a country that carries the flag in Europe, especially in the Danish communication-based signal system. It aims to upgrade the system by using this technology in all lines until 2021. Denmark aims to reduce the delay time due to signaling by 80% thanks to the use of CBTC. The use and communication of CBTC is based on IEEE standards [12].

The CBTC system consists of 3 general systems as on-board ATC system, regional or wayside ATC system and ATS system.

Information such as current speed, direction of movement, location of the train is sent to the system in the site at certain periods. With the information received from the system, the wayside system determines the maximum speed that the train can go and the amount of movement it can move and sends it to the train. The speed and current location information sent to the train is called the movement authority. When the A train's trajectory information is traced continuously with the train C in front and behind the train C and the current location position is known, it is not necessary to use the trackside equipment used in the classical signaling system.

The speed and current position information of the moving train is calculated by speedometer, tachometer, speedometer, Doppler radar and odometer. According to IEEE CBTC standard, sensitivity of current location should be between 5 and 10 meters.

In the 21st century, there are two basic signaling systems used in railway systems.

3.2.1 Fixed block

In fixed block systems, the most commonly used system for detection is track circuit system. Although different track circuit methods have been applied over the years, the principle continues in the same way. The system used as an alternative to the track circuit is the axle counter system. Counts the axles of the trains entering and leaving the block area and determines whether the train is in the area. If the number of axles entering the block area is not equal to the number of axes leaving the block area, it is assumed that there are trains in the block area with fail-safe logic.

Detection the block occupation in railway systems does not give information only on the position of the train. By means of the systems communicating by train, the speed that the train should go is sent in the information. It also contributes to a safe operation based on this information.

The occupancy information in a block is used to check the operation of all trains under operation. For example, if train activity is detected in block x, it causes the stop

command in the block immediately after the train to be sent. Depending on the length of the block, the stop and deceleration information may vary. This is the case in the fixed block, while the movement authority in the moving block changes according to the current position and speed information. Figure 3.7 shows basic concept of fixed block.

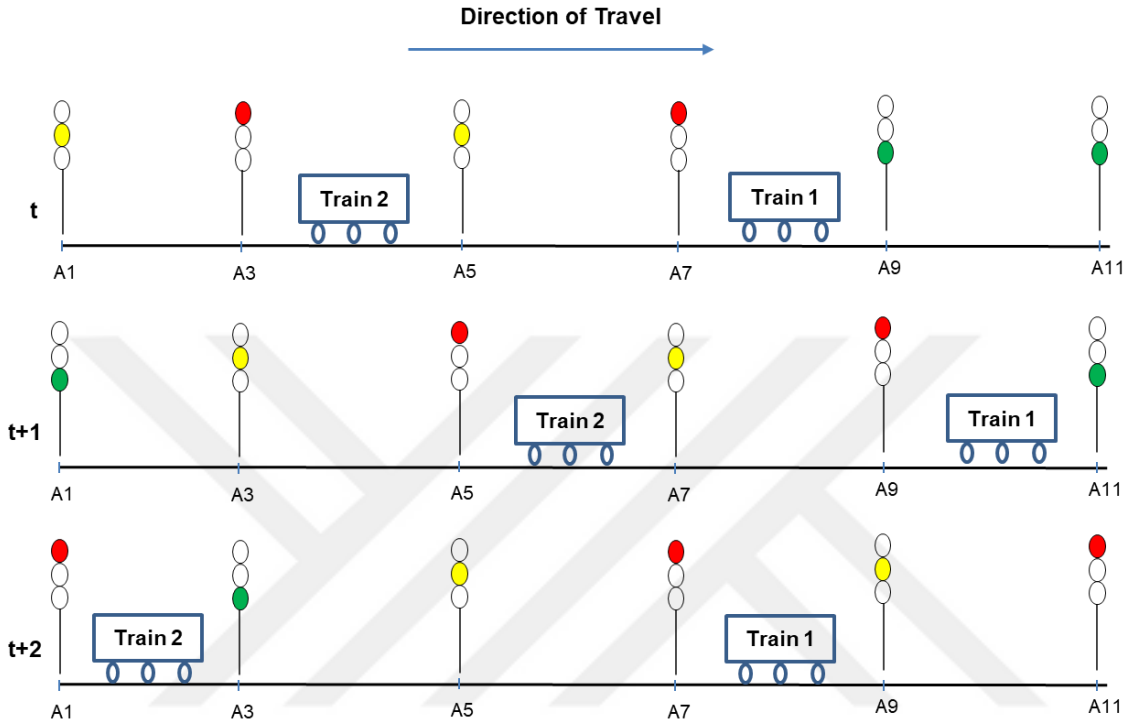


Figure 3.7 : Basic concept of fixed block.

3.2.2 Moving block and CBTC

In 1864, in London, William Robert Sykes tested the first track circuit. In 1872, William Robinson invented the first fail-safe track circuit and the concept of the track area occupation emerged. The detection of occupation in conventional signaling with the track circuit after the last 140 years is still in use. Figure 3.8 shows the comparison of fixed and moving blocks.

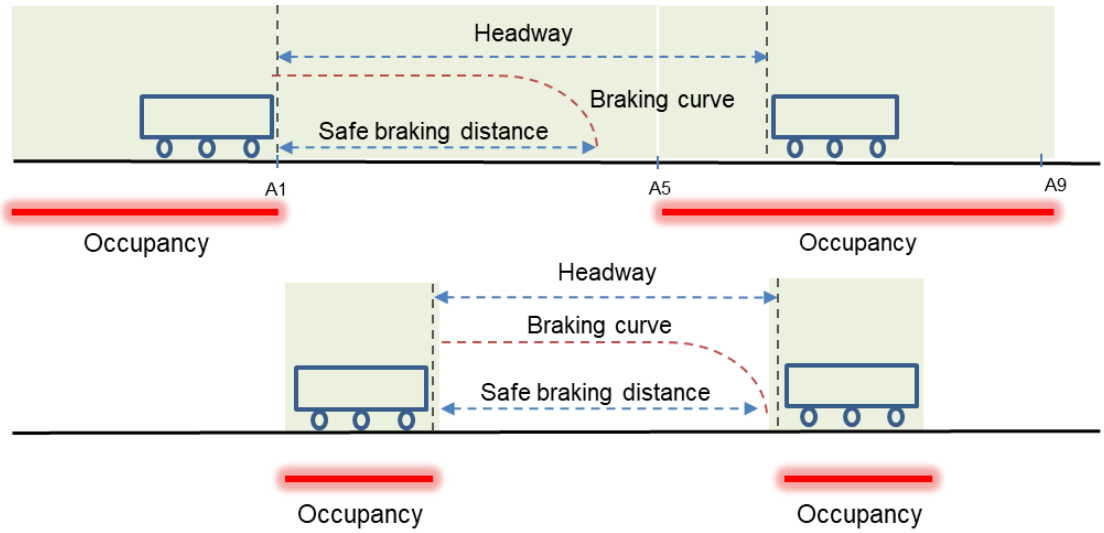


Figure 3.8 : Fixed and moving block system.

Demand for CBTC solutions has been increasing over the last 25 years according to traditional track circuit applications. The most important advantage of CBTC systems is that the trains can be operated safely and with minimum headway.

If CBTC remains the preferred technology, the demand for track circuits will decrease every year. CBTC mainly includes the following features:

- High resolution train position detection independent of track circuits.
- High-capacity, continuous bidirectional communication between train and wayside equipment.
- There are on-board and wayside processors performing vital functions [13].

In other words, the CBTC system obtains the precise position of the train, independent of the track circuits, using the system safe with a bidirectional communication.

3.2.2.1 High resolution train position detection

The main feature that differentiates the CBTC from conventional signaling systems is that the train position can be obtained independently of the track circuits. The currently position calculation is made by means of transponder tag and beacon equipment located along the line. When the train passes through the tag and beacon, it learns the approximate position information due to on-board equipment. The train does not use only the position information received from the tag and bacon. In addition, exact position information is provided by tachometers mounted on the axles and Doppler radar.

In fact, when the train passes, due to the tag and beacon, it corrects the error in the current position information calculated by tachometer and Doppler radar. As the train

moves, the tachometer and Doppler radar accurately calculate how many meters are moving.

In one example, when the train passes over the tag or beacon at point B, the on-board unit gives approximately 200 m information as to the train. As the train progresses, the tachometer and Doppler radar accurately calculate how many meters the train moves. As described above part is shown in Figure 3.9 and 3.10 in below [13].

The on-board unit decides how many meters away from the reference point of the train, using the approximate location information and how much the train is moving. The on-board unit decides how many meters away from the reference point of the train, using the approximate position information and the train's actual footprint information from the tachometer and Doppler radar.

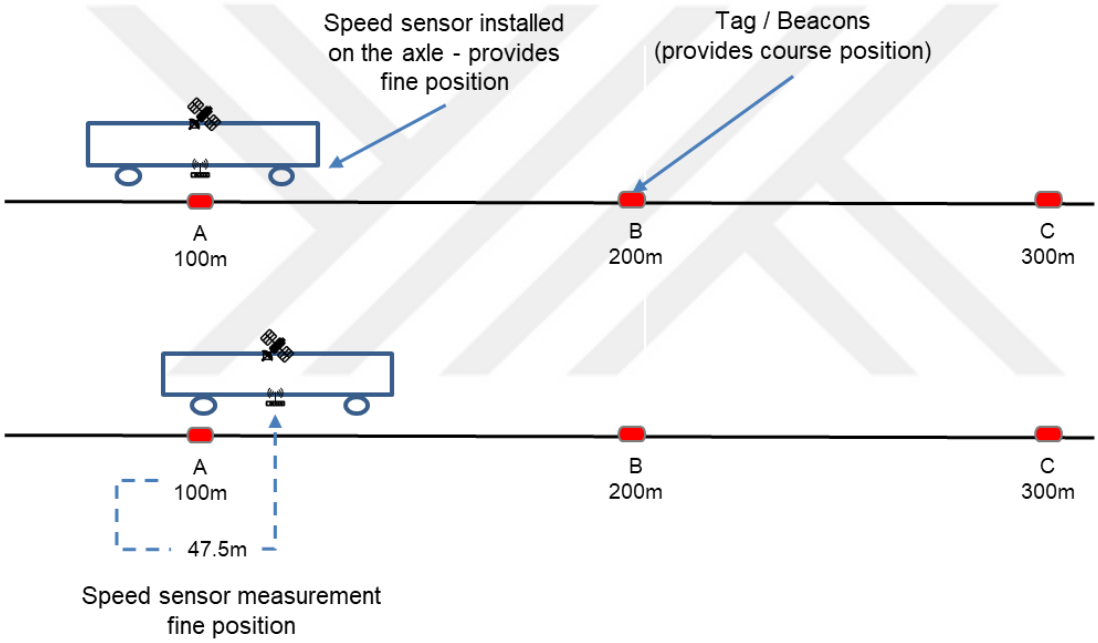


Figure 3.9 : Position calculating.

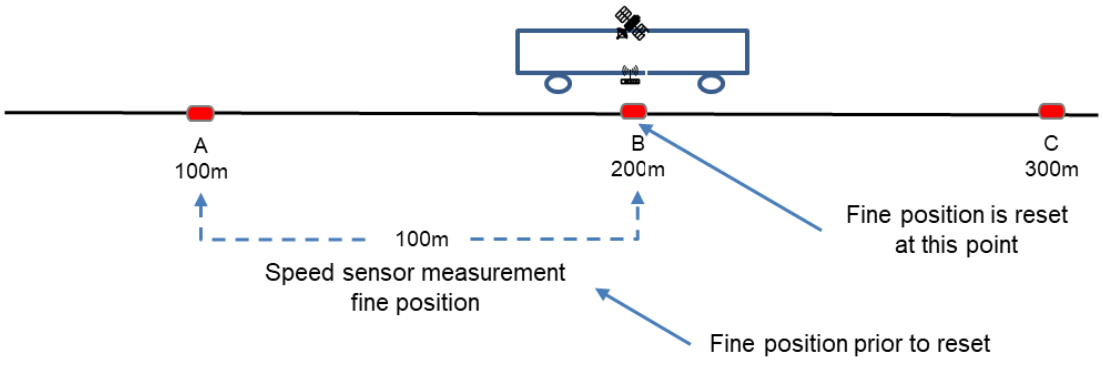


Figure 3.10 : Position reset.

3.2.2.2 High-capacity, continuous bidirectional communication

When the exact position of the train is obtained, this information must be transmitted quickly to the pathway equipment. There are several methods for this process. For the last decade, signaling companies preferred the method of wireless communication system via WiFi or RF.

In railway applications, wireless access points are located along the line. There are 2 options, one is the access point and the other is the use of coaxial cable.

When the train is in moving, when the antenna on the train reaches the range of an access point, it locks its signal to this access point and breaks it off from the previous access point. Figure 3.11 shows bidirectional communication.

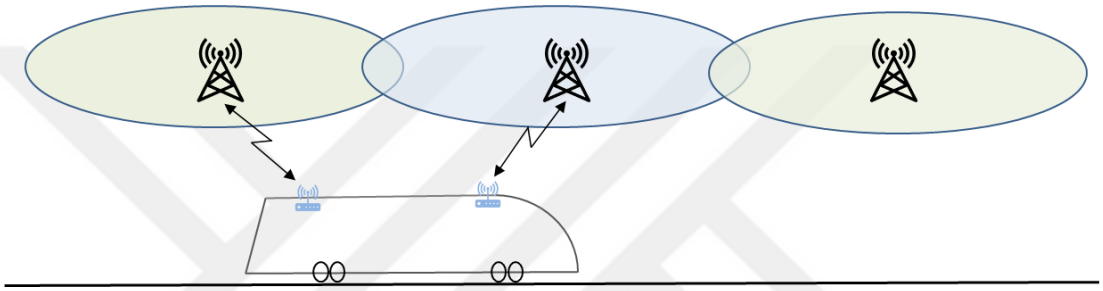


Figure 3.11 : Bidirectional communication in CBTC.

TCP / IP or UDP are generally used as communication protocol in this communication environment. These protocols provide flexibility and expandability to the solution. All vital or non-vital data is sent in this environment. However, this bond is not vital. In order to make sure safety integrity, end-to-end vitality must be ensured. In other words, on-board and wayside units must guarantee that the data they receive is lossless and uncorrupted.

3.2.2.3 Processors performing vital functions

For CBTC systems it is not enough to obtain the accurate position information of the train. In addition, it is the duty of the system to protect the train from all kinds of fails. In IEEE 1474.1 describes the vital functions that CBTC system must provide. Figure 3.12 shows vital function communications.

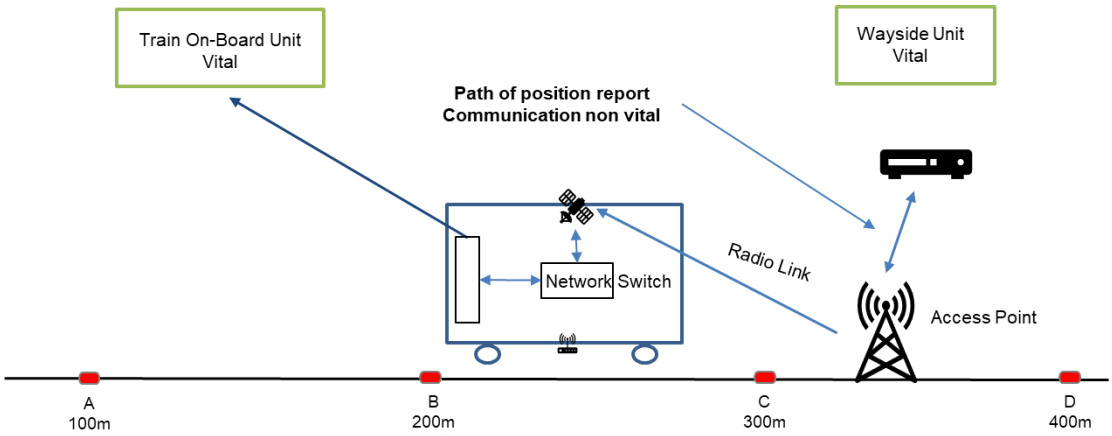


Figure 3.12 : Tracking train in CBTC.

Vital functions can be summarized in 3 categories: Collision avoidance, over speed protection and various protections. If we talk about these 3 definitions briefly;

***Collision avoidance**:* The basic principle of the CBTC system is the ability to keep trains safely separated from each other and from other obstacles on the planned route.

Over speed protection: The CBTC system can accurately determine the speed of the train and control it tightly.

Various protections: These are functions that do not fall into any general category and are not the core parts of the CBTC system. However, the IEEE states that the CBTC system must fulfill its function to protect against them.

According to CBTC conditions, IEEE CBTC defines subsystems as follows.

Without ATO (Automatic Train Operation) or ATS (Automatic Train Supervision) functions, it can only include ATP (Automatic Train Protection) functions.

It includes ATP functions but may also include some ATO and / or ATS functions to meet the application-specific, operational requirements. It can be the only train control system within the application, or it can be used with other auxiliary wayside systems. At the top we have a fully automated ATP, ATO and CBTC system with ATS function. At the bottom point, there is only a solution with ATP.

The CBTC configurations also vary according to the desired solution. If it is to increase the desired efficiency, then a fully automatic system is required. If the need is to provide an extra layer of security, only the configuration with ATP may be enough.

There are currently more than 150 radio based CBTC projects around the world, including ongoing and operational projects. The Figure 3.13 and 3.14 show a regional and supplier breakdown of these projects [12].

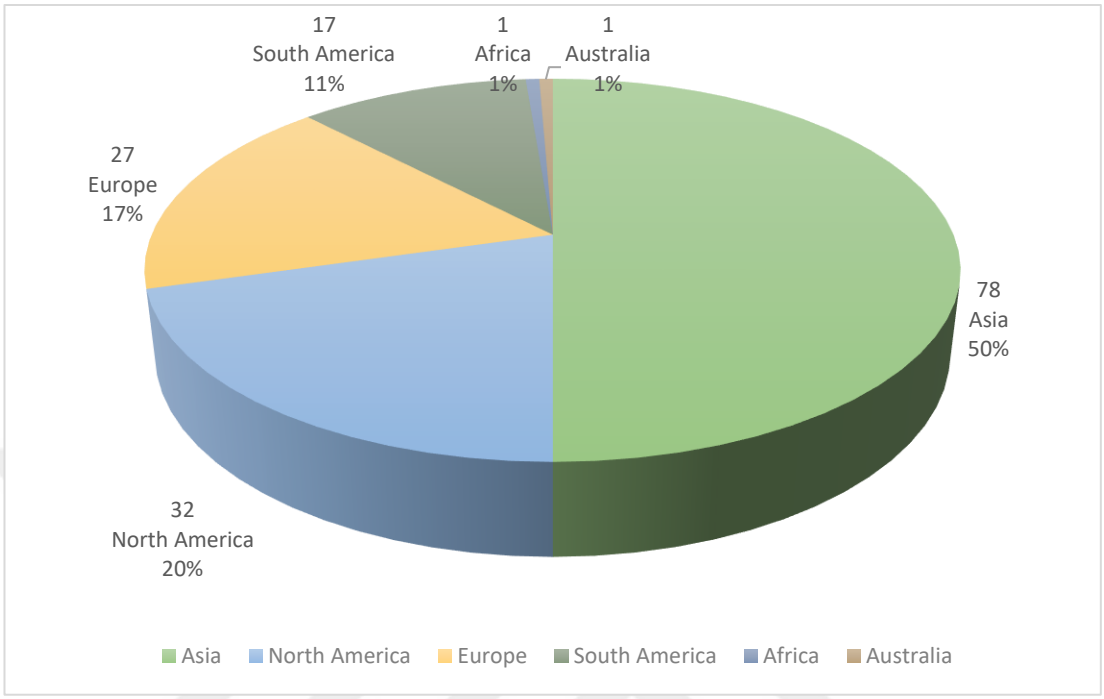


Figure 3.13 : CBTC project worldwide by region.

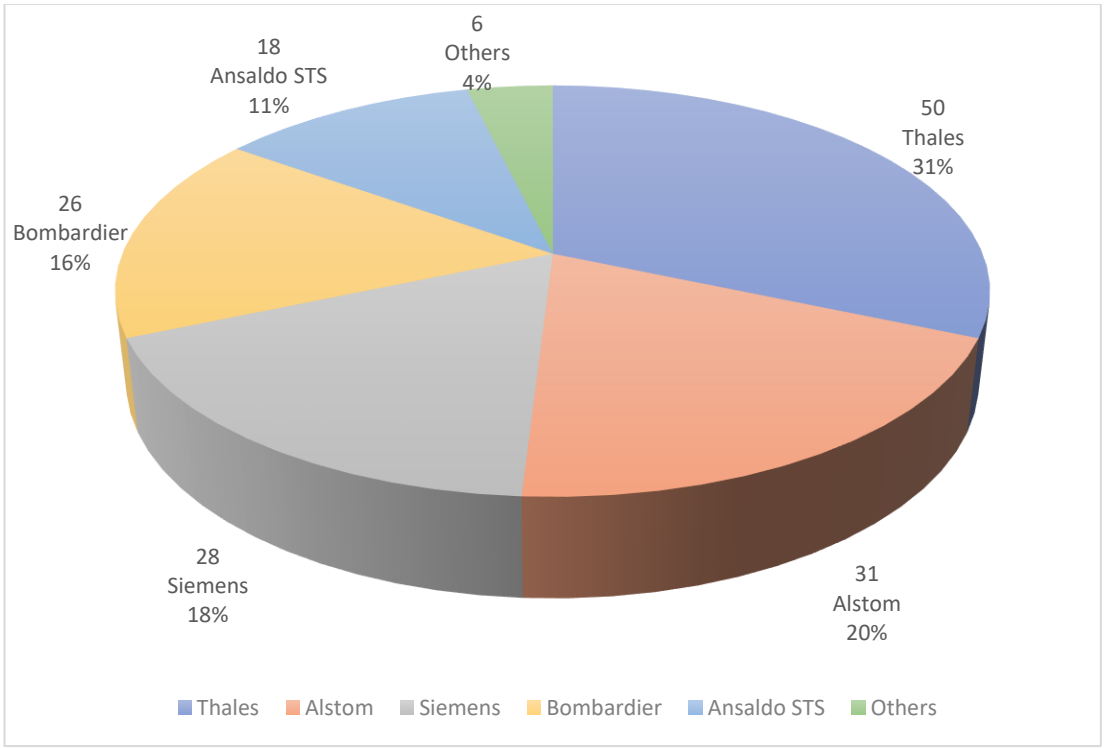


Figure 3.14 : CBTC projects worldwide according to companies.

The point in this section is that CBTC does not mean driverless. In the basic frame, the CBTC system only provides automatic protection. More complex systems can also provide ATO and ATP functions, but they are not required to call CBTC.

3.3 Metro, Commuter, Conventional and HST Signaling Systems

In this section, signal systems used in urban lines and conventional lines will be discussed. Signal technologies are described in chapter 3.4.

3.3.1 Grade of automation

The term Grade of Automation is used in metro or commuter train lines. The position, direction and movement of these trains are provided by the signaling systems. As mentioned in chapter 3.4.2, Communication-Based Train Control System is used for these trains. This system is very advanced technology and is so safe. The probability of making mistakes is near zero.

According to UITP World Metro Figures 2018 report, compared to the situation at the end of 2014, Shenzhen joined the Top 10 of the longest subway systems at the level of individual metros, replacing Mexico City. Seoul climbed to number three in one position, and Guangzhou climbed in the ranking from number nine to number seven. London, Moscow and Madrid all went one way down. Asia has as many as six of the top ten longest subways as possible [14]. In the Figure 3.15 below, the above is summarized.

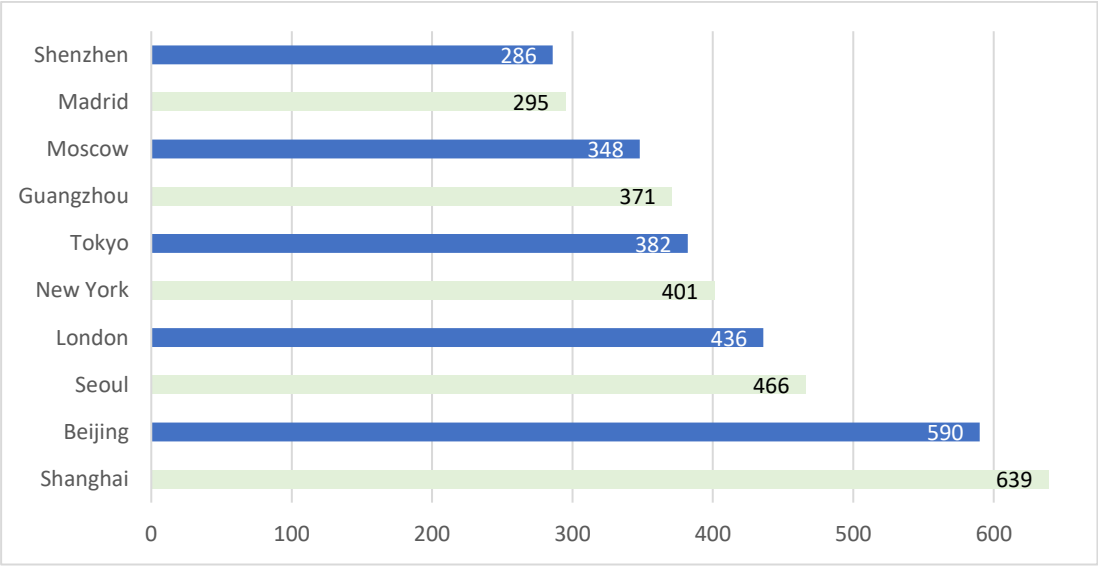


Figure 3.15 : Top 10 longest metro systems (km).

Due to the continuous and bidirectional data communications between the train and the OCC, both the exact location of the train and the remote control of the train can

be made more accurately and faster than conventional signaling systems. The high-resolution train location can be determined more clearly. In addition, the remote control of the train can be made smoother and faster than conventional signaling systems. The sub-units of these systems are as follows;

Automatic Train Protection: It is a control system used to help collision avoidance by automatically controlling the over speed protection that a train can move at any time according to the movement authority of a train. ATP will be explained in more detail in section 3.4.1 and 3.4.2.

Automatic Train Supervision: This system follows the movement of the trains instantly, also regulates the performance of the trains. ATS will be explained in more detail in section 3.4.3.

Automatic Train Operation: It is a system used to help the automatic operation of trains and increases safety. Essentially, this system is an important parameter to ensure safety of people. ATO will be explained in more detail in section 3.4.1 and 3.4.2

Automatic Train Control: The ATC system ensures the safety of the train by automatically controlling the train movement. It manages its own subsystem ATO and ATP systems according to their needs. ATC will be explained in more detail in section 3.4.1 and 3.4.2

In some project, these two systems lead to confusion because the ATS and the wayside ATC responsibilities are the same. ATS and Wayside ATC responsibilities may change according to the design architecture of the companies.

Looking at the metro's historical evolution, in the 1970s Asia started making major investments in the metro. Investments in China and India have risen dramatically over the past 10 years. The investments made are admirable, even though there are not opened lines. Recent investments, however, are bigger than in the past. The above is summarized in Figure 3.16 below. Look at the next page.

There are 5 levels of automation. These levels are defined based on the responsibility of the system and the main functions of the train operation. For example, a Grade of Automation Level 0 corresponds to the appearance of a street-traffic-like tram. Grade of Automation Level 4 means a system in which the trains are fully automated without any driver or operating personnel.

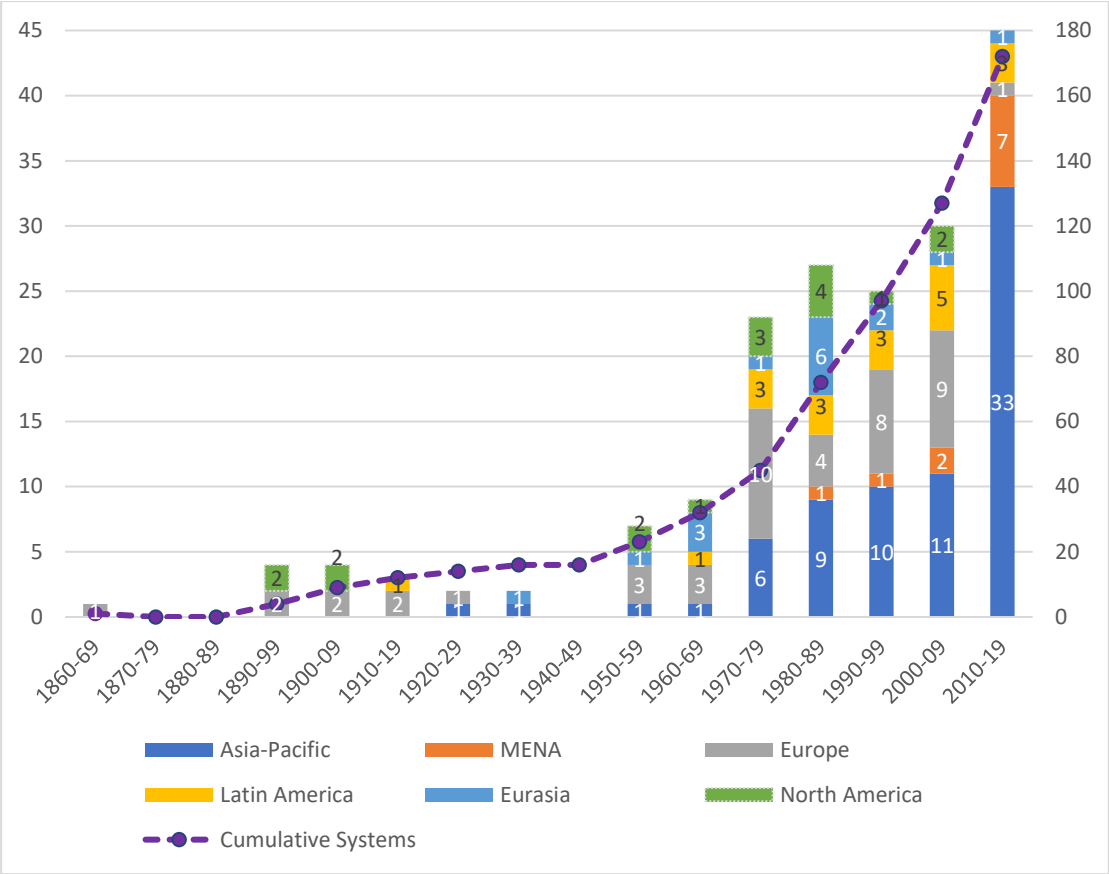


Figure 3.16 : Metro system opening per decade 1860 – 2017.

3.3.1.1 GoA level 0

Street trams are an example of this level. There may be points in the control authority of this level. Points control is not required.

3.3.1.2 GoA level 1

At this level, the ATP system prevents the collision by applying automatic braking to the train. If the train only has ATP system, this system is called GoA 1.

3.3.1.3 GoA level 2

This level is a fully automatic train driver system with no driver functionality. At this level, the ATO performs all function of the driver functionality. This corresponds to the degree of GoA 2.

3.3.1.4 GoA level 3

Thanks to new generation ATO system, the system manages all kinds of systems until the end of operation. However, in case of emergency situations, there is personnel in the passenger cabinet of the train. This system is called GoA 3.

3.3.1.5 GoA level 4

At this level, the system operates fully automated and unattended. In the responsibility of this system, there are setting route and arrangement of the train operation according to timetable under the responsibility of this system. A train with ATC corresponds to the GoA 4, which is the Unattended Train Operation.

In the next five, it is expected that more than 200 new lines will open in many parts of the world, made in the conventional signaling system and in the GOA 4 signaling system. 5,400 kilometers were being constructed or tested in the summer of 2018, while 1,700 kilometers were being designed and tendered. The Figure 3.17 below shows the expected development of cumulative infrastructure over the next five years, as well as the strong release of the GOA4 signaling system in metropolises worldwide. It is expected that a total of 32 GOA4 lines will operate in 2022, 16 of which will be in Chinese cities [14].

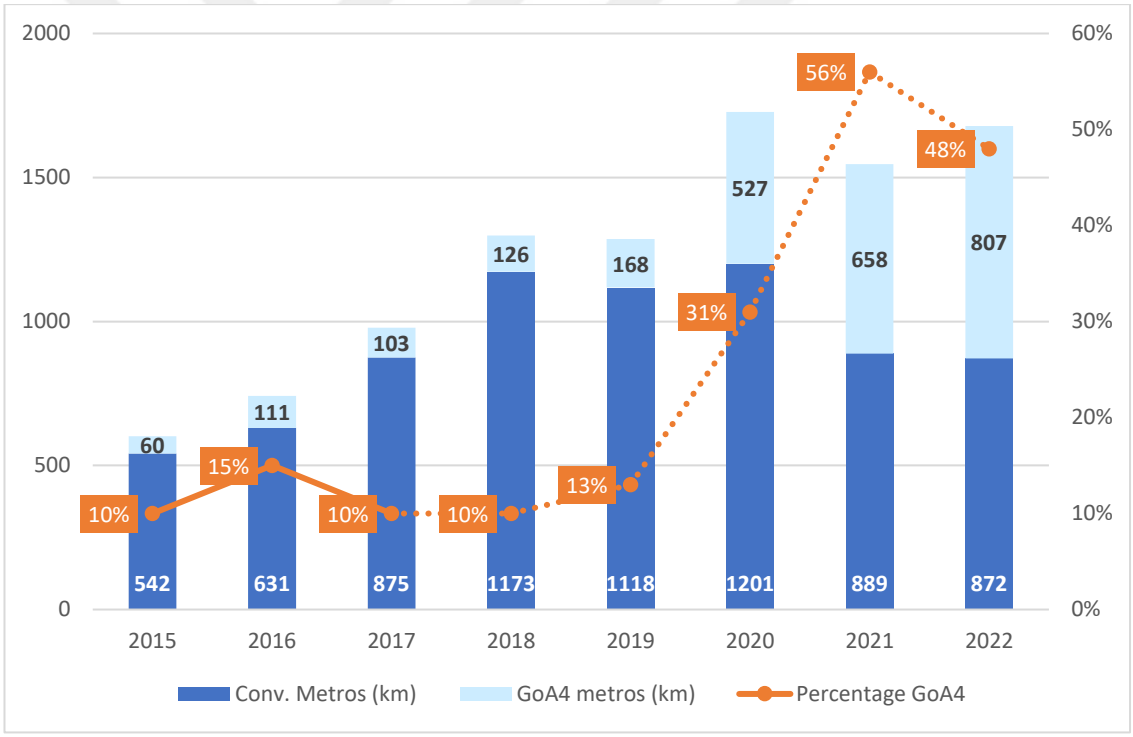


Figure 3.17 : Annual metro growth & prognosis (km) 2015-2022.

According to IEC 62290-1 standard, the following Figure 3.18 and Table 3.6 describes the grade of automation levels in detail [15].

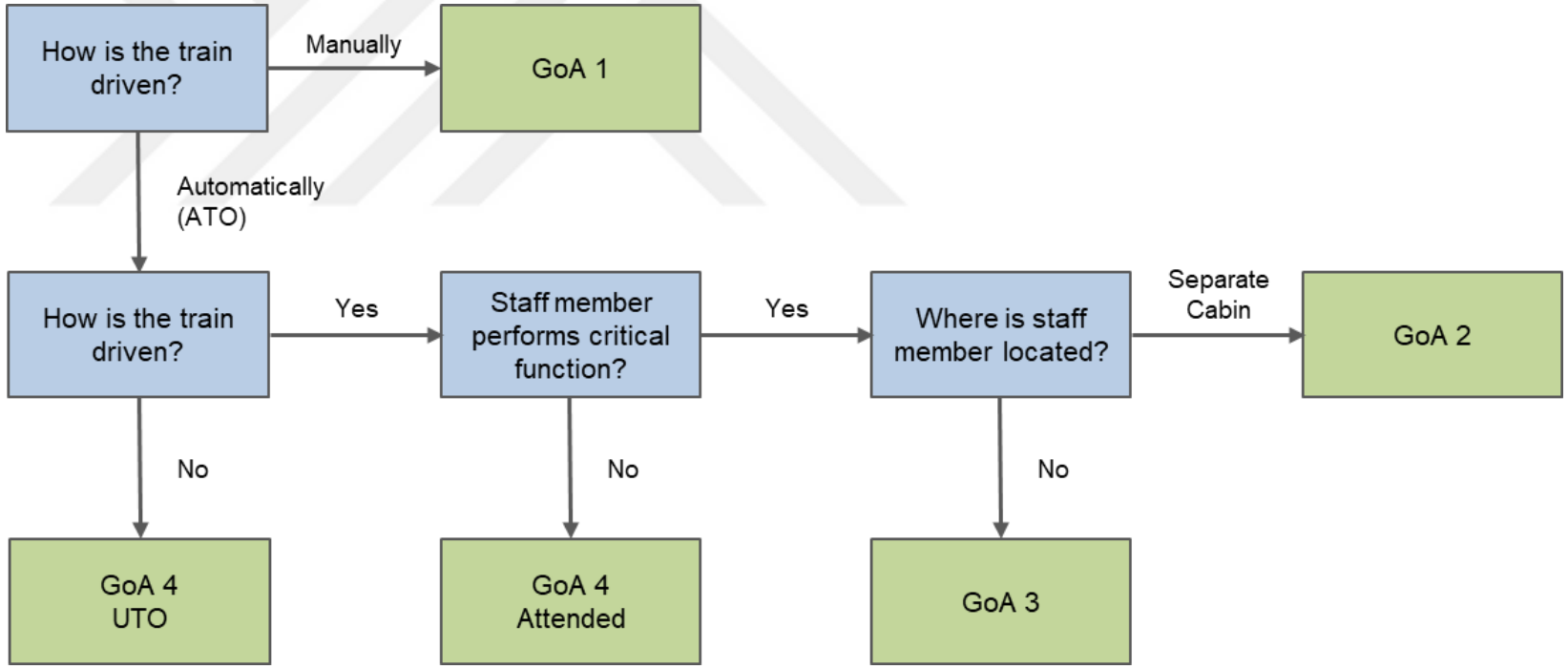


Figure 3.18 : Grade of automation levels flow chart.

Table 3.6 : Grade of automation levels.

Basic functions of train operation		On-Sight	Non-Automated	Semi-Automated	Driverless	Unattended
		GoA 0	GoA 1	GoA 2	GoA 3	GoA 4
Ensure safe movement of trains	Ensure safe route	x - points control in	system	system	system	system
	Ensure safe separation of train	x	system	system	system	system
	Ensure safe speed	x	x	system	system	system
Drive Train	Control acceleration and braking	x	x	system	system	system
Supervise guideway	Prevent collision with obstacles	x	x	x	system	system
	Prevent collision with persons on tracks	x	x	x	system	system
Supervise passenger transfer	Control passengers' doors	x	x	x	x	system
	Prevent injuries to persons between cars or	x	x	x	x	system
	Ensure safe starting conditions	x	x	x	x	system
Operate a train	Put in or take out of operation	x	x	x	x	system
	Supervise the status of the train	x	x	x	x	system
Ensure detection and	Detect fire/smoke and detect derailment, detect	x	x	x	x	system and/or staff

NOTE x = responsibility of operations staff

3.3.2 ERTMS

In those years when the railway first started to develop, it was considered only a fast mode of transportation and it was unnecessary to take any precautions with regard to possible problems such as accidents, collisions. With fewer number of intersections and lines it was easier to check the speed of the trains until the last 70-80 years. However, in order to solve accident problems originated from collisions through years, new system developments arise. The main goal in railway transportation is to prevent collisions from now on. In other words, the signaling system is used to ensure safe traffic on railways respectively.

Thanks to the signaling system, the line capacity is increasing, reliable and fast passenger transport is being made. Today, modern signaling systems allow the common use of signaling systems in many countries. There are two types of signaling systems worldwide that stand out [16].

In parallel with the increasing and accelerating railway network in Europe, inter-country railway transport has also been intensified. Problems have been experienced in switching to countries using different signaling systems, which have been tried to be solved by either locomotives or trains with equipment that can solve two different signaling systems. In addition, Special training for different signal systems needs to be given to mechanics.

In Europe, where borders are slowly drifting and the speed of trains is increasing day by day, a protocol has been established under the European Rail Traffic Management System (ERTMS) for these reasons, which adversely affects railway traffic. The aim here is to use a single signaling language in European countries.

Autonomy of functionality in ETCS synthesize universal equipment on board to enforce and monitor speed for all trains. This concept has a major advantage that either interoperability between networks or operability between parts of network [16].

Emerging electronic information communication techniques have increased the quality of the equipment on the train, and the equipment that transmits information to the train, thus providing a much safer transportation with fewer train personnel.

One of the crucial elements in this system is the computer control system that processes ETCS signals and data in the train. It processes the line information sent by the control center and sends it to the driver, adds the current speed of the train to the account, and checks whether the driver complies with this signal notification. If the speed limit is exceeded, the machine sends a warning.

In a short time, if there is no response from the driver, slow down the train or switch to emergency braking and stop the train. The information about the deceleration or stopping operation or the information about the train displayed on the machine display can also be seen in the control center if desired, depending on the ETCS levels used.

The financial situation of the countries is shaped in three different levels in terms of the transmission differences of the signal and control information between the train and the control center, considering the train and line diversity.

3.3.2.1 Requirements

Achievement of interoperability is the overriding technical requirement. Equipped trains from any supplier can therefore share information with other trains from other corporations. If trains commit to pass the borderlines easily today, it is just because of technologies [16].

More than 20 train control systems are getting publicly used throughout the European railway network today. All systems are unique and not compatible with other systems. Thanks to ERTMS, that can be leads to reduce cost even crossing over the borders between countries in Europe. What if there is no replacement for national train control systems and trains need to be operated with all control systems of running countries [17]. I will be ended up with tremendous cost for not only maintenance but also operational. Interpreting these examples, Abed (2010) stated that, “the Thales trains which are running between Paris-Brussels-Cologne and Amsterdam must be equipped with seven different types of train control systems. This adds to the complexity of the overall control systems and increase operational and maintenance costs for running such system” (p. 172).

3.3.2.2 Sub-System and interfaces

ETCS system is composed of:

- The train, considered via the train interface
- The driver, considered via the driver interface specification
- On-board interfaces, representing the national ATP systems present in the train
- External trackside systems (interlocking, control systems etc.)

List of trackside components:

- Balises
- Lineside electronic units (LEU)

- A radio communication network (GSM-R)
- Radio block centers (RBC)
- Loops (Euro loop)
- Radio infill units.

List of on-board components:

- The ERTMS/ETCS on board equipment
- The GSM-R on board equipment for ETCS [18].

Balise: Inside a line is a sensor passage, the electromagnetic waves are the ones that contact the train [16].

Euroloop: The Euro loop is a component that is based on a leaky cable and a modern one that can send telegrams to the sub-system on-board.

LEU: The LEU is an electronic device that creates telegrams for Balises to send.

GSM-R: This system (Global System of Mobile Communication) which is called global mobile communication system is a network system used by mobile phones which is an indispensable tool today. Radio waves provide access to areas where the obstacles in the area cannot reach due to the high buildings in the settlements, thanks to small regional transmitters like base stations.

This is a system that provides continuous digital communication wherever you are in the current geography. Of course, base stations also have the power to send and receive data to a certain distance. The coverage is expanded by placing a base station in places where this power is not enough.

There are base stations on the 900 MHz system, located about 20 kilometers away.

RBC: Another computer-based system, The RBC develop massages to be sent to the train on the basis of information received from external trackside systems and information exchanged with on-board subsystems.

Radio Infill Unit: ERTMS component is using GSM-R transmission to pre-signalize the next main signal in the running direction of the main train.

ETCS on Board Equipment:

- The kernel module, applying the major logical functions,
- The trains interface module, controlling the interfaces between the train and the ETCS in board sub-system,
- The Balise transmission module, controlling the interface between the ETCS in board sub-system and Balises installed on the trackside.

- The Euro radio module, controlling the interface between GSM-R mobile devices and the ETCS on board equipment,
- The odometer module, including a processing part and different sensors, to estimate the movement of the train,
- A Driver-Machine interface (DMI) [16].

The following Table 3.7 describes the ETCS level levels in detail [18].

Table 3.7 : ERTMS levels.

Level	0	1	2	3
Lineside Signals	Yes	Yes	Not needed	Not needed
Infill	No	No	No	No
Transmission	Balise	Balise	Balise, Radio	Balise, Radio
Radio Network	No	No, Partially	Full	Full
RBC	No	No	Yes	Yes
Train Integrity	No	No	No	Yes
High Performance Block	No	No	Yes	Yes
Moving Block	No	No	No	Yes
Localization	Balise	Balise	Balise	Balise
Track Clearance Detection	Trackside	Trackside	Trackside	On-Board
Balise Types	Fixed	Fixed and Controlled	Fixed	Fixed
LEU	No	Yes	No	No
Signaling	Trackside	Trackside	On-Board	On-Board
DMI	Speed	Overlay	Cab Signaling	Cab Signaling

3.3.2.3 Level 0 of ETCS

ETCS used in conventional lines may be considered as Level-0 CTC (TSI-Technical Specification for Interoperability). In this system, the signal posts on the roadside are not at Level 3 and signal information is shown on a screen in the cabin. ETCS levels are downwardly compatible, meaning that a train equipped with Level 2 can travel safely on a line set up with Level 1, but a train equipped with Level 1 cannot be expected to progress safely on a line equipped with Level 2. In a train control system installed in a zone, the operation of a train with another system on it is not safe.

3.3.2.4 Level 1 of ETCS

In ETCS level 1 system, all information that can limit the speed of signal color notification of the signals to arrive in the direction of train movement, the maximum speed to be made on the line segment on which the train is going, the distance to the

train point and the speed of the train, tunnel or train in the direction of the train is allotted on the train by allocated equipment To the on-board train equipment.

All information taken from the neck of the train is evaluated by the computer on-board equipment and is reported to the driver visually and audibly by the indicator in the cabin of the engine and the speed of the train is evaluated continuously according to the received information.

If the driver does not take into account the warning, the computer assigned to the train will automatically slow down or train the train according to the information it receives. Figure 3.19 shows ETCS level 1 operation diagram.

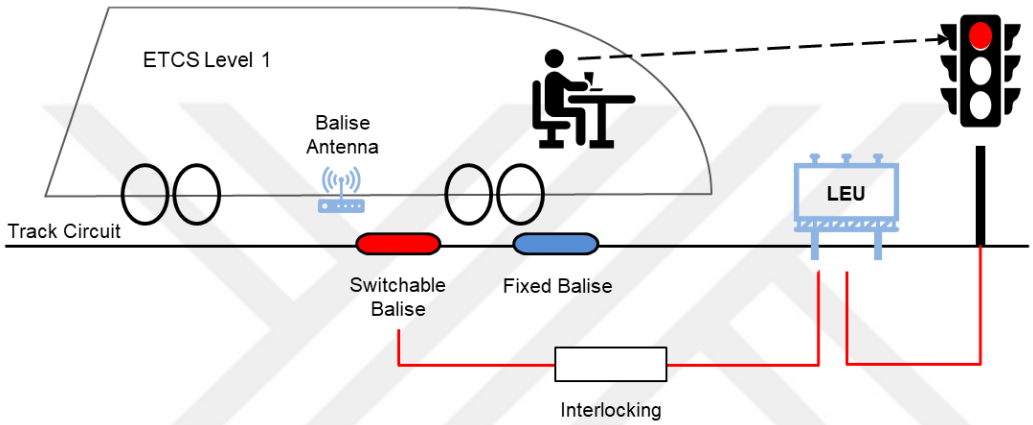


Figure 3.19 : ETCS – Level 1 operation diagram.

3.3.2.5 Level 2 of ETCS

ETCS level 2 is a radio-based train control system built on top of the signaling system. GSM-R is used as radio environment. The functionality provided by ETCS level 2 covers all the features and functionality provided by ETCS level 1. Unlike ETCS level 1, the train movement authority produced by line-length signaling systems is transmitted to the train over the counter via GSM-R.

Since there is a continuous communication between the road size and the on-board equipment of the train, the changes in the signaling information can be instantaneously transmitted to the train. Level 2, it is not obligatory to use road-length signals. Figure 3.20 shows ETCS level 2 operation diagram.

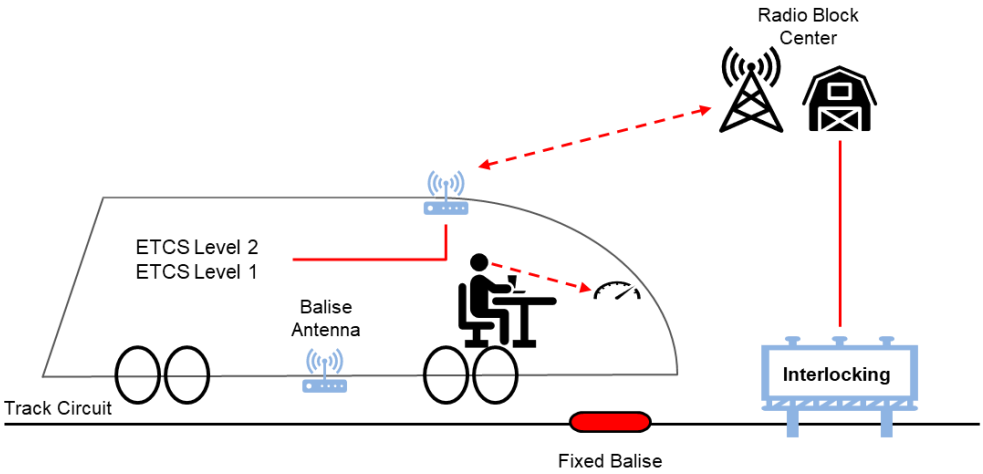


Figure 3.20 : ETCS – Level 2 operation diagram.

3.3.2.6 Level 3 of ETCS

The train is fully controlled by GSM-R. The GSM-R carries the signaling information, as well as the information that can be remotely controlled from the train. Balises located on the line are used to verify the position of the train and for ATS purposes.

Block signal is not applied in this system. On the screen of the control center, the movement of the train is followed step by step. The information between the computer in the control center and the computer on the train is constantly exchanged through the ETCS signaling encoder. Such the automatic pilot system as on airplanes, the train can be operated without a machine. Of course, a train carrying an average of 450 passengers at a speed of 320 km/h cannot be left to the control of computers alone. The remote train control system is used to stop the train unnecessarily and to stop the machine traffic and interfere with unusual events, without the opportunity to slow down or slow down the line traffic.

Based on level 3, there is GSM-R technology which provides continuous and fast data communication. The 4G technology that takes place in our life is likely to be tested in a short time with GSM-R 4G technology for Level 3 ETCS. Figure 3.21 shows ETCS level 3 operation diagram.

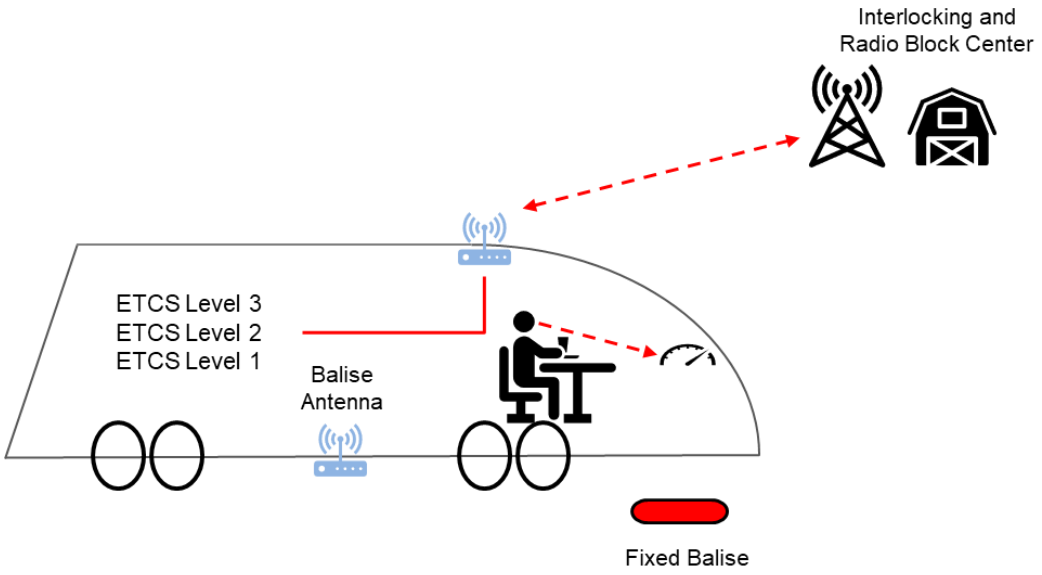


Figure 3.21 : ETCS – Level 3 operation diagram.

3.3.2.7 Operation modes

There are many different modes of operation system:

- Full Supervision (FS) is normal case with the train fully supervised by ETCS.
- Limited Supervision (LS) is only defined for Level 1 and uses reduced functions.
- In on Sight (ON) mode, the train proceeds on sight onto a track which can be occupied by trains or obstacles.
- Shunting (SH) mode is used for shunting movements and can be selected by the driver or the trackside.

3.4 Automatic Train Control Systems

In this topic, Automatic Train Control systems of systems with GoA 2 and GoA 4 levels will be described. GoA levels are described in detail in chapter 3.3.1. Generally, CBTC systems are described, ATO, ATP and ATC and ATS. However, ATO and ATP systems are classified as subsystems of ATC architecture.

3.4.1 Automatic train control system on-board

The ATP subsystem is responsible for the safety of the train. The ATO automatically provides the movement of the train by assuming the driver's role. Each of these subsystems is available both on the on-board system and in the wayside system. Figure 3.22 shows train speed by on-board ATO segment.

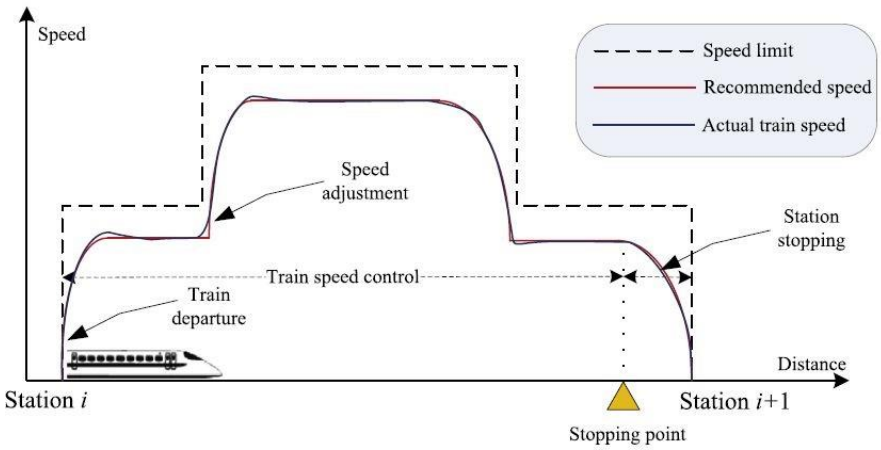


Figure 3.22 : Train speed by on-board ATO segment [19].

Probably the most critical subsystem, the ATP subsystem, helps prevent collisions as the driver does not observe a signal or speed restriction. It monitors and controls the train speed and applies brakes if necessary. Figure 3.23 shows optimal headway with ATO, Figure 3.24 shows CBTC on-board component

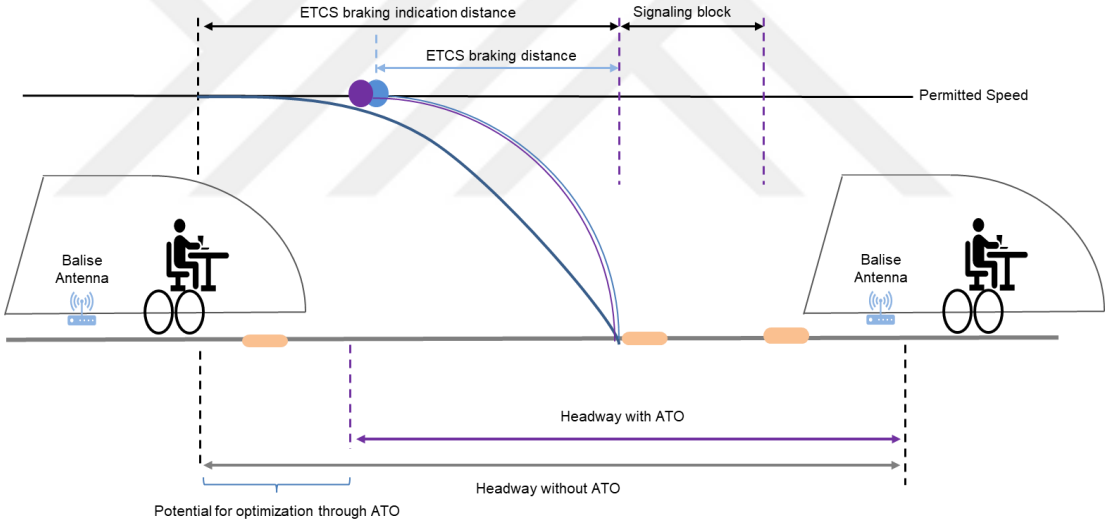


Figure 3.23 : Thanks to ATO optimal headway.

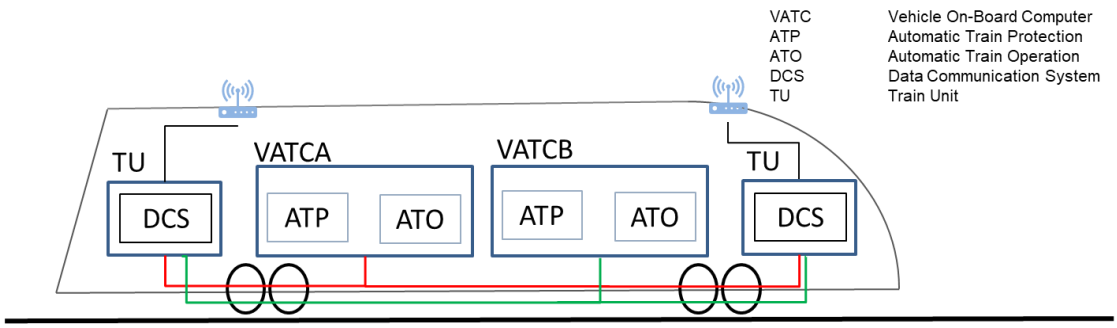


Figure 3.24 : CBTC on-board components.

The ATO subsystem is normally responsible for automating the train operation, including starting and stopping a train, stopping accurate location, applying dynamic driving modes, energy-saving braking, acceleration and deceleration.

3.4.2 Automatic train control system wayside

In Figure 3, the CBUS system has sub-components of the wayside system. Even so, trackside components are located either on or close to the train in general, wayside and trackside terms are often used interchangeably.

The Zone Controller or Road Controller is responsible for controlling a specific area on the railway network. The wayside network is divided into multiple and independent zones, each with its own wayside infrastructure, ensure the availability even in the event of failure. The main function of AoC is to ensure safe train separation in its area.

An AoC is also typically components of the wayside ATP and ATO subsystems. ATP subsystem of AoC manages all communications with trains and calculates the movement authority for each train in its zone, too. Figure 3.25 shows between wayside and on-board communication.

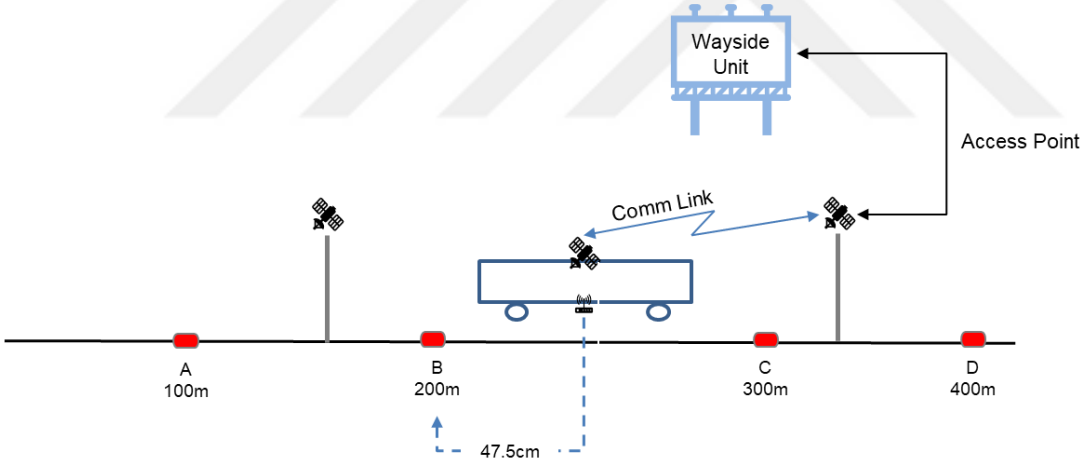


Figure 3.25 : Wayside and on-board communication.

A Computer-based Interlocking (CI) system is within side as an independent system or as part of the ATP subsystem. CI directly control trackside equipment, such as point machines and signals. It is also responsible for the arranging of trains' routes.

The ATO subsystem ensure train destination and dwell times for all trains in its area.

Regardless of the AoC, there is the Automatic Train Supervision (ATS) system, which is responsible for monitoring and arranging traffic schedule for trains [12]. The next

chapter will describe details of this system. Figure 3.26 shows CBTC wayside components.

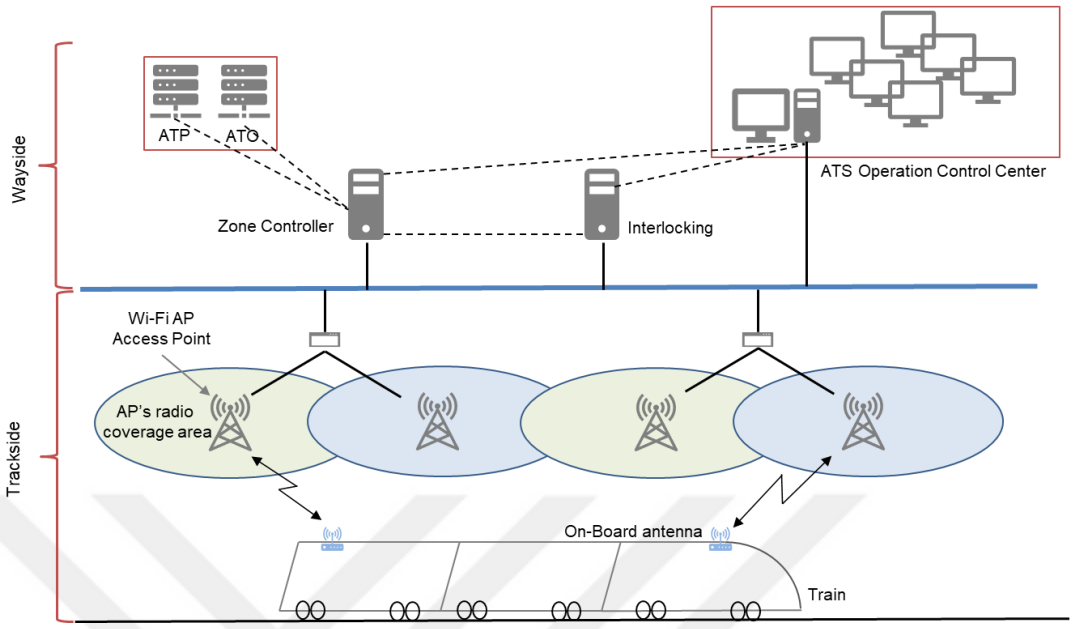


Figure 3.26 : CBTC wayside components.

Trackside is divided into multiple Wi-Fi cells, each served by an Access Point (AP). Figure 3.26 uses green and soft blue colors to make different radio coverage areas of APs. Trains communicate with APs via a radio link. This creates a typical CBTC system monitoring radio network. APs are respectively connected to wayside components over the trackside backbone network. A typical configuration of the trackside backbone network is the star topology as shown in Figure 3.27 wherein each AP is directly connected to the wayside.

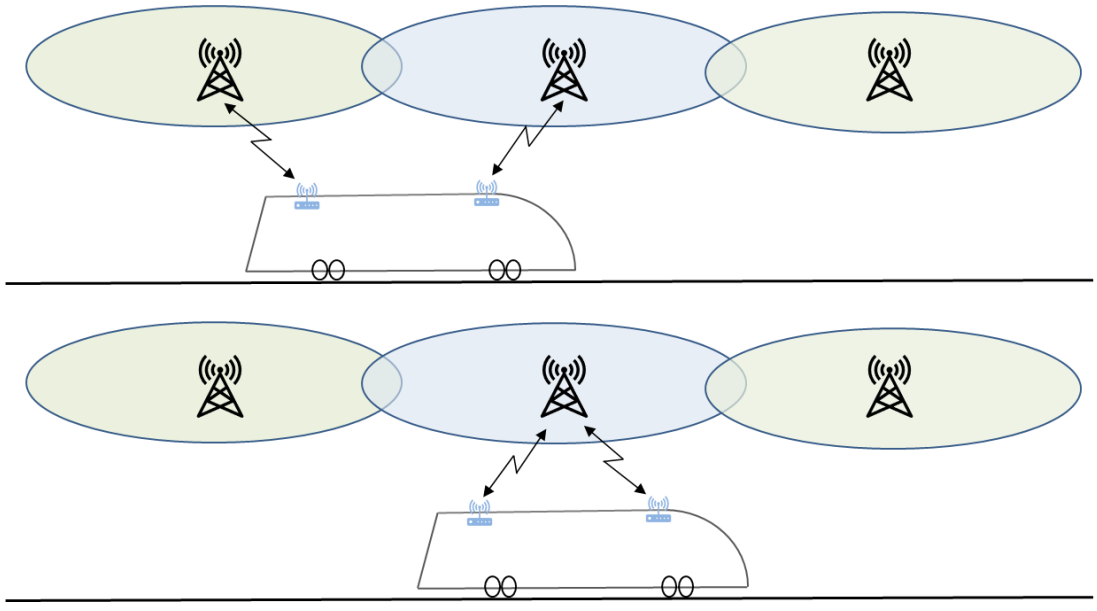


Figure 3.27 : CBTC radio roaming handover.

3.4.3 Automatic train supervision

Most CBTC systems include a sub-system called Automatic Train Supervision (ATS) to monitor traffic and regulate CBTC trains in real time according to the traffic information on the line. The main purpose of the ATS system is to monitor and control the operation in the depot area and main line of a fully automated train operation. ATS receives information from external systems, sends commands to these systems and can set routes and arrange routes automatically [20].

In order to complete these tasks, the OCC communicates with the interlocking system, wayside ATC and on-board ATC, receives information from the line components that they control and transmits the commands requested by the user. ATS provides following main functionalities:

- Automatic Route Setting
- Automatic Train Regulation
- Continuous Monitoring of Train Position
- Display videowall & workstation interface
- Link to PID for online information
- Computation of train schedules, dwell time and timetable

4. TIMETABLE, HEADWAY AND REGULATION IN MARMARAY

Marmaray Project is one of the substantial projects of the Turkish Ministry of Transportation constructed to be an essential solution for the in Istanbul's public transport.

With recognition to this project, a non-stop above ground metro line of 76.3 kilometer was constructed from Halkalı on the European side to Gebze on the Asian side that will be modern, high capacity, fast, and integrated with the other transportation systems. Complete project also builds a huge network between East and West in the future when it will be implemented with the European high-speed trains and/ or with Istanbul - Ankara High Speed Train and Kars - Tbilisi railway projects.

Marmaray Project is mainly deal an arrangement to decrease the pollution of passenger car traffic and create a modern transport system that forms the foundation of modern urban life [21].

4.1 History of Marmaray Project

A railway tunnel project under the Bosphorous was first mentioned by Sultan Abdulmecid in the 1860s. By order of II. Abdulhamid in 1890, the American engineer Frederic E. Strom designed the project of the tube passage. In 1902, the American engineers made great efforts on the project and received the title of "Tunnel-i Bahri".

The project has arranged according to a preliminary feasibility study was conducted in 1987. In 1997, the Japanese Export Credit Agency (JICA) signed a loan agreement between the Turkish Government. The Marmaray Project has been finally awarded a contract in 1998, and in consultancy agreement has signed in 2000. Construction has been started in 2004 conclusively [22].

The main contractor of the project is the Japanese Taisei Corporation. BC1 part opened on October 29th, 2013. For the improvement of the geological lines of CR3 is OHL-Siemens was assigned as contractor. The remaining part of the line was opened on March 12th, 2019 and the first passenger was carried on March 13th, 2019.

4.2 Preliminary Information About the Marmaray Project

Every day, approximately 12 million people travel to and through Istanbul and the Marmaray Project maintains mass public transport to the population of the city [23].

The second phase of the Marmaray railway line has been introduced that connects Europe and Asia in March 12th, 2019. After the official announcement, the regular commuter service start running along the 76.3 kilometers route between the Gebze and Halkalı station on the Asian and European sides jointly. Over 75,000 passengers can be carried by a line per hour per direction and it reaches to 1.7 million passengers at the end of the day [24].

4.3 Signaling Architecture

The Marmaray Project signaling system consists of the following basic components.

A globally recognized signaling architecture

- OCC for Commuter, Intercity and depot area
- Automatic Train Supervision
- Automatic Train Control
- Line 1 and Line for CBTC system GoA level 2
- Line 3 and Tunnel line for ERTMS level 1
- Trackside equipment, points, signals, track circuit
- On-Board signaling equipment

The Trainguard Futur 1300 Level 1 ERTMS and Trainguard Sirius CBTC elements are guaranteed to be covered by contract for the great project design, installation, supply, testing and commissioning, train detection systems in example joint track circuits and axle counter systems a new signaling system including electronic interlocking Trackguard WESTRACE Mk II, wayside LED signals, control guide Rail 9000 CTC, telecommunication and SCADA for the whole project. The contract includes two years of maintenance service with an option to extend it to a further five years [25]. Figure 4.1 shows Siemens Trainguard Sirius CBTC architecture.

The current dual-track network is reconstituted by an international two-way triple track gauge system with regard to infrastructure. The third track which equipped with ERTMS Level 1 system will be used for mainline operation of intercity trains. On the other hand, the old double track which equipped both with CBTC system for passenger service and ERTMS Level 1 for freight transportation will be used for mass transit commuter trains. Trainguard Futur, the Siemens Rail Automation integrated

train planning and control system, complies with the specifications of the European Train Control System (ETCS). ETCS and the GSM-R is one of the main elements of ERTMS and is the radio system for voice and data signaling and management system for Europe and the world.

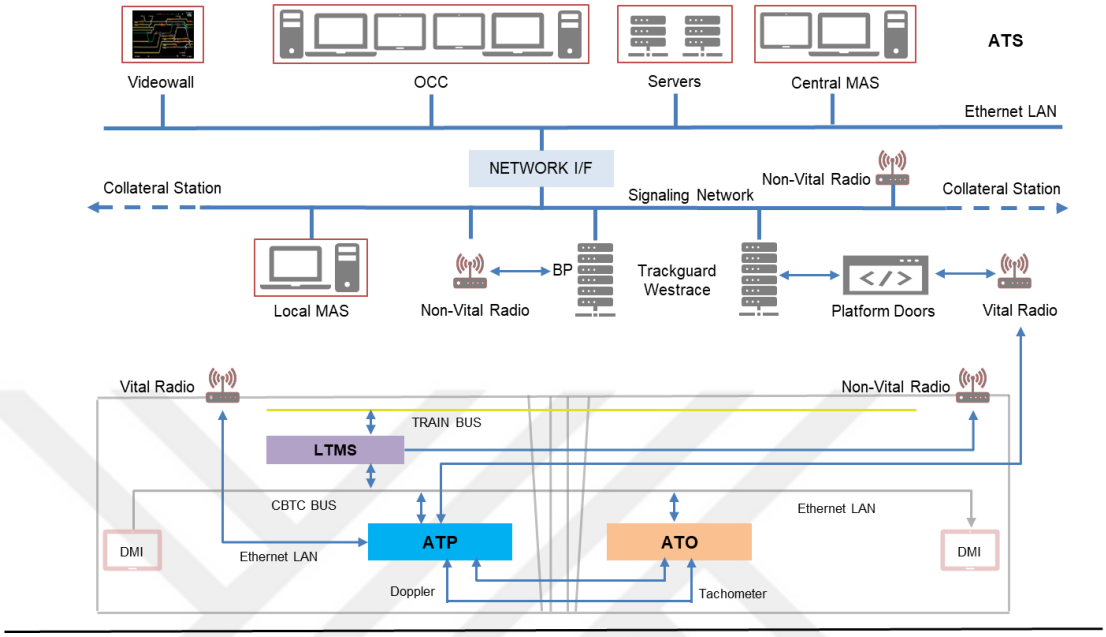


Figure 4.1 : Trainguard Sirius CBTC architecture

Trainguard Futur 1300 which entirely automatic systems of ERTMS Level 1, receives information from the train punctually as of passing over the system's balises. For railway administrations beyond Europe and the entire world, Trainguard Futur 1300 provides great performance in both operation and maintenance aspects. Trainguard Sirius creates a great solution in respect to automatic train control (ATC) system for all conventional, driverless, or fully automatic operations in suburban railways and all kind of mass transit. Figure 4.2 shows Trainguard Futur 1300 ERTMS Level 1 architecture.

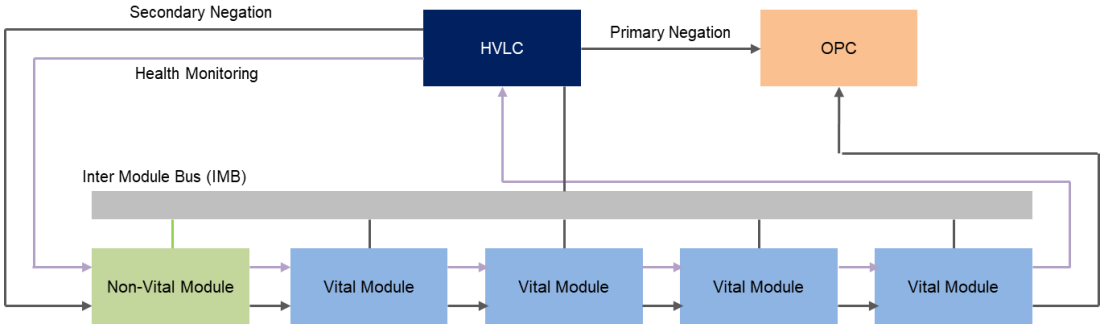


Figure 4.2 : Trainguard Futur 1300 ERTMS Level 1 architecture.

Trainguard Sirius is designed specifically for high-density traffic lines with usage of the latest state of-the-art digital radio transmission approach. With headway optimization tool, the operator can be able to obtain maximum transport capacity on the assumption of the shortest possible interval between consecutive two trains. Control guide Rail 9000 allows the integration of its functions of the automatic route setting and the regulation adaptively. The integration with other systems in the Operation Control Centre (OCC) is provided by a secure a dedicated, open protocol between from exchanging information to external system. A high-technology Control guide Rail 9000 is adaptable to various railway network.

4.4 Automatic Train Supervision System Signaling Architecture

In this section, details of the studies carried out within the scope of the thesis will be explained. The main purpose of the Rail9000 ATS system is to control and monitor the operation of a fully automated with driver or driverless train on the main line and in signaled depot areas.

To achieve this objective, the ATS uses the information supplied by different external systems present in its operating environment, making decisions and sending commands to these systems so that system functions according to the needs at any given time, using automatic routing and regulation techniques. System monitoring information will be provided through alarms, diagrams and inspector panels as appropriate. The ATS is communicates with the following systems to carry out its functions:

- Interlockings. The ATS communicates with interlockings in order to receive information on the status of the signaling elements and to send commands to trigger these elements.
- CBTC. The ATS communicates with the CBTC system to send it start and stop commands for trains, as well as direction changes and automatic reverses. It also listens to the messages sent by the CBTC system to the train.
- Trains. The system receives information from the trains. This information is used to determine train location and behavior, as well as for maintenance and to determine and manage the status of auxiliary train equipment when travelling in driverless mode.
- Public information systems. The ATS system provides the passenger information system with information on train positions and their identification, as well as the state of field elements.

- Regulation signs. The ATS system manages the regulation signs in order to indicate to the driver when trains should be started to fulfil the established regulation.
- Information signs to drivers. The ATS uses these signs to inform drivers of the time that is available to complete the front reverse manoeuvre.
- Other ATSs. The ATS system will be prepared to communicate with other ATSs in order to exchange train numbers, and also, in centralized mode, to send commands to the ATSs in order to manage and control the area belonging to the ATS in question. This communication will be transmitted via the external interface system, specifying in each case the conditions in regard to both the scope and format of the exchanged information that will be applied to carry out this function.

In addition to these interfaces, the ATS provides the information that it handles to be used by any other system that requires it. To do this, the ATS defines standard for communication and information delivery via messaging.

4.5 Headway

In local railway systems passenger services, urban railway transit systems accommodate lines within and around urban or suburban areas. Urban railway transit systems service concentrates two main groups: peak time and off-peak time. Fewer trains run on the line in off-peak time, while at the same time the headway between two consecutive trains is larger than peak time. The buffer time is aided to be valued to save energy. During peak time, the system ships the trains more intermittently so as to carry more passengers. This can be cause to initial delays and knock-on delays especially while trains are working with smaller headways. Delays in urban railway transit system may lead to adverse events such as retaining on the platform and outside of the station.

Scheduled headway deviation adjustments can be rescued by headway regulations with changes of dwell time and/or trip time mid stations for each train. Generally using method is holding control in the station and skipping the station. Automatic train regulation (ATR) has been recently adopted to maintain headway. Headway regulation is one out of the three functions of ATR, also one of the core items of the automatic train supervision (ATS) system in urban railway transit [26]. Absorption of the disturbance originated by random fluctuation of passenger flow, immature manual driving, system abnormality is generally intended to. For the punctuality of urban

railway mass transit, desired technique should be a robust and real-time train regulation.

Headway and punctuality are the examples of the Beijing metro, in 2017, the punctuality of Beijing metro trains was 99%. The concept of punctuality is explained as follows: a train arrives at the destination with a maximum deviation of 1 minute from the estimated time of arrival [26].

Nowadays, the biggest concept that prevents the punctuality of such systems is the increase of human density. Therefore, the top priority in the headway is to develop a regular system or to help improve it. In addition, the increase in the number of passengers on the one hand is also an increase in energy consumption. Five years ago, Communication Based Train Control (CBTC) system was widely applied in Beijing metro system. The two-way communication system ensures better operation with continuous information transfer. And thanks to this information, it increases the accuracy of the headway layout.

4.6 Timetable

According to the demand and capacity in railway transportation, a timetable is prepared which includes transport schedule and transport strategies to meet the needs of people and stakeholders. Framework of timetables should be based on demands of passengers, carriers, operators, infrastructure manager as well as public authorities. Service aim that infrastructure is always available in a high quantity and quality with efficient use of material inventory, personnel, transport and traffic services.

Arrangements on timetable highly settled according to main objective of railway transportation that engaging as many customers as possible when operating with minimum input in terms of energy consumption, operation and maintenance costs, cost of investment, personnel and also equipment.

The effectiveness of a timetable can be expressed by indicators as:

- Number of trains, passengers and load per time period
- Amount of passenger-kilometer and ton kilometer per time period
- Operating and circulating speed of train
- Headways and buffer times
- Scheduled dwell times
- Time and effort for modification and updating [27].

The quality of timetable design for a given traffic demand, railway infrastructure and train mix depend mainly on:

- Frequency
- Regularity
- Precise and realistic running a dwell time
- Sufficient but not too large recovery times
- Exact minimal headway times between different pairs of trains
- Estimated dwell time [27].

4.6.1 Frequency

The higher the train frequency in the operation, the greater the demand of the customers. However, the high train frequency is a factor increasing the operating costs. Depending on the travel distance of the people living in the city, the transportation demand and the other transportation options offered, according to the researches, the frequency of 12 times per hour in subway systems and 6 times per hour in local trains are excellent.

As commuter passenger train frequency having a number of 3 times per hour per direction is considered to be operationally good. For local freight trains, a frequency is satisfactory twice a day per direction. As international freight train frequency having a number of 2 times per day per direction is considered to be operationally excellent. Table 4.1 and 4.2 show quality levels of train frequencies [27].

Table 4.1 : Quality levels of passenger train frequencies.

	Passenger train lines per hour per direction			
	Subway	Commuter	National Regional	International
Excellent	12	6	3	4
Good	6	3	1	2
Satisfactory	4	2	0.5	2
Poor	2	1	0.25	1

Table 4.2 : Quality levels of freight train frequencies.

	Freight train lines per day per direction		
	Local	National Regional	International
Excellent	4	4	2
Good	2	2	1
Satisfactory	2	1	0.5
Poor	1	0.5	-

4.6.2 Punctuality

In order to prevent the excessive demands on the platforms and trains, it is very important to have a punctuality operation. The irregularity of a timetable can be easily calculated by the standard deviation of determined intervals between trains in stations in a network. The smaller the standard deviation, the higher the punctuality of scheduled train services.

4.6.3 Trip and recovery times

Minutes are standard on the scale of deterministic trip times most train timetables. Minimum trip time can be applied for trains that are delayed at the previous station and have no obstacle to go to the next station. Trip times, it depends on the type, length and weight of the trains operated according to the alignment, the number of dwell times in the intermediate stops, the behavior of the train drivers and the weather conditions.

4.6.4 Minimum headway and buffer times

In practice, timetable designers often based on the standard average minimum headway time between train routes depending on the type of conflict and the train order. It is very difficult to detect buffer times in the graphical timetable, which shows train paths and headway times in minutes. The minimum headway between two trains on the railway line is managed by preventing blocking time and speed difference between trains.

The theoretical dwell times, which are usually calculated for operation, are exceeded during real operation. This affects the trip time of the trains coming from behind because it creates occupation in the track of the train.

4.6.5 Dwell times

Each timetable creates unplanned dwell times during planned dwell times and practical operations. Scheduled dwell times are due to the differences between scheduled and desired running, stopping, departure and arrival times by train operating companies, and timetable constraints. Scheduled dwell times depend on passenger demand [27].

In the railway lines operated by the periodic timetable, the timetable flexibility of the interconnected lines depends not only on the buffer times of the individual lines, but also on the buffer times between scheduled train arrivals and departure times at the transfer stations.

The following criteria should be considered when performing timetable design in an integrated network with other lines:

- The sum of the arrival and departure times of a line must be greater than the one-way journey time.
- The sum of all trip and dwell times between terminal stations must be equal to half of the total time of arrival and departure. According to the world average, this period is 60 minutes.
- The schedule arrival and departure times of the interconnected lines must correspond sufficiently.
- The sum of the journey times on a circuit between three nodes must be an integer multiple of the cycle time and of the time headway.

4.7 Regulation

The advance features of the ATS system in the Marmaray Project calm down the operator in most command tasks and allow him to focus on the monitoring and control of the line. The ATS system automatically handles most commands to trains and roadside equipment to direct and regulate traffic.

The operator can control the trains manually and set the route to the trains by taking the system under his control in case of emergency. The operator should take control of the operator in such circumstances and in what circumstances the control system should be clearly explained. Operators should know very well which commands should be sent manually to control the line manually.

4.8 Automatic Train Regulation

The main purpose of the regulation system is to automatically manage traffic and operations for all Marmaray lines. This includes CBTC and ERTMS systems.

The Marmaray line topology consists of a common triple loop that is not a common station. For Commuter trains, there is a CBTC infrastructure at the T1 and T2 lines from Halkalı to Gebze. Apart from this, there are ERTMS on T1, T2 and T3 lines for the movement of high-speed trains, conventional trains and freight trains.

However, as daytime commuter trains are in operation on T1 and T2, high-speed trains and conventional trains use the T3 line from Halkalı to Kazlıçeşme and Söğütlüçeşme to Gebze. Figure 4.3 shows 3 different loops in Marmaray project.

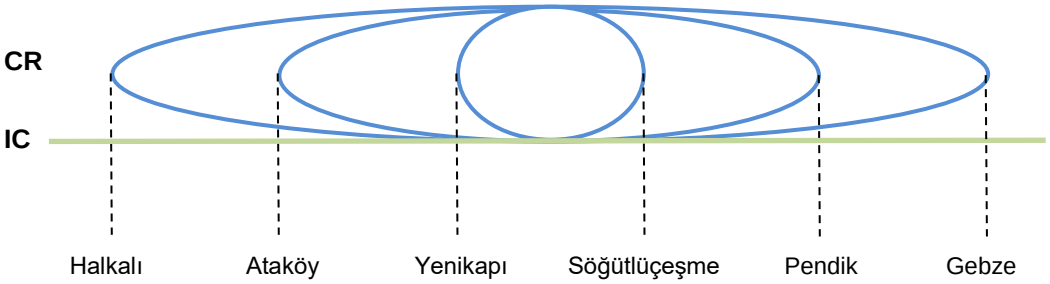


Figure 4.3 : Marmaray loops.

The regulation is based on a timetable also including the arrival and departure times of the stations, service and schedule numbers. A timetable is created by a joint venture or a company specialized in this business. Any additional adjustments or modifications to the table are made by the operator after the time table is designed.

The ATR receives traffic events from the OCC component, such as the status of trackside elements and trains location and sends regulation commands to the OCC. Then the OCC forwards these commands to the corresponding trains or trackside equipment.

The ATR also supplies the OCC with regulatory data related information about the PIS or train delay used for the AFC interface. Trains are controlled when inside a carrousel, by combining n-different loops, a carrousel is integrated. Monitorization of the train journey is available for operators in the ATR HMI using a space-time graph. If the train arrives and leaves the station and the new ATS train number when the train leaves the terminal, it will be displayed. The operator can generate the timetable promptly with regulation of timetable or regulation headway with headway.

The ATR provides two different types of regulation functionalities:

Timeline-based editing allows automatic operation of the lines on the train according to the departure and arrival times specified in the timeline. Figure 4.4 shows ATR functionalities.

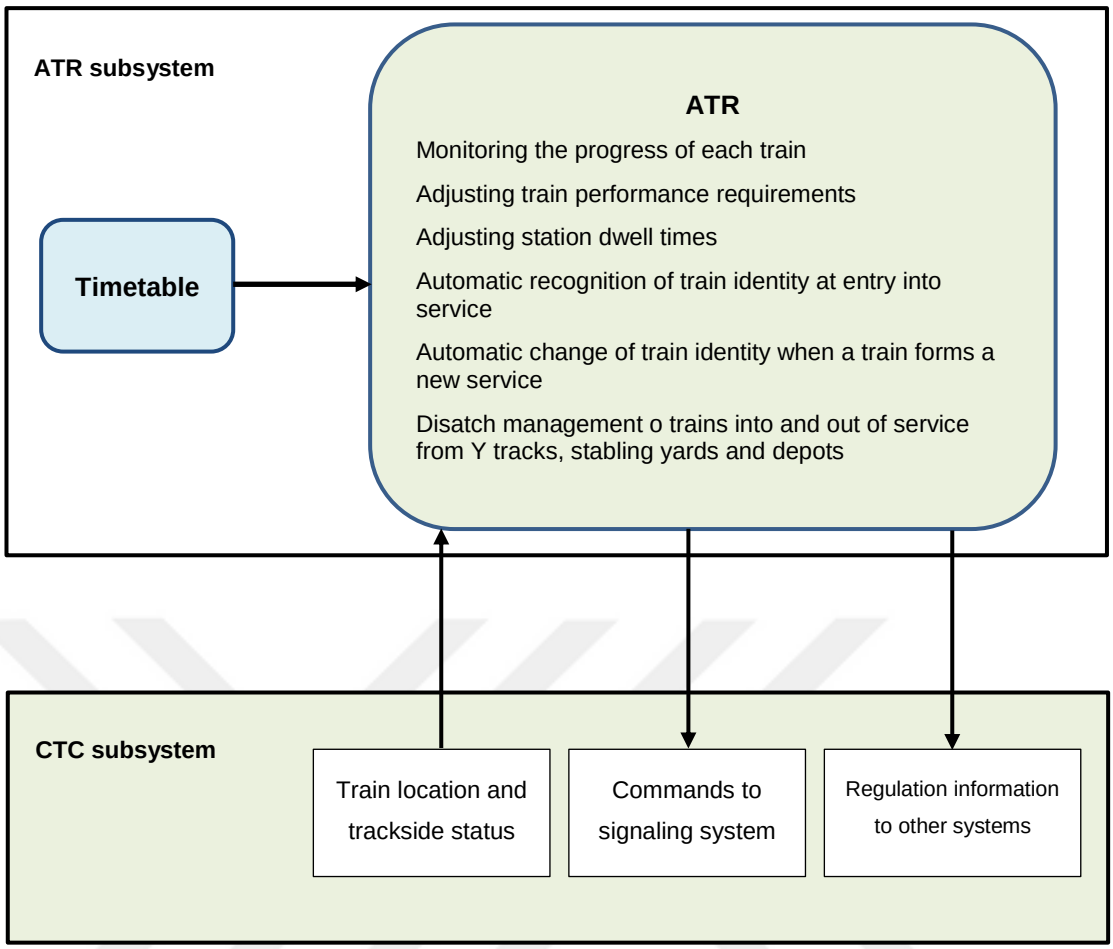


Figure 4.4 : ATR functionalities.

- **Timetable-based regulation:** The ATR system allows trains to move according to the timetable prepared during operation planning. Timetable-based arranging allows automatic operation of the lines on the train according to the departure and arrival times specified in the timetable.
- **Headway regulation:** The ATR system tries to keep the time between trains constant in headway regulation mode. Headway regulation can work without any timetable. The aim is to keep the time between trains constant. For example, if the train in front of the train fails, the following trains slow down to keep the time between them.

The traffic operator can activate headway or timetable regulation at any time. However, only one of the two systems can be active at the same time. In addition, the ATR function provides information to the passenger announcement and information system (PA-PIS) to inform passengers in a timely manner about train traffic schedule for instance estimated time of arrival and arrival of trains. In addition, if there is a delay in metro stations, the AFC may provide a delay alarm to the external system.

The route will not be set if there are any mismatches that prevent the setting of the route. In this case, ATR will not be able to arrange trains automatically. In order to avoid such a situation, the line must be suitable for the ATR system to be activated.

During a railway system operation, trains may be moving too early, on time or too late, according to regulation. When the train movement is too late or too early to regulate, ATR activates the necessary functions and arranges the trains in the system in terms of time.

In the operation of the trains, the delay system according to the regulation system is too late, and the very early status can be called advance. This situation can be in both timetable and headway regulation mode. The ATR system can guide trains in two different ways in case of delay or advance.

The ATR system can affect the time the train travels from one station to the next station. This travel time is called the trip time, or the ATR system can change the dwell time of the train at the platform. This waiting time is called dwell time.

For instance, for a CR train that is delay for the regulation system, the ATR system can handle 2 operations. One of these is to accelerates the train to reduce trip time. The other is to reduce the dwell at the platform. In either case, the ATR reduces the delay according to the regulation system.

For example, according to the regulation system, for a CR train that goes advance, the ATR system can handle 2 operations. One of these is to decelerates the train to increase trip time. The other is to increase the dwell time at the platform.

The ATR system for IC trains keeps the train at the platform for a train that arrives too early. For the delayed train, the train moves from the platform as soon as possible.

Platform minimum and train dwell time: This command holds the train at the station until the minimum dwell time expires. The regulation automatically sends the train dwell time commands when:

The train is in delay: The ATR decreases the dwell time of the train to reduce trip time. For the next platform, the new dwell time for the train is calculated by the following equation.

The train is in advance: The ATR extends the dwell time of the train at the platform to increase trip time. For the next platform, the new dwell time for the train is calculated by the following equation.

$$\mathrm{SDT}_{\mathrm{platform,train}} = \max\{\mathrm{SDmin}_{\mathrm{platform}}, \mathrm{TD}_{\mathrm{train}}\} \quad (4.1)$$

If the minimum dwell time at the platform is higher than the dwell time for the train sent by the regulation, the regulation has no effect on the train trip time.

Platform maximum dwell time: This parameter only affects the ATS level and determines the maximum time a train is held by the regulation at the platform.

The following section will explain how different regulatory strategies change train trip times; These strategies may try to keep a train until a certain decision is reached by ATS. If this dwell time exceeds the maximum dwell time of the platform, the ATR system permits train moving regardless of whether the regulation strategy requirement applies.

Speed profile: If the ATR detects that the train is delay, it sends a faster speed profile to the train at the current speed profile. On the other hand, if the ATR detects that the train is advance, it sends a slower speed profile to the train at the current speed profile.

Although the ATS sends the speed profile to the train, the train ATC system decides to implement this speed profile.

Automatic route setting: The ATR automatically sends the maneuver routes determined by the regulation strategy to trains. The manoeuvre is set for CR trains, at the train insertion, train withdrawal and turn-backs at terminal stations and for IC trains, for the departure at stations and turn-back at terminal stations.

4.8.1 Timetable-based regulation

Within the scope of the project, ATR system performs normal operation based on timetable. The timetable is a criterion for determining whether a train is moving or waiting at a station. The ATS timetable-based regulation system enables automatic operation of both CR and IC trains.

The timetable data defines the operation plan. A single timetable can contain information for the type of both CR and IC trains. If desired, this timetable can also be designed separately. But at the same time the only one timetable can be connected to the system. In principle there are two timetables in the system.

Planned timetable: The planned timetable can be any timetable that is stored in the regulation database. These timetables can be connected to the system at any time by the regulation supervisor. A planned timetable can be changed by the person in charge of the timetable on a different computer and updated in the system.

Working timetable: The working timetable is the timetable that runs on the ATR. According to this timetable, the system of regulation moves the trains that are even.

This timetable can be changed by the supervisor and each train can be updated with arrival and departure at each station. Table 4.3 shows timetable example.

Table 4.3 : Timetable example.

Service Number	Time
80001	06:00
80002	06:10
80003	06:20
80004	06:30
80005	06:40
80006	06:50
80007	07:00

Changes to this timetable are not saved in the database. Changes are made to the timetable in order to prevent the failure of the railway or even the train traffic. However, the next day the system operates the system according to the default working timetable. Briefly, changes are not permanently saved in the system.

In the timetable-based regulation system, there are three different control modes depending on how the maximum dwell time is evaluated on the platforms.

Full supervision: The maximum dwell time is ignored. Therefore, a train departs from a platform only when it is time to depart. This ensures maximum adherence to the working timetable.

No Supervision: The ATR system attempts to ensure that trains comply with the planned timetable. However, it ensures that the minimum dwell time is not exceeded. This means that a train may have to leave the platform, if the maximum dwell time has expired, even if the train is already advance.

Supervision in terminal stations: This mode is a mixture of the two modes described above. In this mode, the regulation system behaves as if it was in full supervision mode at terminal stations, as if it was in no supervision mode at other stations. Table 4.4 shows summarize the above.

To summarize the above in a Table 4.4:

Table 4.4 : Timetable based on managing train in the regulation mode.

	Full Supervision	No Supervision
Delay	Depart	Depart
On Time	Wait until depart time	Wait until depart time or maximum dwell time
Advance	Wait until depart time	Wait until depart time or maximum dwell time

The terminal stations defined in the system are: Halkalı, Ataköy, Yenikapı, Söğütlüçeşme, Pendik and Gebze.

4.8.2 Headway-based regulation

Considering the headway-based regulation in the Marmaray project, this headway-based regulation needs to work if the operation supervisor wants to operate in headway-based regulation instead of timetable-based regulation. Headway-based regulation keeps the distance between trains at a certain level. However, the system aims to achieve this headway time by accelerating or decelerating trains.

Headway in Marmaray signaling system is used for Halkalı - Gebze or for a loop or shuttle service. Loop is the process of departure and arrival between multiple trains between terminal stations. It is possible to apply headway mode only in combination with loops or shuttle services. Timetable-based regulation is not compatible with headway mode and shuttle service. Therefore, if the headway-based regulation mode is to be activated, the timetable-based regulation mode must be deactivated. Headway based regulation can be applied in simulation within the scope of this thesis and can only be applied for CR trains. Headway-based regulation is not applicable for regional trains, high-speed trains and trains to the T3 line.

Referring to Figure 4.5 below, the loop is composed of Station 1 and Station 3 and these stations are terminal stations. Trains in this loop are T0001, T0002 and T0003. The route of the train indicated by the red line. The movement authority on this route changes as the train moving.

The ATR sends route commands according to the block occupancy from IXL to ATS. If the line is not available and ATR is unable to set a route, it does not try to send the route again. The route is done manually via ARS.

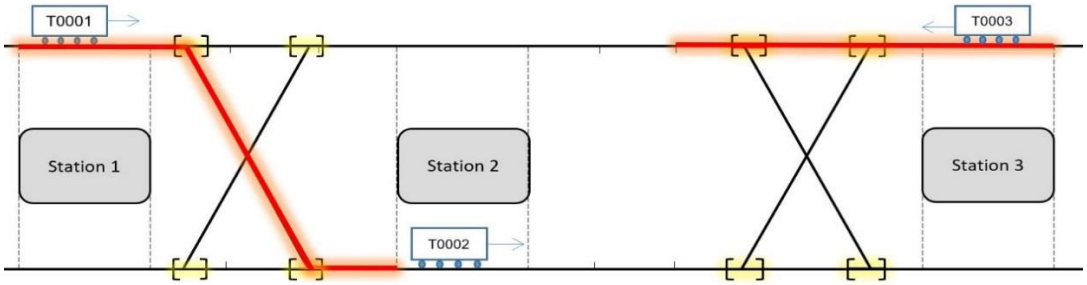


Figure 4.5 : Headway loop.

When Headway based regulation mode is active, ATR automatically sends the following commands:

- The ATR sets the routes between all stations in the loop.
- ATR sets the signals in terminal stations to fleet mode. As a timetable-based regulation is operated between terminal stations, a loop is selected between which stations the headway-based regulation, the system sets a route for the trains. This means that the system can also switch to fleet mode at terminal stations.
- In addition, if the ATR system sends the route request to the IXL equipment via the ATS, there is occupation in the relevant track block, or if another route is set on that track, interlocking rejects the request from ATR. Therefore, ATR does not try to send the route again to IXL.
- ATR connects the ARS module to all stations in the loop, in order to automatically set maneuvering routes at the terminal stations in the loop. Since the ATR system cannot be connected to the stations in the shuttle service, the shuttle service routes are done manually.

Headway regulation mode has some specific features. Under this mode, a scheduled timetable is not required. The target headway is calculated based on the number of trains in the selected loop and the predefined loop running time. The target headway is automatically calculated as the number of trains in the selected loop has changed. The numbering of trains is of no importance when the system is in this mode. Required to insert or withdrawn train into the loop may be manual operation. When a train arrives at the terminal station, the ATR sets the return maneuver route for the train at the opposite terminal station in the ARS.

On the basis of operating mechanism of ATR system, ATR counts train deviations continuously in terms of the planned headway. This calculation is based on the

distance to the previous train and by calculating the minimum time required to go to the next station after departure. This includes the dwell time on the station and time used to carry out the automatic reverse. ATR also calculates the deflection time instantly while the train is at the station. If the train ahead is slow compared to the normal headway time, the system can hold the rear train to keep the headway constant. Headway mode does not work on 2 loops that are nested. However, the system operates when the first 10 stations are selected as a first loop and the second 10 stations as a second loop.

4.9 Automatic Route Setting

The ATS manages the maneuvering movement by setting the maneuvering route to the trains moving under operation. This means that the operator does not have to set the routes manually. The system verifies that the necessary conditions for setting a route have been met and sends the commands to the interlocking after this verification. This function is provided by the Automatic Route Setting system. Figure 4.6 shows route setting flow chart.

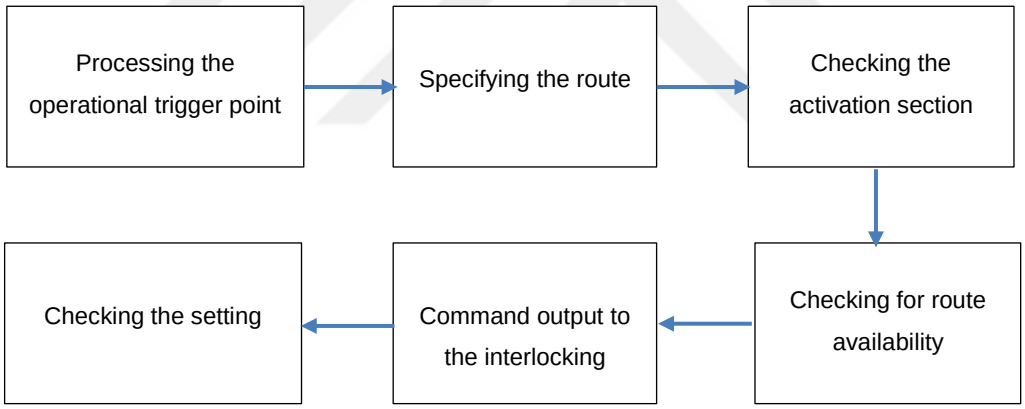


Figure 4.6 : Route setting flow.

The maneuvering route is a command sequence that is sent to the interlocking in a specific order for a train to move from one position to another position. During the setting of a maneuver route, ATS does not try to automatically determine routes that conflicted with other specified routes. The scenarios where ARS is useful are as follows:

- Sets routes for a train moving from one station to another.
- Sets the routes for the return of a train at the terminal or intermediate station.
- Sets the routes to locate a train on the main line from the depot area.
- Sets routes to withdrawn from the main line to the depot area.

- Sets routes to provide service between two different locations within the main line.

In addition, the ARS try to execute all defined maneuver routes. Manoeuvre consist of commands to be sent to the interlocking. However, before these commands are sent, the maneuvers consider the status of the track elements and the location of the other trains, so that the route can be set without affecting the loop of other trains. The ARS module performs its operations with a minimum effect on the current train operation. For this purpose, the module maneuver configuration ensures that the manoeuvre can be carried out without blocking other train movements.

5. CASE STUDY AND SIMUX SIMULATION

This section will explain the simulation made with SIMUX program.,

5.1 Purpose of Case Study

In this section, along with the structural features of the Marmaray line, speed restrictions, location of signals, points, track circuits, slopes, curves, cant, tunnels, station and commuter train working on the line were modeled and the studies of the train's headway-based and timetable-based regulation modes were examined.

5.2 SIMUX Simulation Program

Simulation is an important part of designing and optimizing nearly all railway subsystems. Through simulation, potential problems can be identified, design costs reduced or optimized for different design criteria such as operating costs, man-hour costs, passenger flow and passenger comfort in railway systems.

In this simulation, in headway-based and timetable-based regulatory modes, the effects of some faults and problems on the system were examined. The types of faults and the types of problems to be examined are chosen by taking some of the problems experienced during the operation of the Marmaray line.

The following problems and failures are:

- Block occupancy failure
- Pressing station emergency button
- Non-removed route

Simulation tools are now considered a standard component of signaling systems design and analysis. The timetable or headway to be performed in automatic train controls use various simulators to determine how the operators will behave in the event of a signal failure. The type and scope of features expected from a simulator has significantly increased over time with the advent of computer technology. The basic features that today's simulator should have can be sorted out:

- *Accuracy:* The results of the simulation must reflect the actual system.
- *Fastness:* the results of simulation should be quickly produced.
- *Flexibility:* The simulation tool should allow the parameters of the sub-systems to be interconnected.
- *Interaction:* The simulation tool should provide good interaction for the user. This is achieved by a good user interface.
- *Standardization:* To facilitate data manipulation, the tool should use existing standards.
- *Report generation:* The simulation tool should be able to generate detailed simulation results reports as part of a good user interface.

5.3 Data Input

In simulation programs, data entry is the most important process. Because any error to be made here will result in the simulation result being misinterpreted. Simulation data information must therefore have an easy-to-enter interface. The timetable created here is as an assumption in the timetable regulation. Then, 3 cases that were frequently encountered during the Marmaray operation on the T1 and T2 lines were simulated and the classification of failures was classified according to the delay time of train trips and a delay time for each failure was determined below.

Table 5.1 : Failures classification.

Failures Classification	Delay Time
Block occupancy failure	180 s
Pressing station emergency button	300 s
Non-removed route	600 s

The fault conditions described above were created virtually at Pendik station numbered S06 train from Gebze with 6:07 departing time and the self-recovery of the system was observed.

After the fault condition has been created, the recovery times of the systems in the Traingraph have been observed separately in headway and timetable regulations and in S12 Pendik, S28 Ayrılıkçeşme and S35 Bakırköy stations, train arrival, departure, dwell time and headway times are examined. If we examine 3 different fault conditions;

5.3.1 Non-Removed route – 600 seconds delay

In this failure scenario, there is very advanced traffic and even a big delay is occurring. After a delay of 600 seconds, the timetable and headway regulations can be better understood by the following captures from Traingraph, with different approaches to the trains in the line.

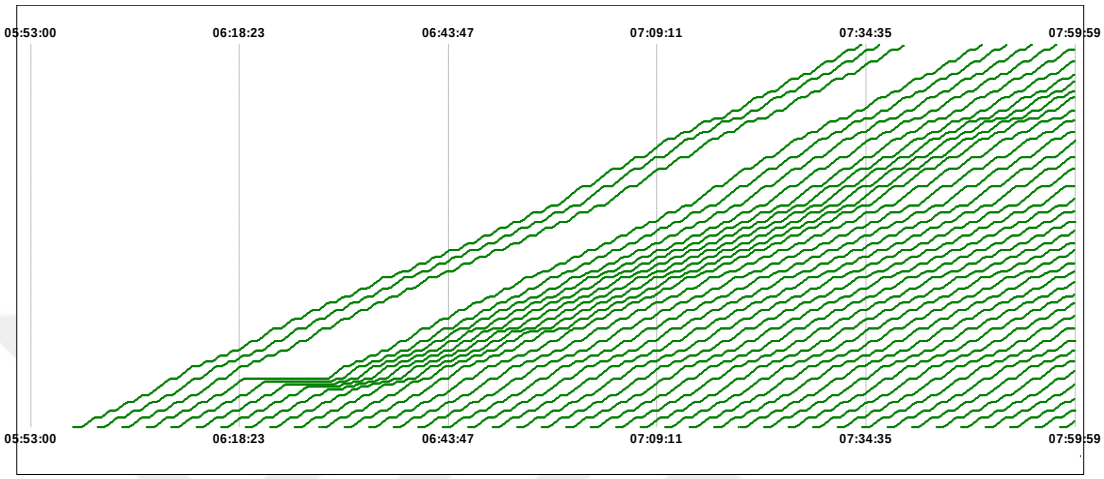


Figure 5.1 : Fixed headway regulation, 600 s delay.

Going over the fix headway regulation logic in the above Figure 5.1, after the failure, the system does not take extra effort to accelerate itself. Because after the train is experiencing failure, trains in the back are trying to maintain a constant 3 minutes between themselves. So, the 10-minute delay between the third and the fourth train is quite difficult to recover.

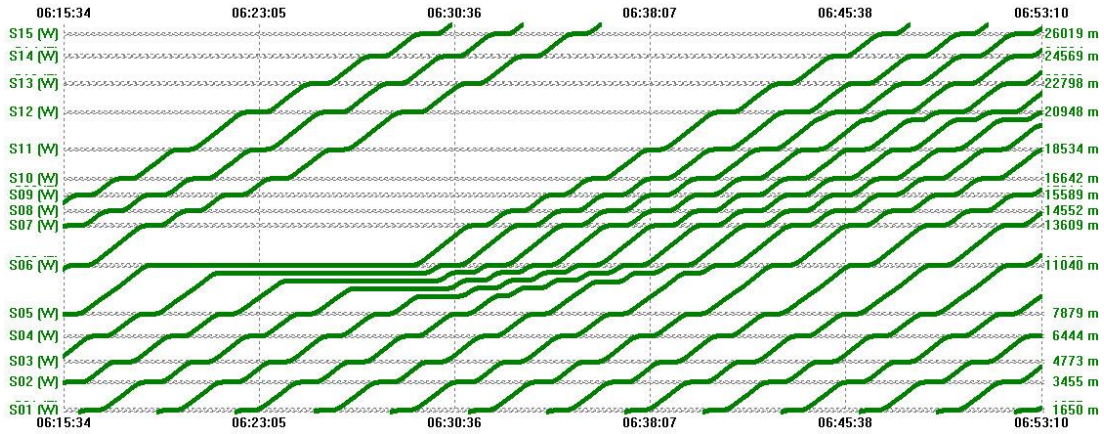


Figure 5.2 : Fixed headway regulation with location, 600 s delay.

The Figure 5.2 below shows the failure situation and the train movements that take place after the failure appear in detail. The difference in headway decreasing after failure is normalized as time goes by. However, Halkalı has not reached the desired position as of the end of the line.

Table 5.2 : S28 Ayrılıkçeşme, T1 line with 600 s delay in Tuzla, fixed headway.

Train	Arrival	Departure	Dwell Time	Headway
T1 (05:58)	06:56:19	06:56:50	31	
T1 (06:01)	06:58:53	06:59:32	39	161
T1 (06:04)	07:01:53	07:02:32	39	180
T1 (06:07)	07:12:32	07:13:02	30	631
T1 (06:10)	07:15:32	07:16:02	30	180
T1 (06:13)	07:18:33	07:19:03	30	180
T1 (06:16)	07:21:33	07:22:03	30	180
T1 (06:19)	07:24:05	07:24:50	45	167
T1 (06:22)	07:26:05	07:26:50	45	121
T1 (06:25)	07:28:06	07:28:51	45	121
T1 (06:28)	07:30:06	07:30:51	45	120
T1 (06:31)	07:32:07	07:32:52	45	121
T1 (06:34)	07:34:02	07:34:47	45	115
T1 (06:37)	07:36:52	07:37:37	45	171
T1 (06:40)	07:39:52	07:40:37	45	180
T1 (06:43)	07:42:52	07:43:37	45	180
T1 (06:46)	07:45:52	07:46:37	45	180
T1 (06:49)	07:48:52	07:49:37	45	180
T1 (06:52)	07:51:52	07:52:37	45	180
T1 (06:55)	07:54:52	07:55:37	45	180
T1 (06:58)	07:57:52	07:58:37	45	180

As shown in Figure 5.2 above and Table 5.2 below, the system returns itself to the 3-minute headway for the train which departures from Gebze at 06:40 reaches to Ayrılıkçeşme at 07:39:52.

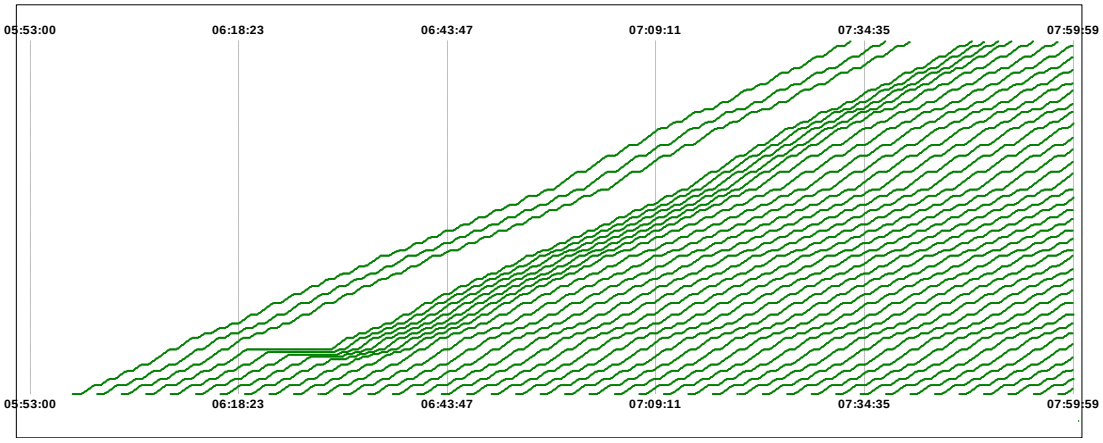


Figure 5.3 : Timetable regulation, 600 s delay.

If we analyze the timetable regulation logic in the above Figure 5.3, after the failure, the system makes extra effort to accelerate itself. The trains are moved as soon as

the minimum dwell time at the station is run out. Fix headway does not try to keep the time between the trains as in the headway and does not recover the delay during the failures but provides a better performance than the fix headway regulation.

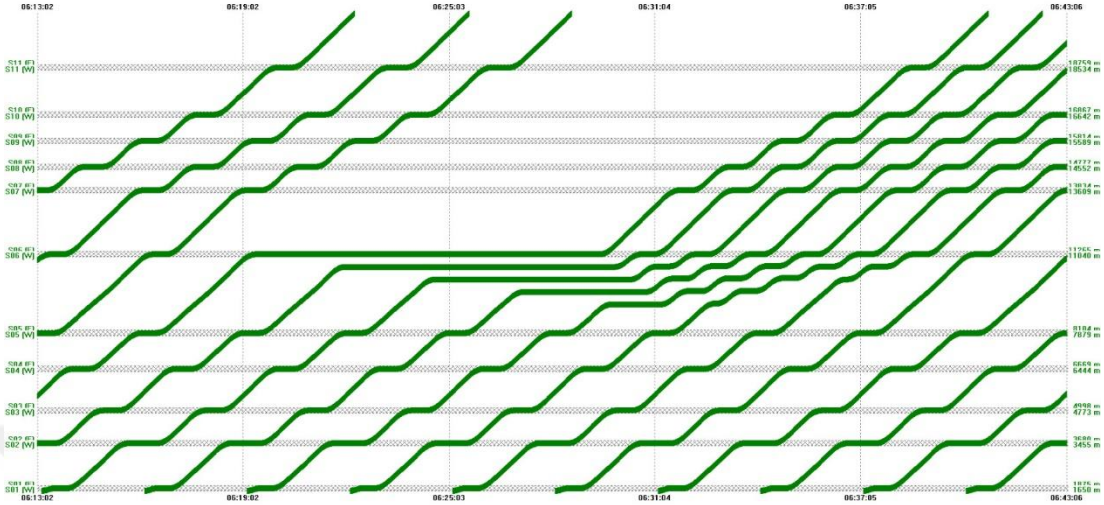


Figure 5.4 : Timetable regulation with location, 600 s delay.

Figure 5.4 shows 10 minutes delay with timetable regulation due non-removed route failure in the S06 Tuzla. As shown in Figure 5.3 above and Table 5.3 below, the system returns itself to the 3-minute headway system for the train which departures from Gebze at 06:25 reaches to Ayrılıkçeşme at 07:23:26.

Table 5.3 : S28 Ayrılıkçeşme, T1 line with 600 s delay in Tuzla, timetable.

Train	Arrival	Departure	Dwell Time	Headway
T1 (05:58)	06:55:53	06:56:24	31	
T1 (06:01)	06:59:26	07:00:04	38	221
T1 (06:04)	07:02:26	07:03:04	38	180
T1 (06:07)	07:12:20	07:12:40	20	576
T1 (06:10)	07:13:56	07:14:16	20	96
T1 (06:13)	07:15:32	07:15:52	20	96
T1 (06:16)	07:17:07	07:17:27	20	95
T1 (06:19)	07:18:42	07:19:02	20	95
T1 (06:22)	07:20:26	07:21:04	38	122
T1 (06:25)	07:23:26	07:24:04	38	180
T1 (06:28)	07:26:26	07:27:04	38	180
T1 (06:31)	07:29:26	07:30:04	38	180
T1 (06:34)	07:32:26	07:33:04	38	180
T1 (06:37)	07:35:26	07:36:04	38	180
T1 (06:40)	07:38:26	07:39:04	38	180
T1 (06:43)	07:41:26	07:42:04	38	180
T1 (06:46)	07:44:26	07:45:04	38	180

5.3.2 Pressing station emergency button – 300 seconds delay

In this failure scenario, advanced traffic is occurring as the same scenario above but there is not a big delay after all. After a delay of 300 seconds, the timetable and headway regulations can be better understood by the following captures from Traingraph, with different approaches to the trains in the line.

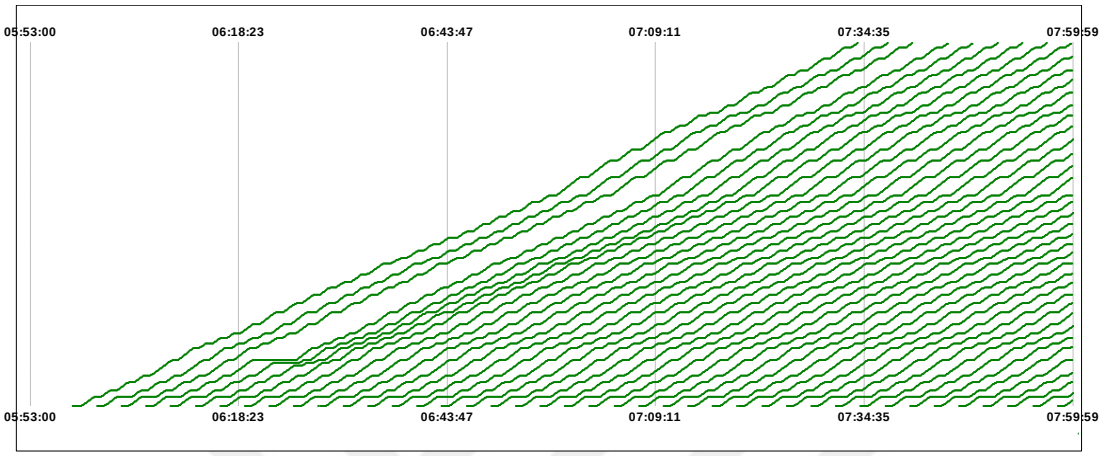


Figure 5.5 : Fixed headway regulation, 300 s delay.

Comparing Figures 5.5 and 5.6, the fix headway-regulated system, as in the case of a pressing station emergency button, takes longer to recover than the timetable regulated system.

Table 5.4 : S28 Ayrılıkçeşme, T1 line with 300 s delay in Tuzla, fixed headway.

Train	Arrival	Departure	Dwell Time	Headway
T1 (05:58)	06:56:13	06:56:47	34	
T1 (06:01)	06:59:46	07:00:28	42	221
T1 (06:04)	07:02:46	07:03:28	42	180
T1 (06:07)	07:08:43	07:09:13	30	346
T1 (06:10)	07:11:43	07:12:13	30	180
T1 (06:13)	07:14:44	07:15:14	30	180
T1 (06:16)	07:17:44	07:18:14	30	180
T1 (06:19)	07:20:03	07:20:48	45	155
T1 (06:22)	07:23:03	07:23:48	45	180
T1 (06:25)	07:26:03	07:26:48	45	180
T1 (06:28)	07:29:03	07:29:48	45	180
T1 (06:31)	07:32:03	07:32:48	45	180
T1 (06:34)	07:35:03	07:35:48	45	180
T1 (06:37)	07:38:03	07:38:48	45	180
T1 (06:40)	07:41:03	07:41:48	45	180
T1 (06:43)	07:44:03	07:44:48	45	180
T1 (06:46)	07:47:03	07:47:48	45	180

As shown in Figure 5.5 above and Table 5.4 above, the system returns itself to the 3-minute headway system, for the train which departures from Gebze at 06:22 reaches to Ayrılıkçeşme at 07:23:03.

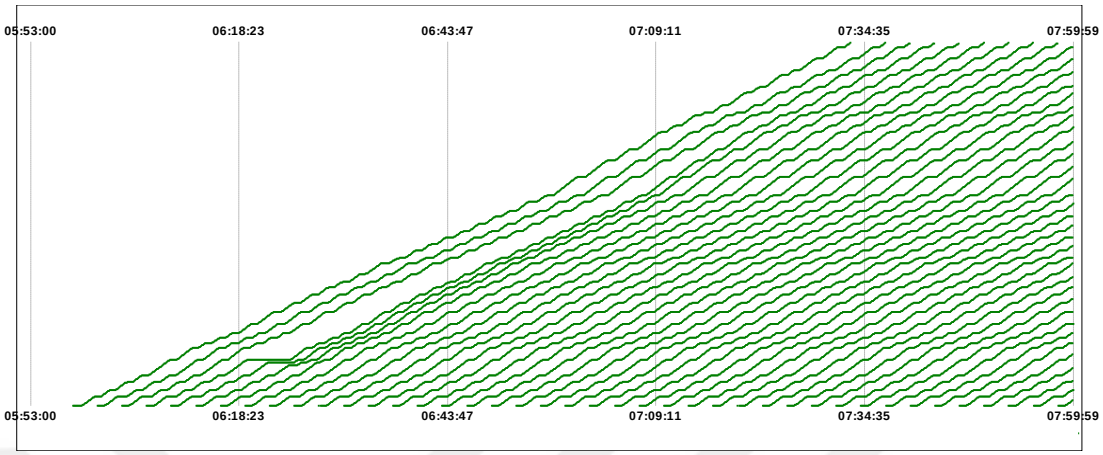


Figure 5.6 : Timetable regulation, 300 s delay.

As shown in Figure 5.6 above and Table 5.5 below, the system returns itself to the 3-minute headway system for the train which departures from Gebze at 06:16 reaches to Ayrılıkçeşme at 07:14:26.

Table 5.5 : S28 Ayrılıkçeşme, T1 line with 300 s delay in Tuzla, timetable.

Train	Arrival	Departure	Dwell Time	Headway
T1 (05:58)	06:55:53	06:56:24	31	
T1 (06:01)	06:59:26	07:00:04	38	221
T1 (06:04)	07:02:26	07:03:04	38	180
T1 (06:07)	07:07:21	07:07:41	20	276
T1 (06:10)	07:08:56	07:09:16	20	96
T1 (06:13)	07:11:26	07:12:04	38	168
T1 (06:16)	07:14:26	07:15:04	38	180
T1 (06:19)	07:17:26	07:18:04	38	180
T1 (06:22)	07:20:26	07:21:04	38	180
T1 (06:25)	07:23:26	07:24:04	38	180
T1 (06:28)	07:26:26	07:27:04	38	180
T1 (06:31)	07:29:26	07:30:04	38	180
T1 (06:34)	07:32:26	07:33:04	38	180
T1 (06:37)	07:35:26	07:36:04	38	180
T1 (06:40)	07:38:26	07:39:04	38	180
T1 (06:43)	07:41:26	07:42:04	38	180
T1 (06:46)	07:44:26	07:45:04	38	180
T1 (06:49)	07:47:26	07:48:04	38	180
T1 (06:52)	07:50:26	07:51:04	38	180

5.3.3 Block occupancy failure – 180 seconds delay

In this failure scenario when moderate traffic is occurring even not a little delay is noted. After a delay of 180 seconds, the timetable and headway regulations can be better understood by the following captures from Traingraph, with different approaches to the trains in the line.

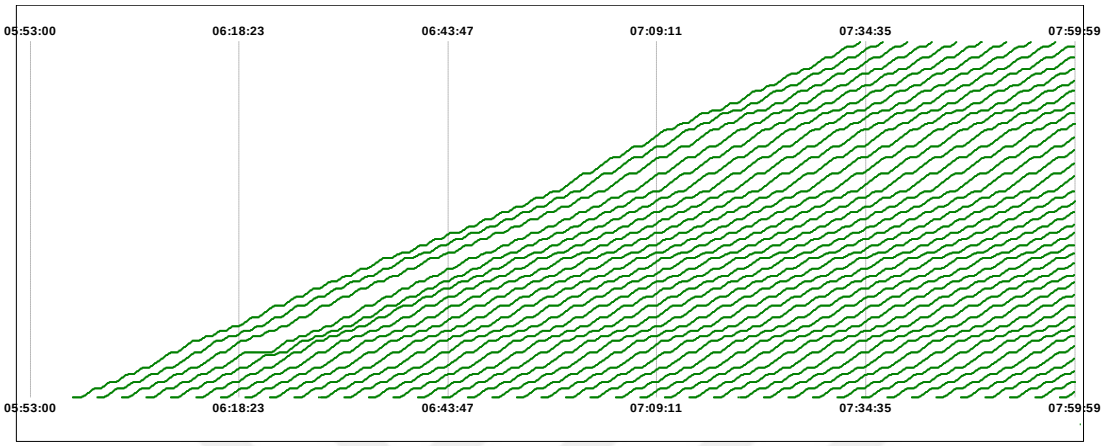


Figure 5.7 : Fixed headway regulation, 180 s delay.

Comparing Figures 5.7and 5.8, the fix headway-regulated system, as in the case of a block occupancy block failure, takes longer to recover than the timetable regulated system but even with a fixed headway, the system can recover itself in a short time.

Table 5.6 : S28 Ayrılıkçeşme, T1 line with 180 s delay in Tuzla, fixed headway.

Train	Arrival	Departure	Dwell Time	Headway
T1 (05:58)	06:56:29	06:57:01	32	
T1 (06:01)	06:59:02	06:59:32	30	151
T1 (06:04)	07:02:02	07:02:32	30	180
T1 (06:07)	07:05:41	07:06:11	30	219
T1 (06:10)	07:08:41	07:09:11	30	180
T1 (06:13)	07:11:41	07:12:11	30	180
T1 (06:16)	07:14:42	07:15:12	30	180
T1 (06:19)	07:17:42	07:18:12	30	180
T1 (06:22)	07:20:42	07:21:12	30	180
T1 (06:25)	07:23:42	07:24:12	30	180
T1 (06:28)	07:26:42	07:27:12	30	180
T1 (06:31)	07:29:42	07:30:12	30	180
T1 (06:34)	07:32:42	07:33:12	30	180
T1 (06:37)	07:35:42	07:36:12	30	180
T1 (06:40)	07:38:42	07:39:12	30	180
T1 (06:43)	07:41:42	07:42:12	30	180
T1 (06:46)	07:44:42	07:45:12	30	180

As shown in Figure 5.7 above and Table 5.6 above, the system returns itself to the 3-minute headway system for the train which departures from Gebze at 06:10 reaches to Ayrılıkçeşme at 07:08:41.

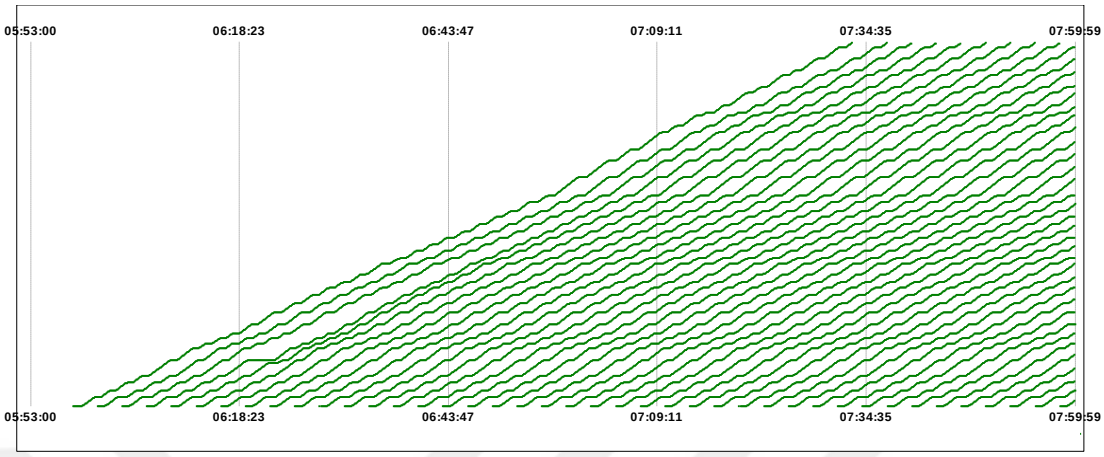


Figure 5.8 : Timetable regulation, 180 s delay.

As shown in Figure 5.8 above and Table 5.7 below, the virtual failure of 180 seconds seems to have lost its effect on the system after the station of Ayrılıkçeşme.

Table 5.7 : S28 Ayrılıkçeşme, T1 line with 180 s delay in Tuzla, timetable.

Train	Arrival	Departure	Dwell Time	Headway
T1 (05:58)	06:55:53	06:56:24	31	
T1 (06:01)	06:59:26	07:00:04	38	221
T1 (06:04)	07:02:26	07:03:04	38	180
T1 (06:07)	07:05:26	07:06:04	38	180
T1 (06:10)	07:08:26	07:09:04	38	180
T1 (06:13)	07:11:26	07:12:04	38	180
T1 (06:16)	07:14:26	07:15:04	38	180
T1 (06:19)	07:17:26	07:18:04	38	180
T1 (06:22)	07:20:26	07:21:04	38	180
T1 (06:25)	07:23:26	07:24:04	38	180
T1 (06:28)	07:26:26	07:27:04	38	180
T1 (06:31)	07:29:26	07:30:04	38	180
T1 (06:34)	07:32:26	07:33:04	38	180
T1 (06:37)	07:35:26	07:36:04	38	180
T1 (06:40)	07:38:26	07:39:04	38	180
T1 (06:43)	07:41:26	07:42:04	38	180
T1 (06:46)	07:44:26	07:45:04	38	180
T1 (06:49)	07:47:26	07:48:04	38	180
T1 (06:52)	07:50:26	07:51:04	38	180

However, as shown in Table 5.8 above, the 180-second delay at the Tuzla station reached at 06:41:04 with a 3-minute headway to Pendik station and the train departed from Gebze at 06:16.

Table 5.8 : S12 Pendik, T1 line with 180 s delay in Tuzla, timetable.

Train	Arrival	Departure	Dwell Time	Headway
T1 (05:58)	06:22:43	06:23:19	36	
T1 (06:01)	06:26:04	06:26:43	39	205
T1 (06:04)	06:29:04	06:29:43	39	180
T1 (06:07)	06:34:13	06:34:33	20	290
T1 (06:10)	06:35:49	06:36:09	20	96
T1 (06:13)	06:38:04	06:38:43	39	154
T1 (06:16)	06:41:04	06:41:43	39	180
T1 (06:19)	06:44:04	06:44:43	39	180
T1 (06:22)	06:47:04	06:47:43	39	180
T1 (06:25)	06:50:04	06:50:43	39	180
T1 (06:28)	06:53:04	06:53:43	39	180
T1 (06:31)	06:56:04	06:56:43	39	180
T1 (06:34)	06:59:04	06:59:43	39	180
T1 (06:37)	07:02:04	07:02:43	39	180
T1 (06:40)	07:05:04	07:05:43	39	180
T1 (06:43)	07:08:04	07:08:43	39	180
T1 (06:46)	07:11:04	07:11:43	39	180
T1 (06:49)	07:14:04	07:14:43	39	180
T1 (06:52)	07:17:04	07:17:43	39	180
T1 (06:55)	07:20:04	07:20:43	39	180
T1 (06:58)	07:23:04	07:23:43	39	180
T1 (07:01)	07:26:04	07:26:43	39	180
T1 (07:04)	07:29:04	07:29:43	39	180
T1 (07:07)	07:32:04	07:32:43	39	180
T1 (07:10)	07:35:04	07:35:43	39	180
T1 (07:13)	07:38:04	07:38:43	39	180
T1 (07:16)	07:41:04	07:41:43	39	180
T1 (07:19)	07:44:04	07:44:43	39	180
T1 (07:22)	07:47:04	07:47:43	39	180
T1 (07:25)	07:50:04	07:50:43	39	180
T1 (07:28)	07:53:04	07:53:43	39	180
T1 (07:31)	07:56:04	07:56:43	39	180
T1 (07:34)	07:59:04	07:59:43	39	180

It is possible to divide data entered from the interface into 3 groups. The first is Marmaray line information, the second is information about the train, and the third is timetable and headway for Marmaray ATS.

As can be seen from the time differences in the tables, in the timetable-based regulation system, the system recovers itself faster. However, when the situation is evaluated in terms of operability, the headway-based regulation system provides a more usable and more flexible possibilities.

6. CONCLUSION

In this thesis, the Marmaray line was modeled with SIMUX program and the train services were simulated between Gebze and Halkalı. Although the time between the stations is known in real terms headway trip time between the stations is calculated in the simulation without timetable. After these values were taken from the simulation, a timetable was created with headway regulation.

Both systems have advantages and disadvantages compared to each other. However, the most important role is to make an operation decision and decide which system they want to use by considering the pros and cons. Regarding the passenger density in Istanbul, it can be predicted that the regulation-based system will proceed more systematically in terms of both passenger and operation availability.

Regulation based on timetable system seems to be more profitable if it is required to function without insertion a train on the line. The most important reason for the timetable-based regulation system is that it moves at minimum dwell time at the stations in order to keep the timetable tariff. Timetable based regulation system uses 20 seconds dwell time to recover the system. However, this period is not enough for the passenger density in the platforms in İstanbıl. In crowded cities such as Istanbul, headway-based regulation system comes to the forefront instead of timetable regulation system.

Headway-based regulation system provides a more comfortable operation in terms of passenger satisfaction. In addition, operation is provided without a delay in the journey after the failure. Delay can be avoided by insertion train in front of the failure train. In short, there is the possibility of readjustment the delay in the headway regulation system. This delay can be eliminated by insertion or withdrawal the train. Headway-based regulation system is used for train insertion and withdrawal on scenarios in many parts of the Marmaray line called Y track regions are designed.

Briefly summary of 3 cases, the timetable-based regulated system recovers to the normal level faster than the headway-based regulation system. However, it is observed that the headway-based regulation system has more advantages when considering the number of passengers and operability in Istanbul.

REFERENCES

[1] ***Railway Systems Vehicle Technique.*** (2011). Republic of Turkey Ministry of National Education, Ankara.

[2] **Philips, D.** (1998). Transportation. IEEE Spectrum 35(1), 84-89. doi:10.1109/6.645986

[3] **Arlı, V.** (2010). Urban Rail Systems, EMO Technical Journal, Retrieved from http://www.emo.org.tr/ekler/2c1c8c7efa8da3f_ek.pdf?dergi=629

[4] **Toprak T., Aktürk, N.** (2001). Railway public transportation systems and safety threats in railway public transportation systems. 3th. Transportation and Traffic Congress - Exhibition Proceedings Book, 272-197.

[5] **Kölük, E.** (2005). Development of railways in the world and in Turkey. TCDD Education Course Notes, Ankara.

[6] **Evren, G.** (1996). Rail transportation in urban transportation. 1th Public Transportation Congress. Ankara Metropolitan Municipality EGO General Directorate, 272-297.

[7] **Yin, J., Tang, T., Yang, L., Xun, J., Huang, Y., & Gao, Z.** (2017). Research and development of automatic train operation for railway transportation systems: A survey. *Transportation Research Oart C: Emerging Technologies, 85,* 548-572. doi:10.1016/j.trc.2017.09.009

[8] **Jhonson, S.** (2014). *An overview on the Standard European Interoperable signaling and train control system*. Retrieved from http://www.railwaysignalling.eu/wp-content/uploads/2016/09/ERTMS_ETCS_signalling_system_revF.pdf

[9] **Ates, E., & Ustoglu, I.** (2018). An Approach for Moving Block Signalling System and Safe Distance Calculation. IEEE 5.

[10] **Theeg, G., Vlasenko, S.** (2009). Railway Signalling & Interlocking International Compendium. Eurailpress.

[11] **IEEE 1474.1.** (2008). IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional, IEEE Vehicular Technology Society.

[12] **Farooq, J., & Soler, J.** (2017). Radio Communication for Communications-Based Train Control (CBTC): A Tutorial and Survey. *IEEE Communications Surveys & Tutorials,* 19(3), 1377-1402. https://doi.org/10.1109/COMST.2017.2661384.

[13] **Ali, N.** (2017). What is CBTC? (IEEE 1474.1). *CBTC Solutions.* Retrieved April 25, 2019, from https://www.railtech.com/infrastructure/2019/03/13/marmaray-railway-finally-connects-europe-and-asia/

[14] **UITP** (2018). *World Metro Figures 2018* (Report No: September). International Association of Public Transport.

[15] **IEC 62290-1.** (2014). Railway applications – Urban guided transport management and command/control systems – Part 1: System principles and fundamental concepts, *International Electrotechnical Commission.*

[16] **Winter, P**. (2009). *Compendium on European Rail Traffic Management System (ERTMS).* Eurailpress.

[17] **Abed, S.** (2010). European Rail Traffic Management System – An Overview. *Iraq Journal Electrical and Electronic Engineering, 6 (2),* 172-179.

[18] **Stanley P.** (2011). *ETCS for Engineers.* Eurailpress.

[19] **Yin, J., Tang, T., Yang, L., Xun, J., Huang, Y., & Gao, Z**. (2017). Research and development of automatic train operation for railway transportation systems: A survey. *Transportation Research Part C: Emerging Technologies, 85,* 548-572.

[20] **Pochet, J., Baro, S., & Sandou, G.** (2017). Automatic train supervision for a CBTC suburban railway line using multi objective optimization. *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC), 1-6. https://doi.org/10.1109/ITSC.2017.8317670*

[21] **Lykke, S., & Belkaya, H.** (2005). *Marmaray Project: The Project and its Management. Tunneling and Underground Space Technology, 20(6),* 600–603. https://doi.org/10.1016/j.tust.2005.08.004

[22] **Karayanık, S.** (2017). Marmaray Signaling Systems and Interlocking System Simulation with Scada. (Master's thesis). Marmaray University, Graduate School of Science Engineering and Technology, ISTANBUL.

[23] **Marmaray Railway Engineering Project.** (2014). Retrieved April 27, 2019, from *https://www.railway-technology.com/projects/marmaray/*

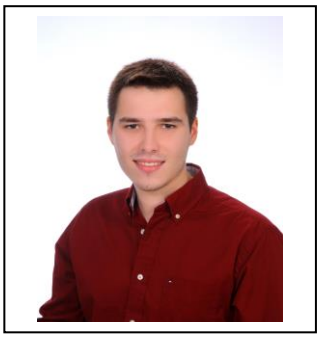
[24] **Zasiadko, M.** (2019). Marmaray railway finally connects Europe and Asia. *Railtech.* Retrieved April 27, 2019, from https://www.railtech.com/infrastructure/2019/03/13/marmaray-railway-finally-connects-europe-and-asia/

[25] **Siemens Mobility.** (2019). Marmaray Project, Crossing the Bosphorus with cutting-edge-technology [PDFSlides]. Retrieved from https://www.mobility.siemens.com/mobility/global/SiteCollectionDocuments/en/rail-solutions/rail-automation/train-control-systems/marmaray-references-en.pdf

[26] **Ning, B., Xun, J., Gao, S., & Zhang, L.** (2015). An Integrated Control Model for Headway Regulation and Energy Saving in Urban Rail Transit. *IEEE Transactions on Intelligent Transportation Systems, 16(3),* 1469-1478. https://doi.org/10.1109/TITS.2014.2366495

[27] **Hansen, I A.** (2010). Railway Network Timetabling and Dynamic Traffic Management. *International Journal of Civil Engineering, 1,8(1),* 19-32.

CURRICULUM VITAE



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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Ates, A. Dagli, M., Kurtkaya, M., Uz, Y.** 2018: Internet of Trams. Conference in Intelligent Transportation Systems, April 19-20, 2018 Balıkesir, Turkey

- **Çelik, H., Ates, A.** 2015: The Role of Vending Machines for Recycling Systems. TMMOB ÇMO 11th National Environmental Engineering Congress, October 15-17, 2015 Bursa, Turkey

- **Ates, A., Çelik, H.** 2015: Passenger Interface Systems in Modern Railway Application: A Dedicated Passenger Information System for Istanbul Tramway, *Advances in Railway Engineering, An International Journal,* 2(2), 121-126.