Interaction of Lifecycle Properties in High Speed Rail Systems Operation

by

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Submitted to the Institute for Data, Systems, and Society
in partial fulfillment of the requirements for the degree of

Master of Science in Engineering Systems
at the
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ABSTRACT

High-Speed Rail (HSR) has been expanding throughout the world, providing various nations with alternative solutions for the infrastructure design of intercity passenger travel. HSR is a capital-intensive infrastructure, in which multiple subsystems are closely integrated. Also, HSR operation lasts for a long period, and its performance indicators are continuously altered by incremental updates. With this background, design and monitoring of lifecycle properties, or "ilities", is an important factor to achieve long-term successful operation. This thesis aims to analyze and evaluate dynamic behaviors of "ilities" and their interactions in HSR operation.

After the literature review and the study of industrial trends about HSR "ilities", safety, availability and profitability are chosen as key "ilities" which should be monitored in HSR operation. The Tokaido Shinkansen in Japan, and Amtrak's service in the US Northeast Corridor (NEC) are chosen as cases to study "ilities" trends. In the Tokaido Shinkansen, three "ilities" form a positive feedback loop to make HSR operation successful. The NEC shows high profitability, but it does not perform as well in terms of safety and availability due to several systemic factors.

System Dynamics (SD) is applied to visualize interactions of "ilities" and other variables of interest. Qualitative causal loop diagrams (CLD) reveal several feedback loops affecting "ilities". In particular, the integration of train operation and infrastructure / rolling stock management results in the emergence of major feedback loops which cannot easily be captured by other methodologies. Qualitative SD models are converted into quantitative SD models, and numerical simulations are run to further understand the structure of causal loop diagrams. Estimated parameters in the Tokaido and the NEC suggest the different relationships among "ilities" and other variables. Further, sensitivity analyses are conducted to evaluate how different policies affect "ilities" in future HSR operations.

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I also thank all the readers, for your interest in this thesis, and we hope that it has offered you some useful perspectives to consider long-term HSR operation from systemic standpoints.

Finally, I would like to say great thanks to my family: Koichiro and Yurimi, my parents, for always supporting me to pursue my career. Fumie, my dearest wife, for your selfless love and giving me an opportunity to be a father. Reina, our precious daughter, for your birth and healthy growth. I love you all.

Tatsuya Doi
Cambridge, Massachusetts
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LIST OF ACRONYMS AND ABBREVIATIONS

ARRA	American Recovery and Reinvestment Act	LGA	LaGuardia Airport
ASM	Available Seat Mile	MIC	Japanese Ministry of Internal Affairs and Communications
ATC	Automatic Train Control	MBTA	Massachusetts Bay Transportation Authority
BOS	Boston area market, or Boston Logan Airport	MCMC	Markov chain Monte Carlo method
BWI	Baltimore Washington Airport	MLIT	Japanese Ministry of Land, Infrastructure, Transport and Tourism
BTS	Bureau of Transportation Statistics	MNR	Metro-North Railroad
CAPEX	Capital Expenditure	MTA	Metropolitan Transportation Authority
CAST	Causal Analysis based on STAMP	NASA	National Aeronautics and Space Administration
CLD	Causal Loop Diagram	NEC	The Northeast Corridor
CLIOS	complex, large scale, interconnected, open and sociotechnical system	NER	Northeast Regional train service
CPI	Consumer Price Index	NORAC	Northeast Operating Rules Advisory Committee
DB	German Railway	NRT	Tokyo Narita Airport
DC	Washington DC area market	NTIS	National Technical Information Service
DCA	Washington Reagan National Airport	NTSB	National Transportation Safety Board
DoD	Department of Defense	NY	New York area market
ERTMS	European Rail Traffic Management System	OPEX	Operating Expense
EWR	Newark Liberty Airport	OTP	on-time performance
FAST	Fixing America's Surface Transportation Act	PPP	Public-Private Partnership
FRA	Federal Railway Administration	PTC	Positive Train Control
FY	Fiscal Year	PRIIA	Passenger Rail Investment and Improvement Act
IAD	Washington Dulles Airport	RAMS	Reliability, Availability, Maintainability and Safety
IEC	International Electrotechnical Commission	RMSE	Root Mean Squared Error
IHRA	International High-speed Railway Association	RPM	Revenue Passenger Mile
ITM	Osaka Itami Airport	RRIF	Railroad Rehabilitation and Improvement Program
HND	Tokyo Haneda Airport	RSIA	Rail Safety Improvement Act of 2008
HSIPR	High Speed Intercity Passenger Rail Program	SD	System Dynamics
HSR	High Speed Rail	SHC	Shinkansen Holding Cooperation
JFK	John. F. Kennedy Airport	SOGR	state of good repair
JNR	Japan National Railways	SNCF	National Society of French Railways
JR	Japan Railway Group	STAMP	System Theoretic Accident Model and Processes
JRC	Central Japan Railway Company	STPA	System Theoretic Process Analysis
KIX	Osaka Kansai Airport	TGV	French high speed rail service
LCC	Life Cycle Cost (Chapter 3)	UIC	International Union of Railways
LCC	Low-Cost Carrier (Chapter 4)	UKB	Kobe Airport

Chapter 1 Introduction

1.1 Motivation

Emergence of HSR

Since the latter half of the 20th century, a growing population and expanding economic activities have driven the surge of people's movement both at domestic and international levels. In markets where transportation demand has rapidly increased, existing transportation systems such as highways or air transportation have had difficulties in providing adequate capacity. Congestion in highways and airports has been chronic in many countries, resulting in significant economic losses. Furthermore, in many cases, the expansion of highways and airports in urban areas is difficult because of spatial limitations or environmental barriers such as noise and CO_2 emission.

High Speed Rail, HSR, contains the potential to solve this problem. The first HSR system was born in Japan in 1964, responding to the exploding transportation demand in the Tokaido Corridor connecting Tokyo and Osaka. This new line eased the severe congestion on saturated conventional rails and roads, and the travel time savings (initially from 6h to 4h, today 2.5h from Tokyo to Osaka) have induced new travel demands, making connections among economic blocks tighter. Since the 1980s, several European countries have launched HSR operation, expanding their networks to serve international O-D pairs as well as various domestic markets. They have utilized existing conventional rail networks along with newly constructed lines, which enabled them to serve HSR services to more cities than purely HSR dedicated lines like in Japan.

Figure 1.1 shows the modal share of public transportation by distance in Japan [1], and Figure 1.2 shows the HSR market share by travel time in rail-air competitive markets in Europe [2]. These two figures suggest that there is a "sweet spot" in medium-distance markets (around 300km-750km), where HSR can attract trips too long for driving and too short for air transportation. Indeed, HSR fulfills an important role in many countries as a fast, convenient intercity passenger travel mode. Both in developed and developing countries there exist multiple ongoing HSR projects.

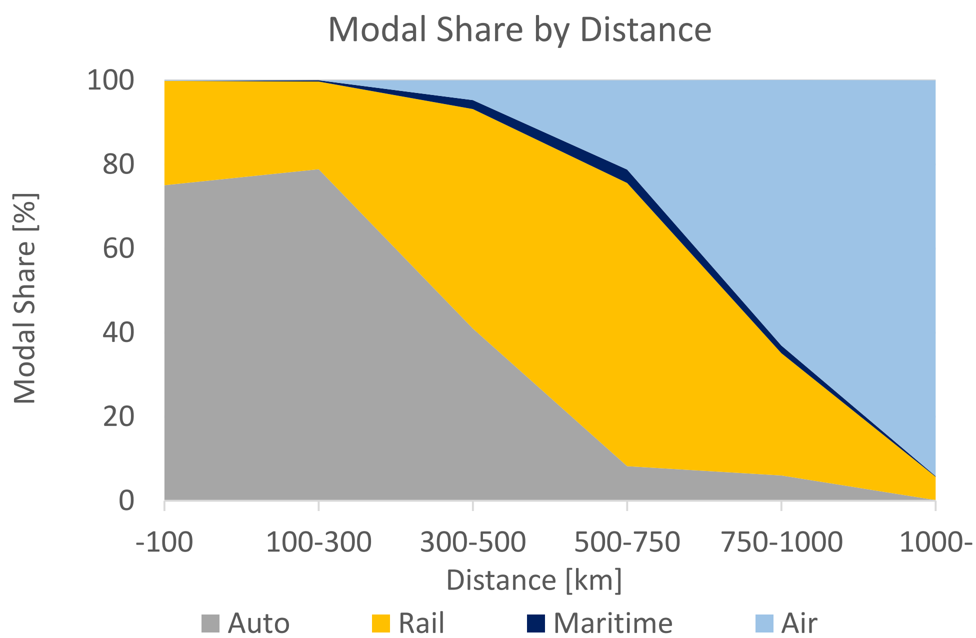

Figure 1.1 Modal Share of Passenger Travel in Japan

(Source: MLIT)

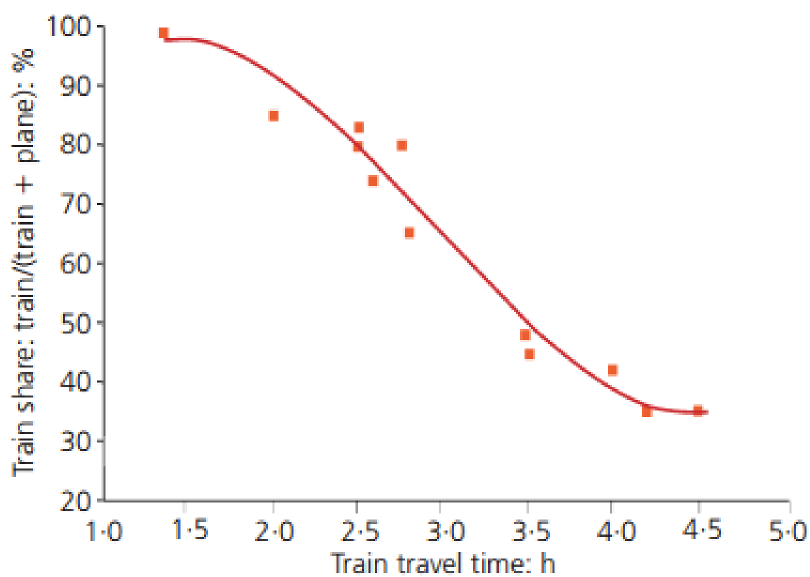

Figure 1.2 Rail-Air Share in European HSR Markets

(Source: Pita, 2012)

HSR lifecycle

HSR is composed of various subsystems such as tracks, signals, power supply systems, stations and rolling stock. The lifecycle of each subsystem in HSR operation is quite long. Infrastructures such as tracks, tunnels and bridges can last decades or sometimes centuries, if maintained and/or upgraded regularly. In the long-term operation, system properties such as service quality, safety, reliability, and productivity are influenced by various factors in technical, economic, institutional or even political domains. Technical improvements of rolling stock and infrastructures have enabled train operators to run trains faster, while keeping damages to tracks to a minimum. The maximum operation speed in commercial HSR was initially 210kph (131mph) in 1964, but today it is 350kph (219mph) in conventional wheeled systems and 430kph (269mph) in magnetic levitation (maglev) systems. Economic growth has been the main driver for the demand increase in intercity passenger travel, which has pushed the expansion of HSR capacities and networks. Regarding institutional impacts, HSR productivity has become much better after privatization of HSR operators (responsible for both train operation and infrastructure management) in Japan [3]. Also, in Europe, HSR productivity has improved after deregulation (separation of infrastructures from train operations, and allowance of third parties' access) [4].

Lifecycle Properties ("ilities")

In such a long-term operation, it is important to consider and design non-functional system properties which emerge after HSR is launched as well as initial functionalities such as train speed or track strength. Such non-functional requirements are often called lifecycle properties ("ilities"), and the importance of "ilities" has grown as systems become more complex and attain longer service lives. In the HSR industry, some "ilities" such as safety and reliability are directly related to the success level of service, and they have been studied extensively. However, they are often studied as single and isolated properties, and the relationship or interactions among "ilities" in HSR operation are not often considered.

1.2 Research Objective

The main objective of this research is to understand the behavior of lifecycle properties ("ilities") and their relationship in long-term HSR operation. During the long operational phase, HSR gradually alters its performance, affected by external inputs such as travel demand changes or intermodal / intra-modal competitions, or even by internal inputs such as financial circumstances or quality of rolling stock, infrastructures and human resources. Therefore, it is important to monitor key performance indicators in HSR operation to understand the dynamics of system evolution. In this research, several lifecycle properties are captured qualitatively and quantitatively, and their dynamic behaviors are studied to understand their interactions. System Dynamics is used as a methodology to model the relationship of multiple factors affecting HSR operation.

1.3 Thesis Outline

This thesis is organized as follows:

- **Chapter 2** presents an overview of HSR. The definition and world trends in HSR are shown at first; then HSR characteristics are considered from the perspective of system development and operation.

- **Chapter 3** introduces a key concept in this thesis, lifecycle properties or "ilities". Definition and literature reviews about "ilities" are provided; then their relevance to practical HSR operation is discussed. Three key "ilities" are chosen to be further discussed in Chapter 5 and Chapter 6.

- **Chapter 4** analyzes two HSR markets, the Tokaido Corridor in Japan and the Northeast Corridor (NEC) in the US, from the viewpoint of modal competition. As a main competitor of HSR, air transportation is further surveyed.

- **Chapter 5** discusses the key "ilities" in HSR operation in the Tokaido Corridor and the NEC. Safety, availability and profitability are discussed using several performance indicators with characteristics and background of HSR services.

- **Chapter 6** utilizes System Dynamics models to consider the dynamic behaviors and interactions of “ilities” discussed in Chapter 5. A conceptual model is at first presented, then it is converted to a numerical model. Simulated results are analyzed to evaluate relationships among variables and “ilities”.

- **Chapter 7** summarizes key research findings and conclusions of this research, and then suggests potential areas of future research.

The next chapter begins with an overview of HSR systems. The discussion of HSR definition and its characteristics shows the uniqueness of HSR, compared to conventional rail and other transportation modes. In addition, the relevance of HSR and “ilities” is considered in this context, which forms a starting point for the discussion in Chapter 3.

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Chapter 2 Overview of HSR Systems

This chapter provides the overview of HSR system. The definition and the world trend of HSR is introduced first, then its characteristics is discussed from the standpoint of system development and operation.

2.1 Definition of HSR

There is no single, standard definition of HSR being used throughout the world. In the European Union, for example, HSR is defined as the combination of three conditions shown in Table 2.1 [5]. In the International Union of Railways (UIC) [6], an international railway industry body originated in Europe, HSR is defined as “a complex reality involving various technical aspects (infrastructure, rolling stock, operations) and cross sector issues (financial, commercial, managerial and training aspects)”. The commonality of these two definitions is that HSR is taken not as a single technical element, but as a combination of different, heterogeneous subsystems with technical and non-technical aspects, which are well integrated to operate as parts of a total system.

Table 2.1 Definition of HSR by European Union

Elements	Requirements
1. Infrastructure	Infrastructure shall be specially built, or specially upgraded for high speed travel
2. Rolling Stock	Trains shall be designed at a speed of at least 250km/h on specially-built lines, and at a speed of the order of 200km/h on specially upgraded existing lines
3. Compatibility	Infrastructure and rolling stock shall have excellent compatibility to ensure performance levels, safety, quality of service and costs

(Source: the European Union)

2.2 HSR around the World

In the middle of the 20th century, the spread of automobiles and cheaper public air transportation had made passenger rail a declining industry in many (but not all) countries. However, the first HSR made in Japan has since 1964 attracted numerous passengers and shown tremendous possibility. In 1980s, Western European countries such as France, West Germany and Italy developed their own HSR systems, then expanded them into surrounding countries. In the 21st century, countries and firms with HSR technologies have tried to export their systems to overseas markets mainly in Eastern Asia, and today HSR has become an indispensable intercity transportation mode in many countries.

Figure 2.1 shows the world distribution of HSR in 2013 [7], and Figure 2.2 shows the projected world distribution of HSR in 2025. Most HSR currently in operation exists in Western Europe and Eastern Asia. At the beginning of the HSR era, HSR systems were developed independently by a few countries, and it took a long period to launch new HSR systems in new countries. These days, however, countries with HSR try to export their systems to overseas markets. As a result, the spread of HSR has been accelerating. There are many ongoing HSR projects today, and in 2025 new HSR systems are projected to be in operation in countries in Eastern Europe, Middle East, Southern Asia and the Americas.

Table 2.2 shows the total track lengths of HSR in operation by countries as of 2014 [8]. Japan and Western European countries such as Spain, France, Germany and Italy operate quite extensive HSR networks. These days China has constructed the longest HSR network in the world quite rapidly. Indeed, China owns more than 48% of HSR track miles in the world in 2014, compared with 0% in 2003.

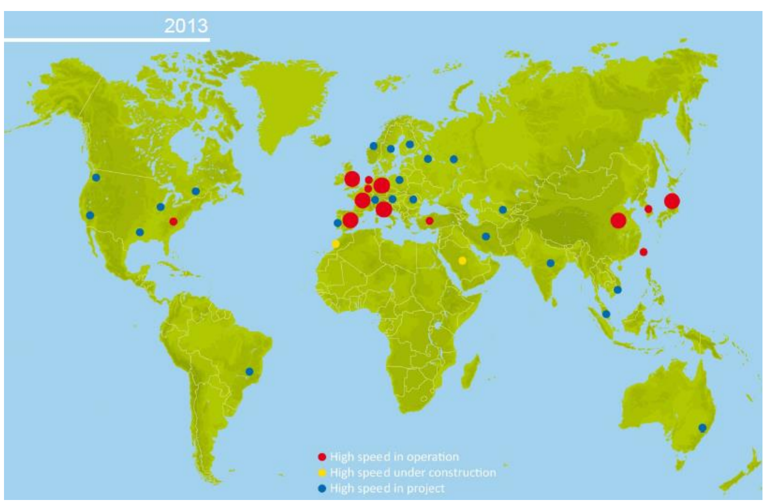


Figure 2.1 HSR in the World as of 2013

(Source: International Union of Railways (UIC), 2013)

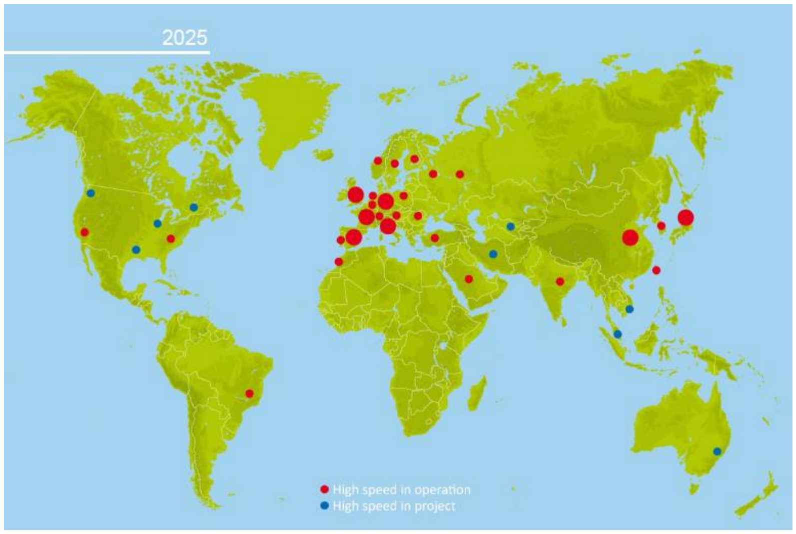


Figure 2.2 HSR in the World in 2025

(Source: International Union of Railways (UIC), 2013)

Table 2.2 HSR Lengths by Countries as of 2014

Region	Countries	Total km	Start
Europe	Spain	**2,515**	1992
	France	**2,036**	1981
	Germany	**1,352**	1992
	Italy	**923**	1981
	Belgium	209	1997
	Netherlands	120	2009
	UK	113	2003
	Austria	48	2012
	Switzerland	35	2007
Asia	China	**11,132**	2003
	Japan	**2,664**	1964
	South Korea	412	2004
	Taiwan	354	2007
Middle East	Turkey	688	2009
Americas	USA	362	2000
TOTAL		**22,963**	

(Source: International Union of Railways (UIC), 2014)

2.3 Characteristics of HSR

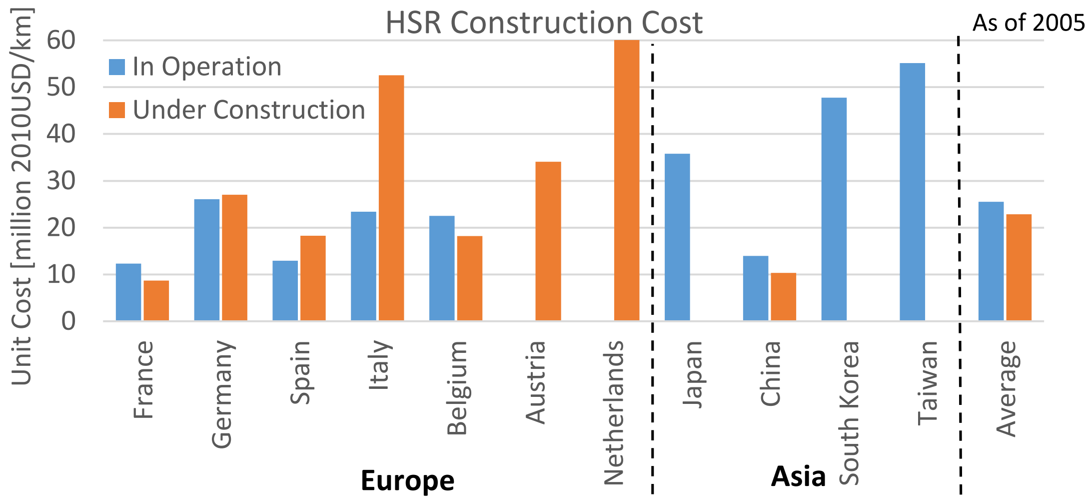
2.3.1 System Development

HSR, as well as conventional rail systems, require significant construction capital to launch their operation, so the HSR system development involves large upfront financing costs. Campos et al. [9] calculated the unit construction cost of HSR by countries as shown in Figure 2.3. The unit construction cost differs by projects or countries because of various factors such as economic (e.g. price, labor cost), environmental (e.g. flat vs mountainous), and infrastructure quality itself (e.g. ballast track vs slab track). The average construction cost in the world is around 25 million 2010USD per 1km of HSR, so it usually requires more than $10 billion to construct a 500km long HSR line.

Due to this large initial capital cost, HSR construction has been usually funded with public financing. Most European HSR was constructed by full public financing, through either accumulated public funds (e.g. tax revenue, infrastructure levies) or government borrowing (e.g. bonds, long-term debts) [10]. Asian HSR has shown a similar trend. After the construction is done, in many cases governments or state-owned enterprises such as national railway companies own the infrastructure and return upfront capital costs by charging access fees to train operators.

These days, there is an emerging trend to apply PPP (Public-Private Partnerships) in HSR development. Henn et al. [10] studied several recent TGV (French HSR system) projects as examples of PPP financing models, and categorized them into several types by the way they allocate responsibilities between public and private sectors. Dutzik et al. [11] stated that HSR development in the US would partially require PPP frameworks, like the ongoing project in California.

HSR projects with full private financing have not been completed yet anywhere in the world. The HS1 project in Great Britain and the Taiwan HSR project were originally intended to be financed fully by the private sector, but eventually heavy public investment was conducted to support financial difficulties of private players [11]. There are still several ongoing projects intending full private finance. The Chuo-Shinkansen project in Japan is the magnetic levitation (maglev) HSR project connecting Tokyo and Nagoya in 2027. Currently, this project is fully financed by Central Japan Railway Company (JRC), a private railway company owning / operating HSR and conventional rails. In the US, Texas Central Partners [12] intends to construct a HSR between Dallas and Houston by 2021, and is now gathering funding from only private investors.



※Construction cost includes Infrastructure costs (terrain, platform etc.) and superstructure costs (track, signal, electrification etc.), not planning and land costs (feasibility study, land acquisition etc.)

Figure 2.3 Comparison of HSR Construction Cost

(Adapted from Campos et al., 2009)

2.3.2 System Operation

HSR is considered a complex sociotechnical system. Sussman et al. [13] [14] defined a "complex, large scale, interconnected, open and sociotechnical (CLIOS) system" to describe engineering systems impacting multidisciplinary domains such as technology, society, economy, policy, and environment. He [15] claimed that transportation is an example of a CLIOS system, since it is complex, dynamic and connected within it and with other CLIOS systems.

As a CLIOS system, HSR is composed of many heterogeneous subsystems, as shown in Figure 2.4. These subsystems are designed, controlled and maintained by human operators or automated procedures, and are integrated with each other by transferring operands such as materials, energy and information. Table 2.3 shows some examples of operands transferred among subsystems. This matrix is sometimes asymmetric (e.g. Power Supply – Signaling, Power Supply provides electricity to Signaling, while Signaling provides nothing to Power Supply), or at least contains asymmetrical operands in diagonal cells (e.g. Rolling Stock – Control Center, the Control Center provides permissions for Rolling Stock to move, while Rolling Stock returns its condition such as positions and speeds to the Control Center). This means that the relationship of two subsystems is often directional, and that one subsystem requires feedback from another subsystem in response to its initial action.

In HSR operation, communications among these subsystems are controlled simultaneously by operators following operating manuals or regulations. These interactions are not simple linear ones, so important system properties such as safety and reliability cannot be expressed as a pure aggregation of subsystems' properties. They emerge as a result of these emergent interactions between these systems.

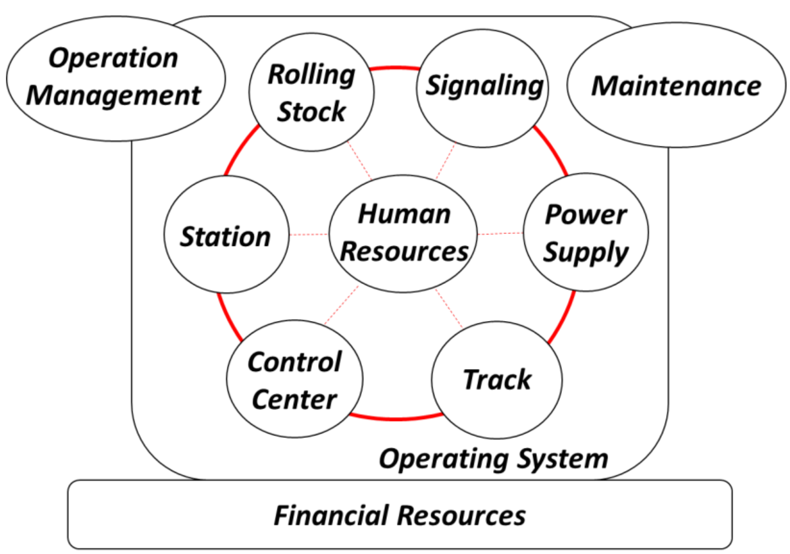


Figure 2.4 Integration of Subsystems in HSR Operation

Table 2.3 Design Structure Matrix (DSM): Transferred Operands between Physical Subsystems

Black: Matter Red: Energy Blue: Information

Sender \ Receiver	Rolling Stock	Power Supply	Signaling	Track	Station	Control Center
Rolling Stock		Regenerated electricity	Location Speed	Axle load Friction force	Passengers	Location Speed Reaction to command
Power Supply	Electricity		Electricity			Condition (e.g. failures)
Signaling	Location Speed limit			Control signal	Train location	Condition (e.g. failures)
Track	Axle load Friction force		Switch direction			Switch direction
Station	Passengers					Information (e.g. accidents)
Control Center	Permission	Power control	Signal change	Turnout switch control	Information (e.g. traffic change)	

Once HSR is launched and begins operations, the subsystems in HSR are maintained, replaced or upgraded regularly to keep the total function of HSR sound. Due to its inherent characteristics, HSR improvements are mostly done incrementally. Since HSR is an industry with a large fixed capital, it is unrealistic to invest in changing all systems from scratch once initial operation starts. Also, as presented in Figure 2.4, many subsystems are closely integrated with each other, so radical design changes in one subsystem can lead unexpected change propagations in other subsystems, making total system unstable or even unsafe. Thus, each change in designs or operating procedures should be carefully examined, so as not to violate technical, organizational or financial restrictions.

Figure 2.5 shows the lifecycle of subsystems in HSR operation. In operational phase, system operation and maintenance are conducted simultaneously, and their results or insights are shared with each other, making a feedback loop between them. Additionally, operation and maintenance data can become an important input for upgrading current operations or designing next-generation facilities. As a result, there are multiple feedback loops in the lifecycle of HSR subsystems, letting each subsystem being improved based on current operating conditions.

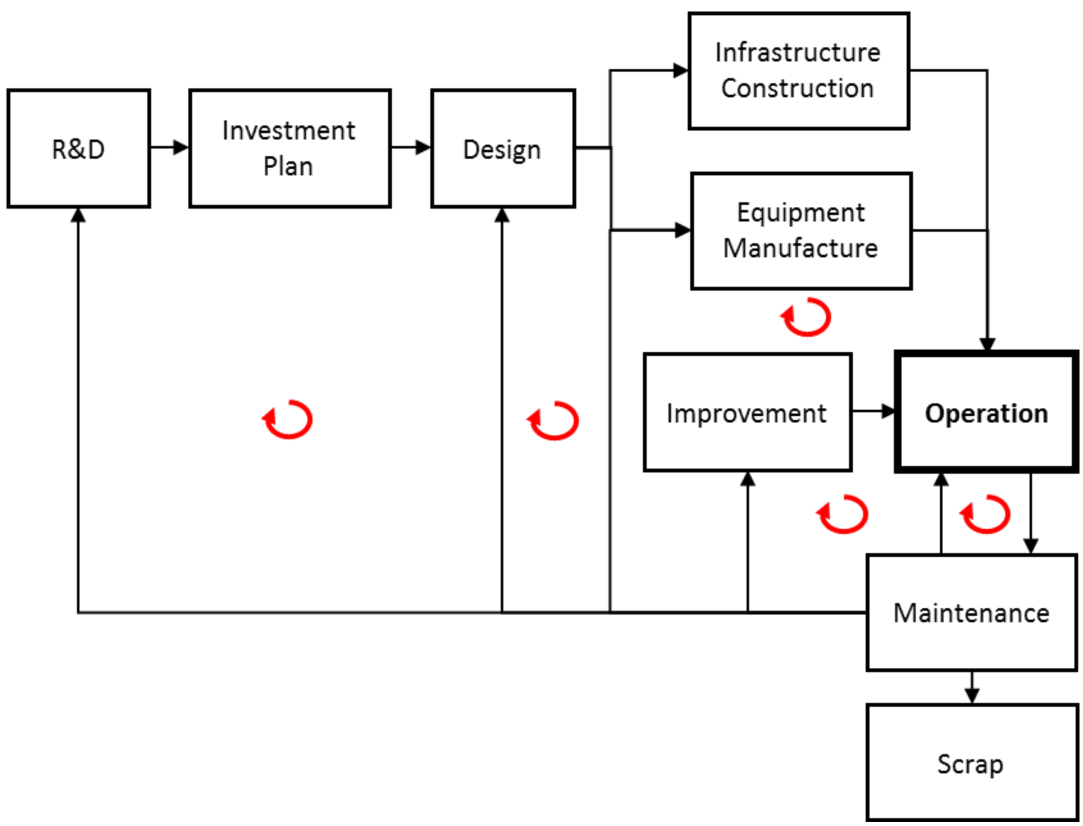


Figure 2.5 Lifecycle of HSR Subsystems

2.3.3 Comparison with Conventional Rail

The biggest difference between HSR and conventional rail is, of course, the operating speed of trains. This simple fact, however, has induced significantly different approaches mainly in safety design. Modern railway systems prevent train collisions or derailments by implementing signals and have drivers comply with signal indications. In conventional rail, where the operating speed is not so high, drivers can see wayside signals and apply brakes when they find stop signal indications. In addition, if drivers find some obstructions in front of them, they can usually apply emergency brakes and stop trains before collision since the braking distance is relatively short. In HSR, however, it is difficult for drivers to confirm wayside signal indications due to the high speed. Moreover, the braking distance becomes significantly longer, so it is too late to apply brake only after drivers visually notice hazards. For example, the maximum distance at which a driver can notice obstacles is only about 600m, but it takes about 4km to stop a train if the train runs at 300km/h.

Therefore, in HSR, systems to prevent train collisions without wayside signals are developed and implemented. Such systems are often called as Automatic Train Control (ATC) or Automatic Train Protection (ATP) systems. Figure 2.6 shows the overview of Japanese ATC system [16]. The positions of preceding trains are detected by track circuits and transmitted to following trains. Following trains use these data and other inputs such as track conditions (e.g. curves, gradients) or weather and calculate the “braking curves”, virtual speed limits with respect to running locations. Drivers need to comply with these braking curves, and automatic brakes are applied if train speeds exceed them.

In Europe, each country has developed its own signaling systems independently, such as LZB in Germany and TVM in France. Figure 2.7 shows the overview of these two systems [17]. The information of braking distance is periodically transmitted to each train by trackside vital computers or track circuits, so the principle of systems are the same as the Japanese ATC, though detailed specifications of subsystems are different. These days, there is a growing trend to standardize European signaling systems to enhance cross-border interoperability. The EU formed the European Rail Traffic Management System (ERTMS), and European countries and some other countries such as China, Saudi Arabia and Turkey [18] are gradually replacing their own signaling system to deploy ERTMS. County-specific HSR systems such as LZB and TVM are projected to be overwritten by ERTMS in the future.

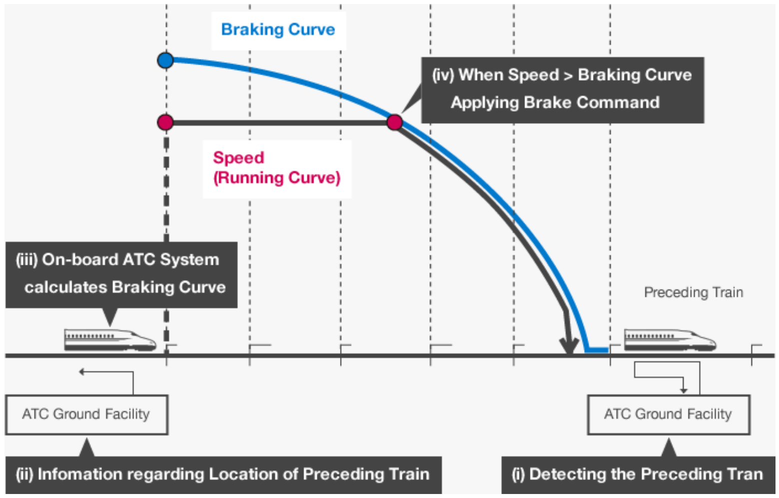


Figure 2.6 Overview of ATC

(Source: International High Speed Rail Association)

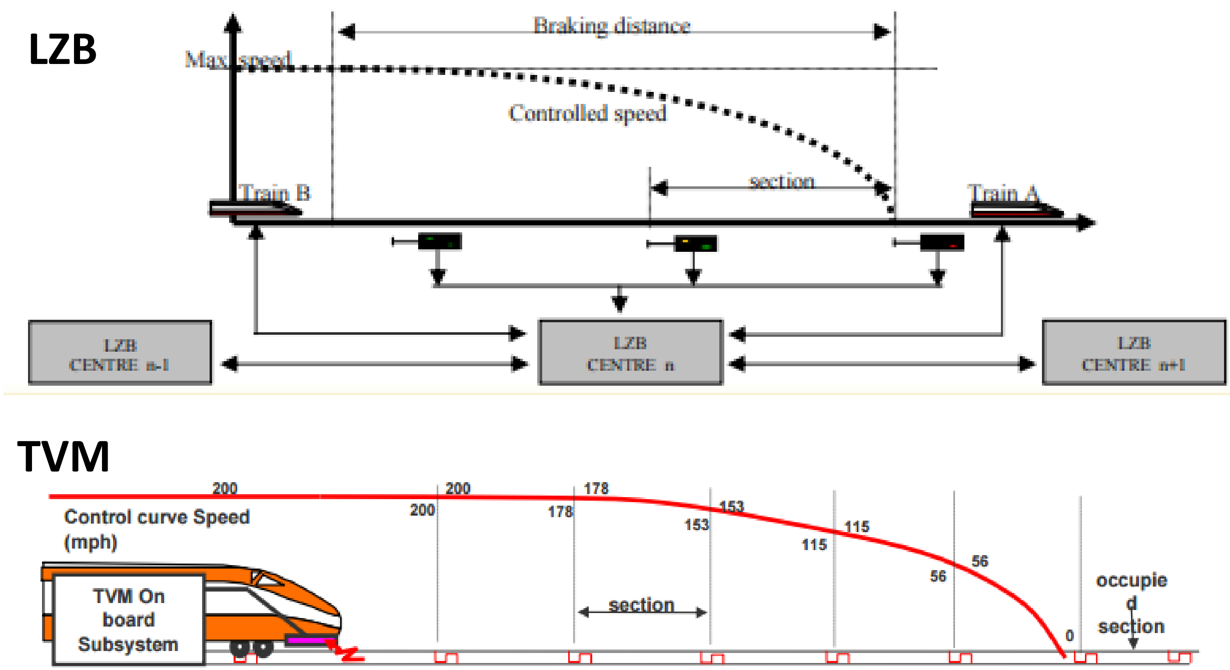


Figure 2.7 Overview of LZB, TVM

(Source: Casale, 2010)

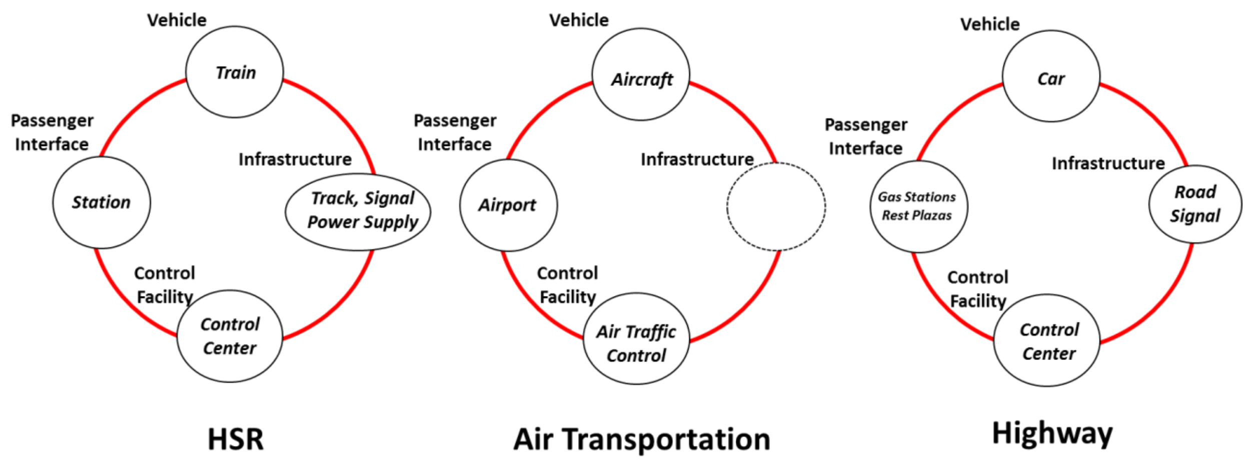
2.3.4 Comparison with Other Transportation Modes

In Section 2.3.2, HSR was divided into several forms to consider transferred operands in its operation. The operation of HSR and other passenger transportation systems can be also divided into several subsystems by their functions. One way for this division is to take vehicles, passenger interfaces, infrastructures and control facilities. In HSR, from Figure 2.4, rolling stock, stations and control centers correspond to vehicles, passenger interfaces and control facilities respectively, while tracks, power supplies and signals are taken as infrastructures.

Figure 2.8 shows the comparison of subsystems and their ownerships in HSR, air transportation and highway systems. In air transportation, there is no infrastructure needed between origin and destination except for Air Traffic Control (ATC). In the highway system, gas stations and highway rest plazas take a role of passenger interfaces, and traffic control centers functions as control facilities in some areas. The emergence of new technology such as autonomous vehicles can change these conventional structures.

Regarding ownership distribution of subsystems, HSR adopts either a vertical integration or a vertical separation, while air transportation and highway system usually adopt vertical separation. In vertically integrated HSR, all subsystems are owned and operated by a single organization. For example, in the Tokaido Shinkansen, JRC operates all HSR train services and owns relevant infrastructures. In vertically separated HSR, train operators pay usage fees to infrastructure and station managers to obtain access to them. Most of European HSR systems and part of the Northeast Corridor in the US (New Haven Line) are examples of vertical separation. This framework is similar to air transportation where airlines pay landing fees to airports or highway systems where car drivers pay tolls to states or other owners. One significant difference in vertical separation between HSR and other modes is that the number of train operators entering the same markets is much smaller in HSR than the number of airlines and cars. For example, Europe is the major HSR market where the vertical separation policy is adopted, but Italy is the only market where multiple HSR operators (Trenitalia and NTV) coexist and compete in the same corridor. In other countries such as France, Germany and Spain, one dominant train operator such as SNCF, DB Fernverkehr and AVE provides most of HSR services, even after deregulation which allowed qualified new train operators to enter the existing HSR markets.

This is mainly because infrastructure is fixed in the railway industry. In air transportation, eligible combinations of O-D pairs significantly increase as the number of airports increases, since there’s no physical infrastructure needed between airports. This enables new entrants to pursue niche markets which large operators do not serve, and in many cases intra-modal competition exists among carriers. In HSR, on the other hand, quite extensive, fixed infrastructures such as tracks and signals are required between stations. This prevents generating flexible O-D pairs and makes it difficult for new entrants to find profitable markets to be pursued. As a result, only few instances of intra-modal competition have been achieved so far.



Transportation Mode	Example	Vehicle		Passenger Interface		Infrastructure		Control Facility	
		Subsystem	Owner	Subsystem	Owner	Subsystem	Owner	Subsystem	Owner
High Speed Rail	Tokaido Shinkansen	Rolling Stock	CJR	Station	CJR	Track Signal Power Supply	CJR	Control Center	CJR
	ICE		DB Fernverkehr		DB Station&Service		DB Netz		DB Netz
Air Transportation	US air transportation	Aircraft	Airlines	Airport	Local Authorities	-		Air Traffic Control	FAA
Highway	Interstate Highway	Car	Car owners	Gas Station Service Plaza	States Private Fund	Road Signal	States	Control Center	DOT

Figure 2.8 Comparison of Subsystems and their Ownership in Different Transportation Modes

2.4 Conclusion

In this chapter, HSR was discussed in term of its definition, history, world trends and characteristics. HSR started its initial operation in limited countries, but in the 21st century HSR is rapidly expanding into new regions where surging travel demand has put pressure on existing intercity passenger transportation systems. The growth of Chinese HSR is one remarkable symbol of the worldwide expansion, and this trend of HSR globalization and diffusion is projected to continue for the foreseeable future.

The HSR system requires a sound integration of different heterogeneous subsystems with technical and non-technical aspects. This characteristic is also clear from the discussion in Section 2.3.2. Each subsystem simultaneously communicates and transfers operands in bidirectional ways, and such complex interactions of subsystems lead several system outputs such as safety or availability to be emergent properties. After the initial operation is launched, multiple feedback loops in its lifecycle properties let HSR be modified and upgraded incrementally.

In such improvement processes, “ilities” in HSR operation are also changed by endogenous and exogenous factors. In the next chapter, “ilities” are studied as an important concept to understand the dynamic behavior in long-term HSR operations.

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Chapter 3 Lifecycle Properties - *"ilities"*

In Chapter 2, the long lifecycle of HSR is mentioned as a part of its characteristics. In particular, from the discussion in Section 2.3.2, these two things can be said for HSR system properties.

- Interactions of subsystems in HSR operation are not simple or linear, so important system properties such as safety and reliability cannot be expressed as a pure aggregation of subsystems' properties; rather they emerge as a result of their complex interactions.

- After the initial HSR operation is launched, there exist multiple feedback loops among various phases of the system lifecycle such as design, operation and maintenance. These feedback loops let each subsystem in HSR be improved incrementally, based on current operating conditions. Therefore, system properties in HSR operation are continuously altered from their initial conditions.

These insights suggest that important system properties in HSR should be always monitored and maintained properly, and that appropriate design and monitoring of lifecycle properties, or "ilities", is an important factor to achieve long-term successful operation. In this chapter, definition of "ilities" is at first introduced, and then its relevance to HSR is discussed. In this chapter, about HSR and "ilities", a literature review in various related academic fields and the study of practical trends in industrial levels are conducted.

3.1 Definition

As a system becomes large, complex and long-lasting, and environmental changes in surrounding technologies and markets become rapid [19] , system properties to cope with the dynamic change of exogenous circumstances and the system itself have become more and more important. Such non-traditional design criteria (e.g. flexibility, reliability and sustainability) are clearly different from traditional static functional requirements (e.g. speed, strength, power). Such criteria are often called as lifecycle properties or "ilities". McManus et al. [20] considered some "ilities" as "system properties that specify the degree to which systems are able to maintain or even improve function in the presence of change", and pointed out that today they are increasingly recognized as critical system properties for successful programs.

de Weck et al. [21] defined "ilities" as "desired properties of systems that often manifest themselves after a system has been put to its initial use". That is, "ilities" are long-term, life-cycle system attributes which emerge after systems are turned on. They are often referred to as non-functional requirements, since "ilities" represent not "what the system should do", but "how the system behaves". Regarding this point, de Weck et al. [21] also stated that "'ilities' are not the primary functional requirements of a system's performance, but typically concern wider system impacts with respect to time and stakeholders than embodied in those primary functional requirements".

Compared to functional requirements, definitions of each "ility" are often ambiguous. Ross et al. [22] pointed out that "ilities" are often colloquial and contain polysemy and synonymy, which makes it challenging to develop clear semantics of "ilities". Table 3.1 shows examples of some "ilities" defined in an approach to seek their means-ends hierarchy [23]. In this research, clear definitions of "ilities" relevant to HSR operation are important for coherent discussion, so definitions of such "ilities" are provided in Section 3.3.

These days, more and more "ilities" are being considered as key properties in complex system design, but in many cases they are treated individually. In order to consider tradeoffs or interdependency between different "ilities", it is important to consider the relationships amongst "ilities". Several approaches are done descriptively and prescriptively. As a descriptive approach, de Weck et al. [21] surveyed the co-occurrence of "ilities" in the literature and on the Internet. Figure 3.1 shows the graphical representation of such co-occurrence. Widths of connections infer the relevance of different "ilities". On the other hand, Ross et al. [22] focused on changeability-type "ilities" (e.g. changeability, robustness and flexibility), and designed a general statement with several parameters (e.g. cause, context and agent) to differentiate such "ilities". Figure 3.2 shows the template of the general statement and its application to identify semantic bases of "ility" labels.

Table 3.1 Examples of "ilities" Definition

Ility Name	Definition ("ability of a system…")
adaptability	to be changed by a system-internal change agent with intent
agility	to change in a timely fashion
changeability	to alter its operations or form, and consequently possibly its function, at an acceptable level of resources
evolvability	design to be inherited and changed across generations (over time)
extensibility	to accommodate new features after design
flexibility	to be changed by a system-external change agent with intent
interoperability	to effectively interact with other systems
modifiability	to change the current set of specified system parameters
modularity	degree to which a system is composed of modules (not an ability-type ility)
reconfigurability	to change its component arrangement and links reversibly
robustness	to maintain its level and/or set of specified parameters in the context of changing system external and internal forces
scalability	to change the current level of a specified system parameter
survivability	to minimize the impact of a finite duration disturbance on value delivery
value robustness	to maintain value delivery in spite of changes in needs or context
versatility	to satisfy diverse needs for the system without having to change form (measure of latent value)

(Source: de Weck et al., 2012)

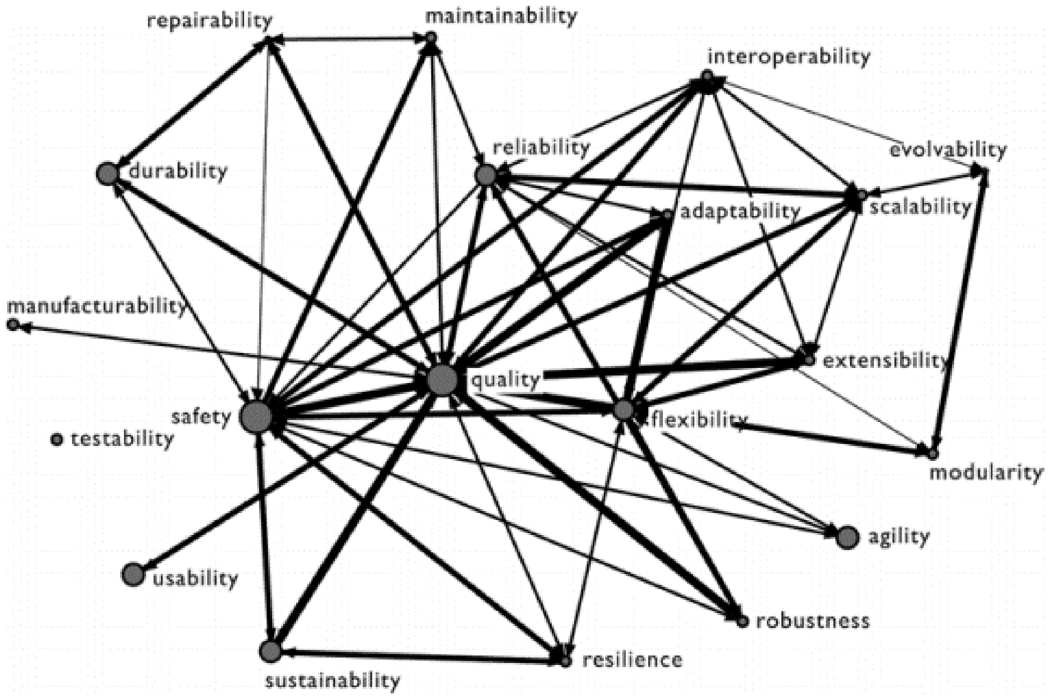
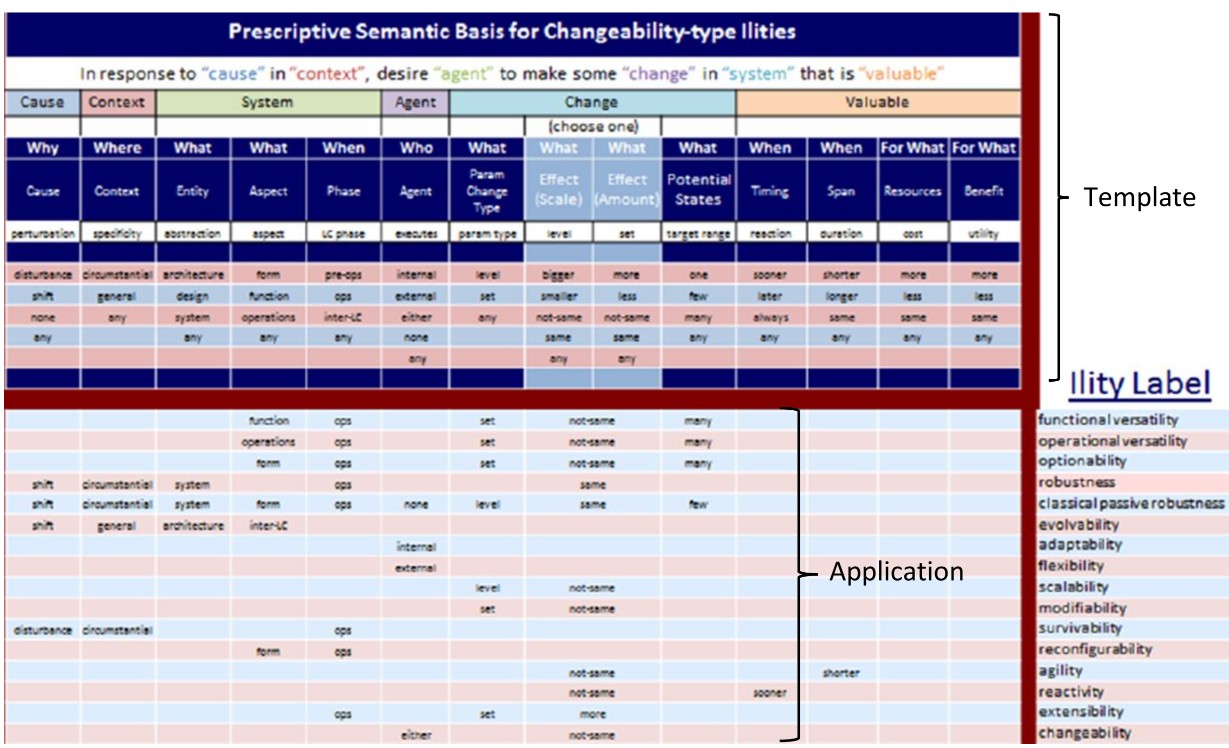


Figure 3.1 Co-occurrence of "ilities" in the Literature

(Source: de Weck et al., 2011)



Prescriptive Semantic Basis for Changeability-type Ilities

In response to "cause" in "context", desire "agent" to make some "change" in "system" that is "valuable"

Cause	Context	System			Agent	Change				Valuable				
							(choose one)							
Why	Where	What	What	When	Who	What	What	What	What	When	When	For What	For What	
Cause	Context	Entity	Aspect	Phase	Agent	Param Change Type	Effect (Scale)	Effect (Amount)	Potential States	Timing	Span	Resources	Benefit	
perturbation	specificity	abstraction	aspect	LC phase	executes	param type	level	set	target range	reaction	duration	cost	utility	
disturbance	circumstantial	architecture	form	pre-ops	internal	level	bigger	more	one	sooner	shorter	more	more	
shift	general	design	function	ops	external	set	smaller	less	few	later	longer	less	less	
none	any	system	operations	inter-LC	either	any	not-same	not-same	many	always	same	same	same	
any		any	any	any	none		same	same	any	any	any	any	any	
					any		any	any						
														Ility Label
			function	ops		set	not-same		many					functional versatility
			operations	ops		set	not-same		many					operational versatility
			form	ops		set	not-same		many					optionability
shift	circumstantial	system		ops			same							robustness
shift	circumstantial	system	form	ops	none	level	same		few					classical passive robustness
shift	general	architecture	inter-LC											evolvability
					internal									adaptability
					external									flexibility
						level	not-same							scalability
						set	not-same							modifiability
disturbance	circumstantial			ops										survivability
			form	ops										reconfigurability
							not-same				shorter			agility
							not-same			sooner				reactivity
				ops		set	more							extensibility
					either		not-same							changeability

Figure 3.2 Semantic Bases for Changeability-type "ilities"

(Source: Ross et al., 2012)

3.2 HSR and "ilities"

3.2.1 Literature Review

There are various approaches to think about HSR "ilities" in the academic field. de Weck et al. [21] conducted a general prevalence analysis of "ilities" by surveying how frequently they have been used in journal articles and on the Internet. The result shown in Figure 3.3 suggests that classic "ilities" such as quality and safety are still prevalent, while many new "ilities" have emerged as systems have become more and more complex. In the same way, a prevalence analysis of HSR "ilities" is conducted to see what kind of "ilities" are frequently considered in the HSR research domain[1]. As research engines for literature, Google Scholar [24], Science Direct [25] and Engineering Village (Compendex, Inspec and NTIS database) [26] are used. In addition to 20 "ilities" chosen in [21], some "ilities" relevant to HSR operation (e.g. availability, profitability, productivity, efficiency) are also taken into account.

Figure 3.4 shows the result of the prevalence analysis of HSR "ilities". The raw data of this figure is shown in Appendix B. The general trend of 20 "ilities" is similar to Figure 3.3. Quality and safety are again the most prevalent "ilities", which shows that the service quality and safety have been on top priority in successful HSR operation for a long time. One notable difference between general prevalence and HSR one is that interoperability and sustainability stand out in Figure 3.4 compared to Figure 3.3. Interoperability is a key issue when HSR is shared with conventional rail networks, or different HSR systems are operated internationally like European case. Sustainability is related to HSR's environmental strength with low carbon emission. Moreover, additional "ilities" such as availability, profitability, productivity, efficiency and effectiveness show similar levels of prevalence as quality, reliability, safety and flexibility, which suggests that these "ilities" are also closely related to HSR.

Studies of "ilities" in HSR operation can be roughly divided into a microscopic approach and a macroscopic approach. The microscopic approach usually focuses on specific technical or operational aspects of HSR such as track, signaling, rolling stock, time table and so on, and studies how to utilize such components to design / improve / optimize specific "ilities" such as quality, safety, reliability and maintainability. Such studies are closely related to the design of HSR subsystems. The macroscopic approach, on the other hand, captures HSR as a whole system, and considers its output or performance in a broader context with external factors such as stakeholders, governments, regulations, institutions and so on. "Ilities" such as safety, reliability, interoperability, availability, profitability, productivity, efficiency

[1] Keywords for searching, "high speed rail" and "ilities" (with double quotations) are used with an AND search Boolean operator to avoid picking up non-relevant results to HSR.

and so on are relevant to this standpoint. This thesis generally tries to capture "ilities" in a macroscopic point of view, and conducts literature review of HSR "ilities" from this perspective.

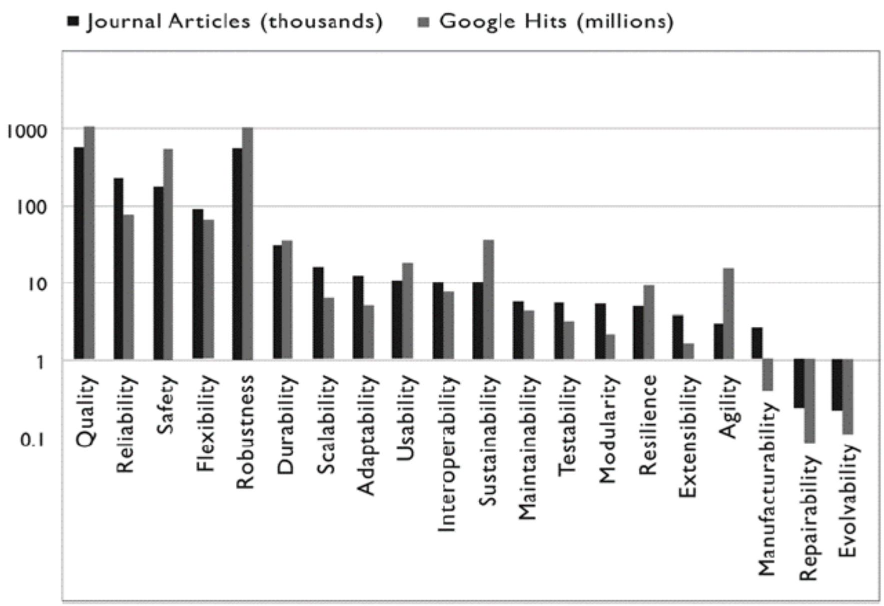


Figure 3.3 Prevalence Analysis of "ilities"

(Source: de Weck et al. 2011)

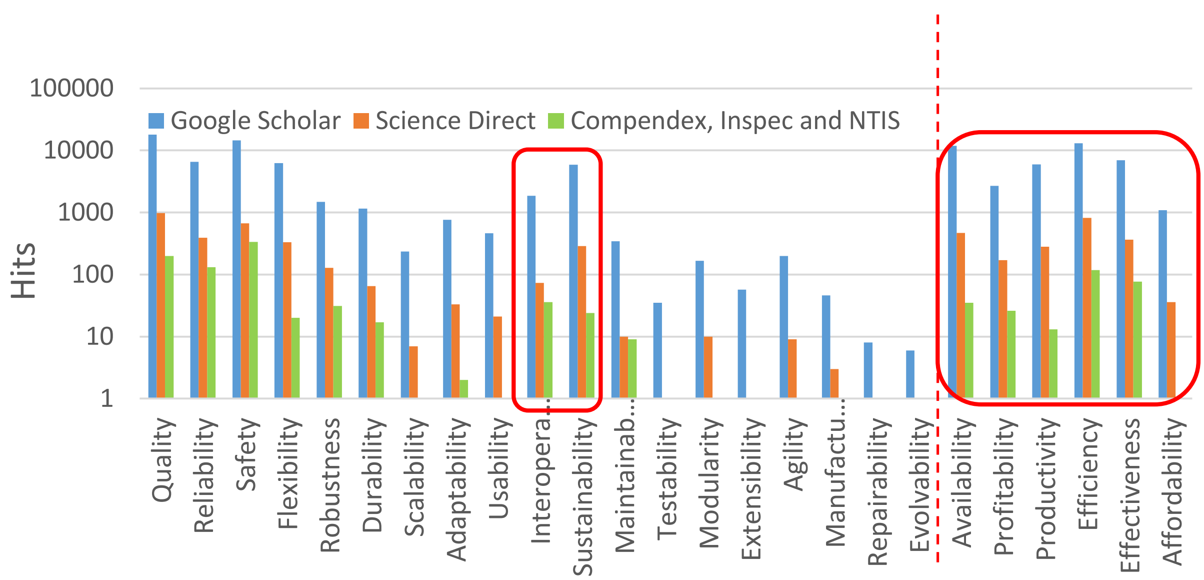


Figure 3.4 Prevalence of HSR and "ilities" in the Literature

3.2.1.1 Safety

Safety has been one of the most important "ilities" in HSR operation. As the example of signaling systems described in Section 2.3.3 demonstrates, HSR are designed to avoid accidents rather than mitigate them, and so HSR is the safest transportation mode together with air transportation. Still, HSR operation contains various technical subsystems and complex institutional interactions, so appropriate design of them is indispensable to maintain high levels of safety.

Kawakami [27] used STAMP (System Theoretic Accident Model and Processes) theory to analyze HSR safety in a high level where not just technical but also institutional and regulatory factors matter. He at first analyzed the HSR collision in Wenzhou, China in 2011 to find systemic factors contributing to the accident, and applied insights from that analysis to consider potential systemic hazards in the future HSR in the US. Wang [28] proposed to use a "hierarchical network model" to consider safe HSR operation. He illustrated safety factors in HSR operation and their interactions and couplings to draw a hierarchical network model shown in Figure 3.5. He stated that the safety level of a system can be described by using "safety entropy", derived from uncertainties of safety factors and their propagations. Both papers share the common idea that safety is the emergent property resulting from the interactions of multiple subsystems, but Kawakami captured safety hazards qualitatively as a result of unsafe control actions, while Wang's approach was theoretical but rather quantitative in that he tried to formulate entropy as a metric for a lack of safety.

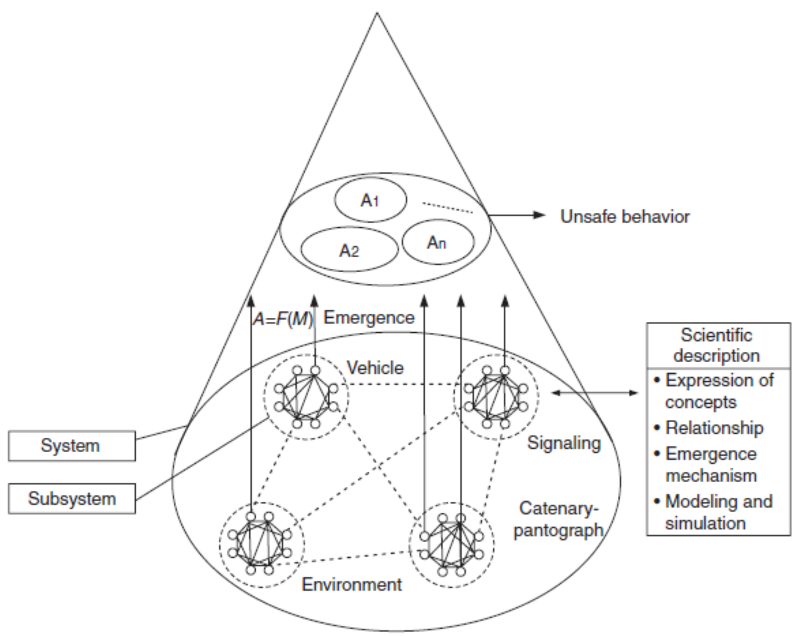


Figure 3.5 Hierarchical Network Model for Safe HSR Operation

(Source: Wang et al., 2011)

3.2.1.2 Productivity, Efficiency and Effectiveness

Productivity, efficiency and effectiveness are often discussed as metrics to quantify how a HSR system provides outputs (e.g. ridership, revenue) compared to inputs (e.g. rail network, fleet, and cost). Such papers can be often categorized as using a macroscopic approach, since they try to capture inputs and outputs as performance indicators of overall HSR system operation, where HSR is treated more or less as a black box.

Doomernik [29] used Network Data Envelopment Analysis (NDEA) and Malmquist Productivity Index (MPI) to benchmark dynamic change of HSR systems efficiency in Europe and Asia. He divided the overall HSR efficiency into production efficiency (how HSR capital efficiently generates service capacity such as train-miles or seat-miles) and service effectiveness (how service capacity effectively attracts passengers), and plotted their changes to compare different HSR systems performance, as shown in Figure 3.6. This figure reveals that Asian HSR as well as French HSR have performed well in these 6 years, while Italy, Germany and Spain have not. Archila [30] used Single Factor Productivity (SFP) to see how the productivity in the Northeast Corridor in the US had changed. He also estimated future productivity in the NEC by using HSR development plans of FRA and Amtrak. Sakamoto [3] also used SFP to see the difference of productivity before and after organizational restructuring of HSR in Japan and France, and showed that privatization or vertical separation of HSR operations positively affected their productivities.

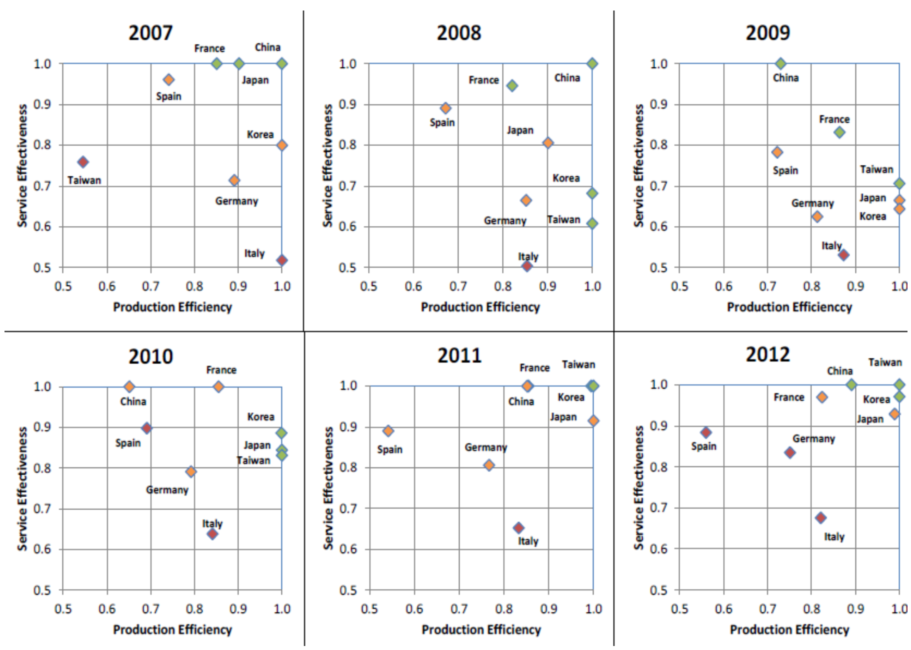


Figure 3.6 Benchmarking of HSR Performance

(Source: Doomernik, 2015)

3.2.2 Industrial Trends

In practical HSR operations, key stakeholders such as HSR operators, infrastructure managers, regulators, manufacturers and so on play their own roles to control HSR “ilities”. Thus, “ilities” are influenced by various factors such as operational procedures, regulations and manufacturing capabilities, and these factors differ by countries or enterprises. These days, “RAMS” has become commonly used as an international standard to evaluate and control key performances of railway systems. RAMS stands for Reliability, Availability, Maintainability and Safety, which are all key “ilities” contributing to service quality**.** In this idea, these “ilities” are somehow quantitatively evaluated[2] to satisfy requirements, with their relationships being considered. This approach is well aligned with the direction of this thesis which quantifies interactions of “ilities” in HSR operation. An overview of Railway RAMS is explained in this section, and it is used as a basis to select key “ilities” in this thesis.

3.2.2.1 Overview of Railway RAMS

The original idea of RAMS derives from reliability engineering practiced at NASA during the “Space Race” era. NPC250, the reliability-based program enacted in 1963, contributed to achieve high reliability in the Apollo program. DoD utilized this methodology and enacted MIL-STD785 in 1965, which enabled the expansion of reliability engineering to various fields as well as aerospace engineering. In the railway industry, US rail operators introduced the idea of RAMS in the mid-1970s and required US rolling stock manufacturers to comply with RAMS requirements. However, US manufacturers such as Budd and Pullman had trouble in complying with such requirements, and eventually it caused their decline. [31]

In Europe, after the inauguration of the European Union in 1993, the promotion of interoperability in railway networks and the privatization of train operations became a common trend in the European railway policy. This led privatized train operators to introduce RAMS requirements mainly in rolling stock procurements. As a result, the movement to formulate a common standard in railway systems engineering emerged. The European standard (EN50126 [32]) was enacted in 1999, and then the international standard (IEC62278 [33]) in 2002. These days, this international standard is becoming

[2] In IEC 62278, RAMS is mentioned as “The RAMS of a system can be characterized as a quantitative and qualitative indicator of the degree that the system can be relied upon to function as specified and to be both available and safe.” That is, RAMS cannot be 100% quantified since there are various qualitative systemic factors (mainly safety), but quantified metrics are used as key indicators of a systems’ capability.

widely used in Europe and other countries as a guideline to design and satisfy RAMS requirements in railway systems procurements.

In IEC62278, the relationship of "ilities" is indicated as Figure 3.7. Quality of service is influenced by Railway RAMS as well as other attributes (e.g. security, fare, frequency). Within RAMS, safety and availability are placed at the top of the hierarchy, which indicates that the satisfaction of reliability/maintainability requirements and well-controlled operation/maintenance procedures are necessary to achieve safety and availability.

One note here is that availability is more directly related to reliability and maintainability in terms of quantification. Although IEC62278 does not specify a particular method to specify RAMS requirements, IEC62278 Annex C suggests that several parameters of availability can be formulated from parameters of reliability and maintainability. Safety, on the other hand, is mainly derived from the evaluation of hazardous events and risks, which are emergent consequences of operation, maintenance and environmental conditions. In IEC62278, "unacceptable risk of harm" is thought as the combination of "the frequency of occurrence of a hazardous event" and "the consequence of the hazard". Table 3.2 shows the example of risk levels evaluation. "The frequency of occurrence" and "the consequence of the hazard" are divided into 6 and 4 categories, respectively, and whether risks are unacceptable or not is evaluated based on their combination. From these perspectives, these days RAM (reliability, availability and maintainability) and S (safety) are sometimes considered separately, though they are closely related with each other in principle. It is important to emphasize that reliability and safety are not synonyms.

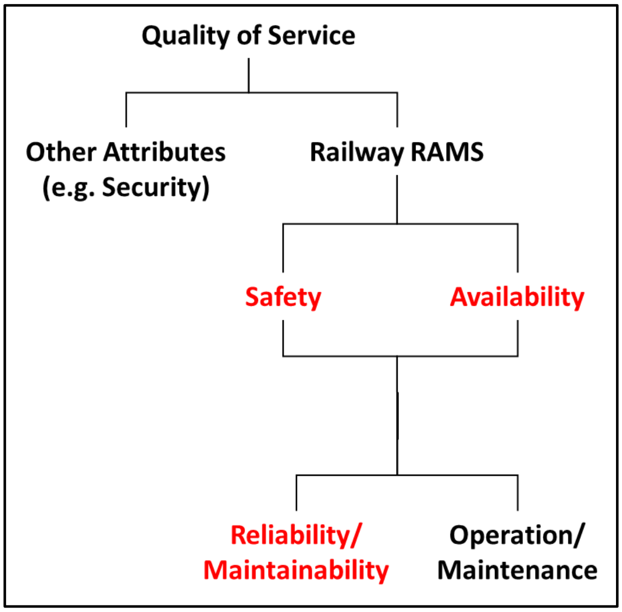


Figure 3.7 Relationship of Railway RAMS

(Source: IEC, 2002)

Table 3.2 Example of Risk Levels Evaluation

Frequency of Occurrence		Risk Levels			
Frequent	Likely to occur frequently	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Will occur several times	Tolerable	Undesirable	Intolerable	Intolerable
Occasional	Likely to occur several times	Tolerable	Undesirable	Undesirable	Intolerable
Remote	Likely to occur sometime in the system life cycle	Negligible	Tolerable	Undesirable	Undesirable
Improbable	Unlikely to occur but possible	Negligible	Negligible	Tolerable	Tolerable
Incredible	Extremely unlikely to occur	Negligible	Negligible	Negligible	Negligible
		Insignificant	Marginal	Critical	Catastrophic
		Consequences of Hazard			

Consequences of Hazard	To Persons/Environment	To Service
Catastrophic	Fatalities, multiple severe injuries major damage to the environment	
Critical	Single Fatality, severe injury significant damage to the environment	Loss of a major system
Marginal	Minor injury significant threat to the environment	Severe system(s) damage
Insignificant	Possible minor injury	Minor system damage

Risk Levels	Risk Reduction/Control
Intolerable	Shall be eliminated
Undesirable	Shall only be accepted when risk reduction is impracticalbe and with the agreement of the Railway Authority
Tolerable	Acceptable with adequate control and the agreement of the Railway Authority
Negligible	Acceptable without any agreement

(Adapted from IEC, 2002)

While specifying RAMS requirements, factors affecting RAMS need to be determined. Such factors are categorized into system, operation and maintenance conditions. Under each category there are multiple contributing factors, as shown in Figure 3.8. These factors and their interactions should be taken into account in considering RAMS requirements. Several factors such as systemic failures or human factors are sometimes difficult to apply in a purely reliability-based approach, and so a system-based approach is required to understand such qualitative factors.

The RAMS standard defines 14 phases of the railway system lifecycle as shown in Figure 3.9, and allocates general tasks, RAM tasks and S tasks into each life cycle phase. These tasks are iterative processes and conducted repeatedly until designed RAMS are satisfied requirements. In these processes, life cycle costs (LCC) associated with RAMS are considered. Mizoguchi [31] showed the processes to deal with RAM, S and LCC in RAMS activities as shown in Table 3.3. These processes suggest that RAM, S and LCC are closely related with each other, and can be systematically specified in the RAMS processes in the system lifecycle.

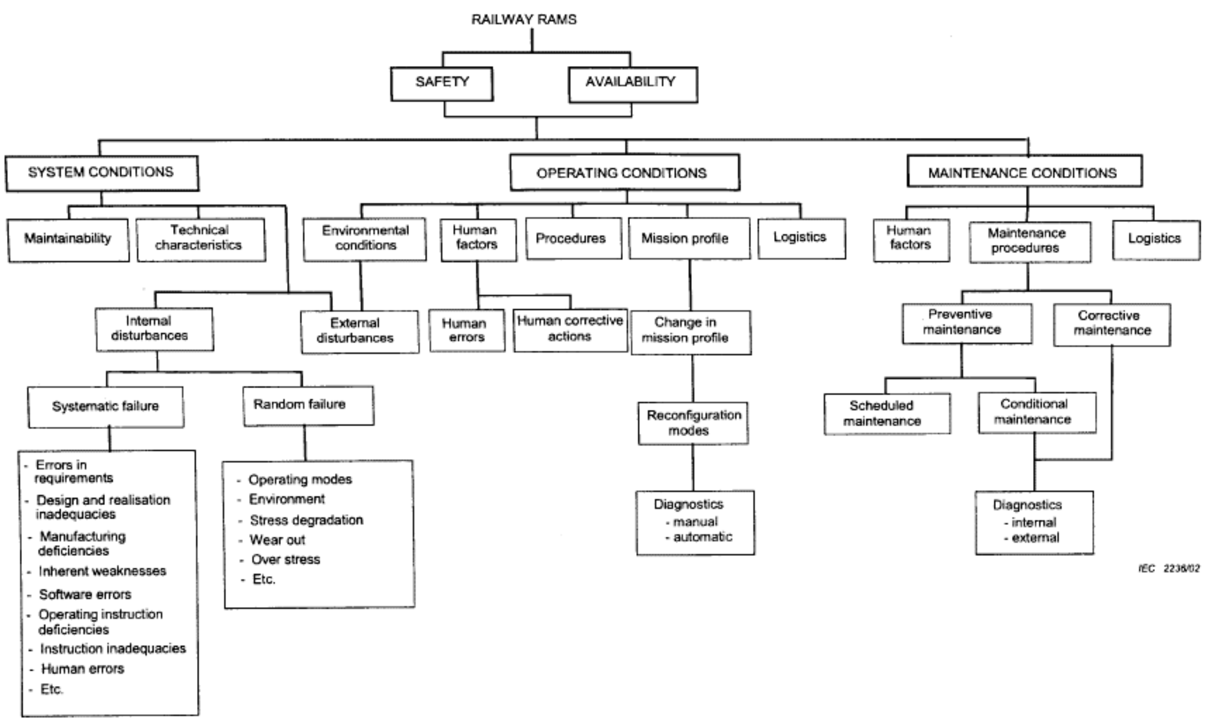


Figure 3.8 Factors Affecting Railway RAMS

(Source: IEC, 2002)

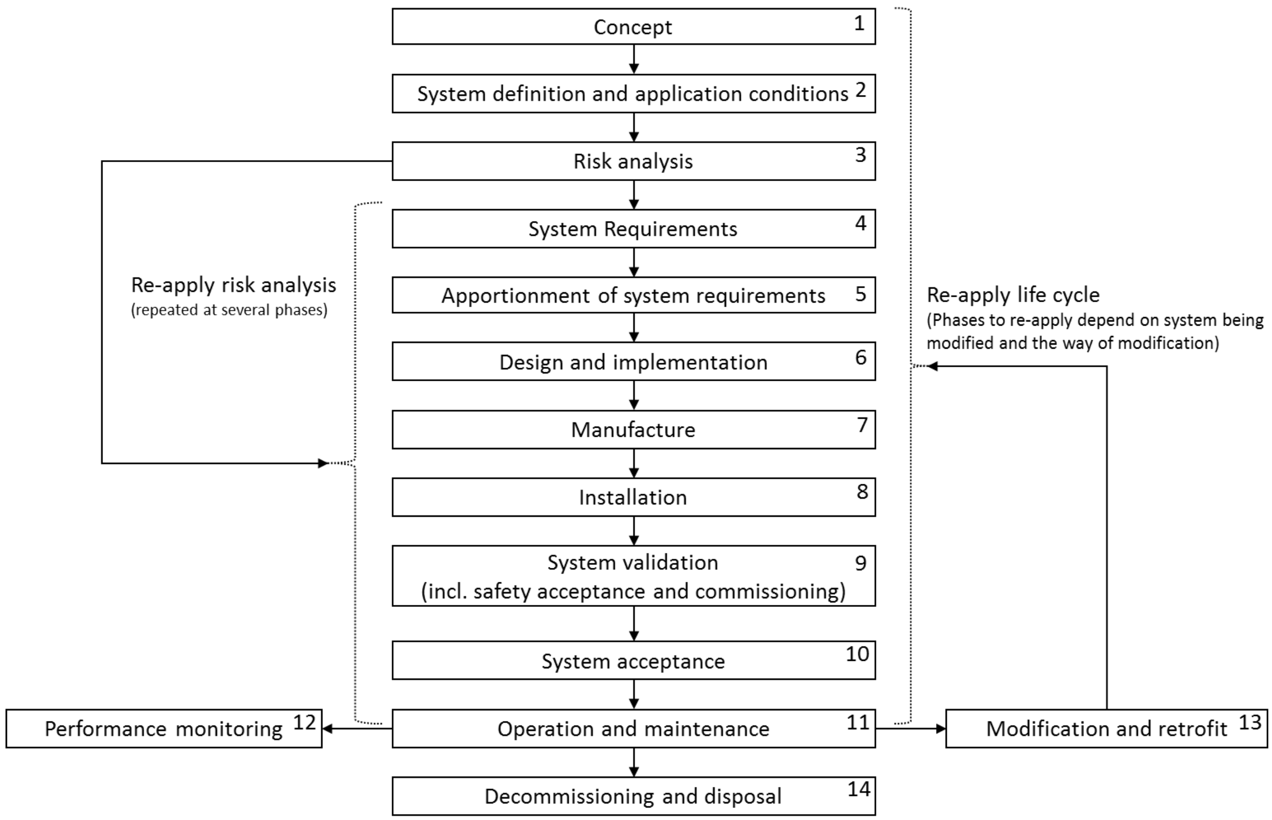


Figure 3.9 Railway System Lifecycle

(Adapted from IEC, 2002)

Table 3.3 Processes to Deal with RAM, S and LCC in RAMS Activities

No	Process
1	Evaluate reliability of a system or a product (R)
2	Based on reliability, evaluate availability and maintainability (RAM)
3	Evaluate safety and life cycle cost from RAM (S, LCC)
4	Specify requirements on RAM, S and LCC
5	Implement control cycle of RAM, S and LCC

(Adapted from Mizoguchi, 2006)

3.2.2.2 Application of RAMS to the "ilities" Study in this Thesis

As shown in the above section, the RAMS standard lets rail operators, infrastructure managers and manufacturers conduct RAMS activities to specify RAM, S and LCC of their systems or products. Based on this notion, in this thesis, **safety**, **availability** and **profitability** are selected as key "ilities" of HSR operation. The rationale for this selection is shown below:

- Safety and availability are at the highest position in RAMS hierarchy, since they are emergent properties resulting from system / operation / maintenance conditions. Also, they exist at the interface between HSR operators and passengers.
- Reliability and maintainability are also important "ilities" in HSR operation, but they can be considered as sub-ilities of availability in the sense of a means-ends hierarchy. This thesis applies a macroscopic approach, so the allocation of reliability and maintainability requirements to each subsystem is out of the scope.
- Profitability is the driver for well-controlled operation and maintenance, as well as a basis for capital investments. The evaluation of LCC is closely related to the long-term economic stability in the system lifecycle. Profitability also includes notions on the revenue side as well as the cost side.

This thesis aims to capture the HSR operation phase mainly from the standpoint of railway operators, so the definitions of each "ility" are slightly different from those in IEC62279 or other literature. To make the discussion in following chapters coherent, the definitions of these three "ilities" are explained in the next section.

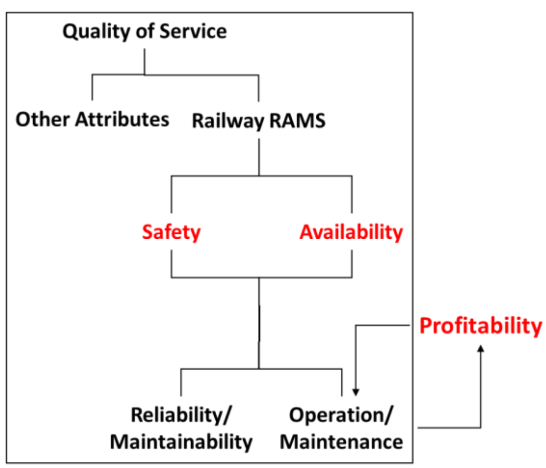


Figure 3.10 Key "ilities" in HSR Operation

(Adapted from IEC, 2002)

3.3 Key "ilities"

3.3.1 Safety

In the literature, safety is defined as

- "Freedom from unacceptable risk of harm" (IEC62278 [33])
- "Absence of accidents, where an accident is an event involving an unplanned or unacceptable loss" (Leveson [34])

The commonality in these two definitions is that they both treat safety as the state of being free from unacceptable consequences. Safety is often treated as synonyms with reliability (i.e. high safety ≒ high reliability), but Leveson [34] stated the differences between safety and reliability in that safety can be achieved by eliminating hazards, while reliability can be achieved by eliminating failures. She insists that there are many systems which are "safe but unreliable" or "unreliable but safe", and recommended to focus on the system level, not only the component level to deal with safety. IEC62278, or the RAMS standard originates from reliability engineering as shown in Section 3.2.2, but takes non-quantifiable elements into account in the assessment of safety.

In this thesis, safety is defined as below:
"<u>Absence of HSR accidents and incidents which generate unacceptable losses / damages for stakeholders</u>"

Stakeholders represent groups of people who may be involved in train accidents or incidents, such as passengers, railway employees and trespassers. Numbers related to fatality / injury and the amount of property damage can be measures of safety.

3.3.2 Availability

In the literature, availability is defined as

- "Ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided" (IEC62278 [33])
- "Probability that a system or component is performing its required function at a given point in time or over a stated period of time when operated and maintained in a prescribed manner" (Ebeling [35])

The RAMS standard is utilized by multiple stakeholders such as train operators, infrastructure managers and manufacturers, and availability for each player is defined differently. For example, highly available rolling stock cannot alone lead to highly available train operation, since other factors such as time tables, track layouts or operation control systems critically influence the availability of total railway operations. This research mainly focuses on the interface between train operators and passengers, so the design and allocation of availability to each subsystem at the manufacturing / operations level is not considered in detail.

In this thesis, availability is defined as below:
"Ability of HSR to provide passengers with their anticipated quality of transportation service"

This definition is close to train operators' perspective, but it is broader in that the passengers' point of view is taken into account. The primary function of transportation systems is to convey passengers from their origins to destinations. Availability is how HSR is capable of providing this primary function credibly. That is, in this thesis, availability is considered as a part of service quality of transportation, aside from soft aspects of service such as food, security and comfort. Also, external factors other than HSR transportation service itself such as connectivity to other modes or accessibility of stations are not taken into account. Service frequency, travel time, on-time performance, and average delay can be measures of availability.

3.3.3 Profitability

Since the railway industry is an industry requiring significant fixed capital, enough operating costs and capital investments are necessary to maintain HSR operation quality at an acceptable level. The word "profit" usually refers to the difference between revenue and cost. In capital-intense industries such as HSR, not only operating costs but also capital expenses or depreciation need to be considered to evaluate long-term profitability. Poor profitability can lead to the shortage of capital investments, which affects other "ilities" in future HSR operation.

In this thesis, profitability is defined as below:
"Financial capability of HSR operators / owners to provide good, stable transportation service"

In vertically integrated operations, HSR operators and infrastructure managers are identical and their financial capability (although subsidies or investments from external organizations are sometimes needed) is the main focus of profitability. In vertically separated operation, on the other hand, different HSR operators and infrastructure managers are involved in HSR operation, so their conditions and interactions need to be taken into account individually. Operating revenues / costs / profits and capital expenditures all contribute to profitability.

3.4 Conclusion

In this chapter, at first the definition of “ilities” is considered. “Ilities” represent not “what the system is” but “how the system behaves after it is turned on”, and they have been recognized as important properties for complex systems emerging these days. The definition and differentiation of “ilities” is important in order to understand their meaning and quantitative determination precisely.

Many approaches are conducted to study HSR “ilities” from macroscopic and microscopic perspectives in academic research fields. This thesis mainly focuses on a macroscopic approach to grasp overall performance in HSR operation, and relevant studies are introduced in the literature review section.

In the railway industry, RAMS has been gradually accepted as a standard to evaluate and control railway systems performance in the long term. Based on the idea of RAMS, safety, availability and profitability are selected as key “ilities” in HSR operation. Definitions of these three “ilities” are clarified to support the later case studies.

Beginning in the next chapter, two cases are selected to study the three key HSR “ilities” (safety, availability and profitability) provided in this chapter. In Chapter 4 and Chapter 5, the characteristics of these cases are studied in the context of competitive intercity passenger travel markets (Chapter 4: Market overview and competitive modes, Chapter 5: HSR). These studies suggest trends of HSR systems in these markets over a period of 10-20 years, and insights are used as inputs in a System Dynamics model in Chapter 6.

Chapter 4 Market Study on HSR cases

In Chapter 4, Chapter 5 and Chapter 6, the Tokaido Corridor in Japan and the Northeast Corridor in the US are chosen as case studies to analyze interactions of "ilities" in HSR operation. In this chapter, these two corridors are studied as large intercity passenger travel markets with intermodal competition. In addition to the overview of modal splits in both corridors, the trend of air transportation is analyzed as the main competitive and relevant transportation mode. In various annual data, not the calendar year but the fiscal year (FY) is used. The definition of FY differs in Japan and the US as shown below:

Japan: FY is the year which starts in April. e.g. FY2010: 2010.4 – 2011.3
US: FY is the year which ends in September. e.g. FY2010: 2009.10 – 2010.9

4.1 The Tokaido Corridor

4.1.1 Overview

The Tokaido Corridor is located in the central part of Japan, on the main island of Honsyu, It connects main Japanese cities such as Tokyo, Yokohama, Shizuoka, Nagoya, Kyoto and Osaka, as shown in Figure 4.1. This corridor passes through the most densely populated part of Japan, and major economic activities are conducted within this corridor. Prefectures located in the Tokaido Corridor represent only 19% of Japanese land area, but represent 57% of the entire Japanese population and 62% of Japanese GDP. Especially, the Tokyo–Osaka market is the biggest intercity passenger transportation market in Japan, and various transportation modes such HSR, air transportation and highways have been developed with high priority to serve this corridor.

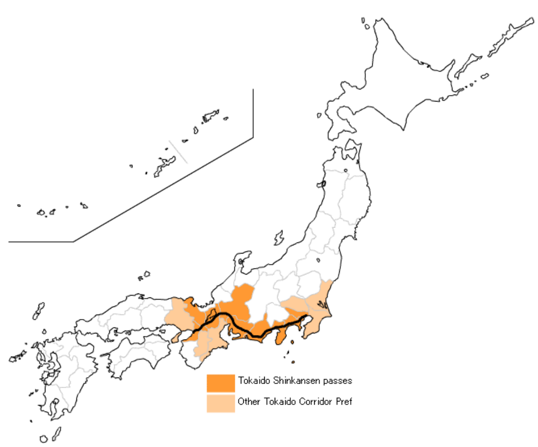


Figure 4.1 Geographical Location of the Tokaido Corridor

4.1.2 Modal Split of Intercity Travel in the Tokaido Corridor

The Tokaido Corridor connects the three largest metropolitan areas in Japan, whose central cities are Tokyo, Nagoya and Osaka respectively. These three areas contain 93% of the population of the Tokaido Corridor shown in Figure 4.1, so travel demand from one metropolitan area to others accounts for a large fraction of intercity passenger travel demand within the Tokaido Corridor. Tokyo, Nagoya and Osaka metropolitan areas are defined as Table 4.1. Geographical location of these three regions is shown in Figure 4.2.

Table 4.1 Definition of Three Major Metropolitan Areas

Metropolitan Area	Tokyo	Nagoya	Osaka	Sum	Japan
Prefectures	Tokyo Kanagawa Saitama Chiba Ibaraki	Aichi Gifu Mie	Osaka Kyoto Hyogo Nara		
Area [$mile^2$]	7,590	8,328	7,185	23,103 (**16%**)	145,925
2010 Population [36]	38,588,334	11,346,216	18,490,198	68,424,748 (**53%**)	128,057,352
Fraction of Japanese GDP within areas	34%	10%	14%	**58%**	100%
HSR Distance from Tokyo [mile]	0	227.4	343.4	-	-

(Source: MIC, 2010)

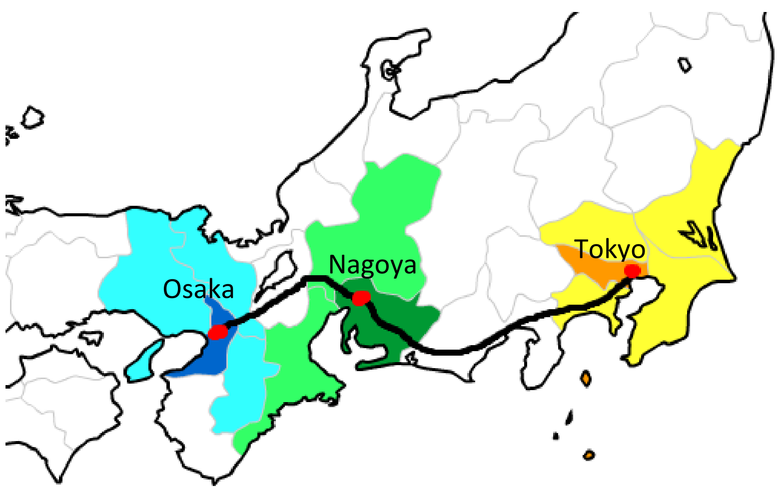


Figure 4.2 Definition of Tokyo, Nagoya and Osaka Metropolitan Area
(Black Line: The Tokaido Shinkansen)

The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) publishes the travel liquidity survey which shows annual inter-prefecture passenger trips in different modes (auto, rail, air and ship) [1]. Figure 4.3 shows modal splits in three O-D markets (Tokyo-Osaka, Tokyo-Nagoya and Nagoya-Osaka) in FY2013. The Tokyo-Osaka market represents the largest ridership, since these two areas are the two biggest economic blocks in Japan. Japan Railway groups (JR) captures 80% share of this market by mostly JRC's HSR service, while air and auto capture 16% and 4%, respectively. In the Tokyo-Nagoya market, air travel demand almost disappears, and JR captures 91% share. In the Nagoya-Osaka market, JR (HSR and conventional rail service) captures 58% share, while other rail operators take 32%. This is because these two areas are adjacent to each other (Mie Prefecture - Nara Prefecture, as shown in Figure 4.2), and another private rail operators (Kintetsu) provide conventional train services from Nagoya to Osaka via these prefectures. Their fare is cheaper than that of HSR, and serves a different region between Nagoya and Osaka.

In the Tokaido corridor, air transportation is the HSR's competitor only in the Tokyo-Osaka market. Figure 4.4 shows the long-term trend of modal share between rail and air in the Tokyo-Osaka market [1]. The rail share is pretty stable between 80%-85%, though the total number of annual trips has increased from 39.5 million in FY2000 to 49.5 million in FY2013. Rail and air both have grown steadily, while the economic recession depressed ridership in FY2007-2011 before the growth trend returned.

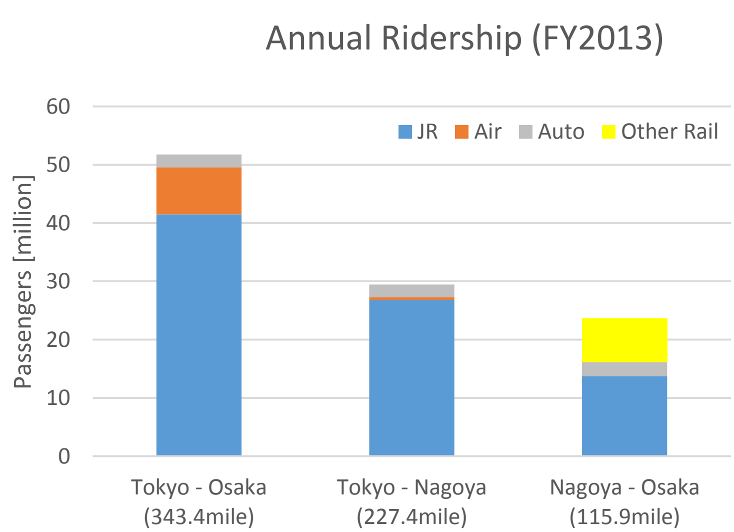
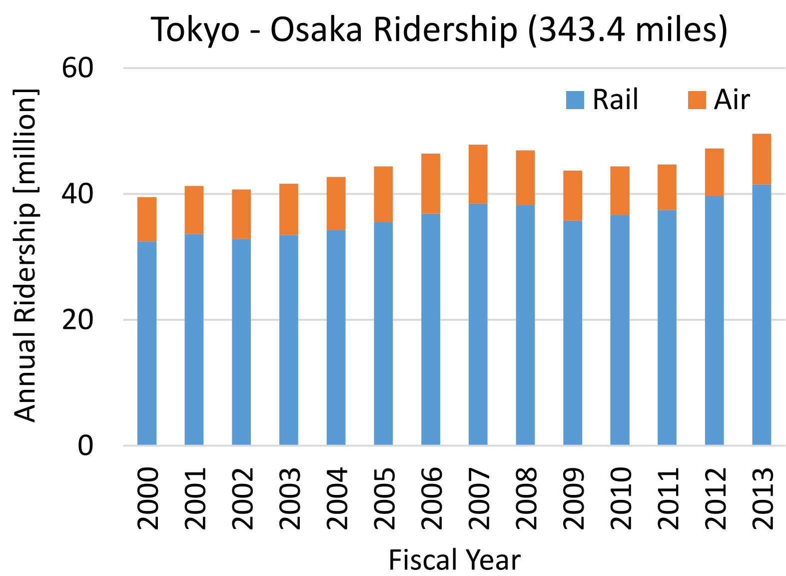


Figure 4.3 Annual Ridership in Three O-D Markets

(Source: MLIT)



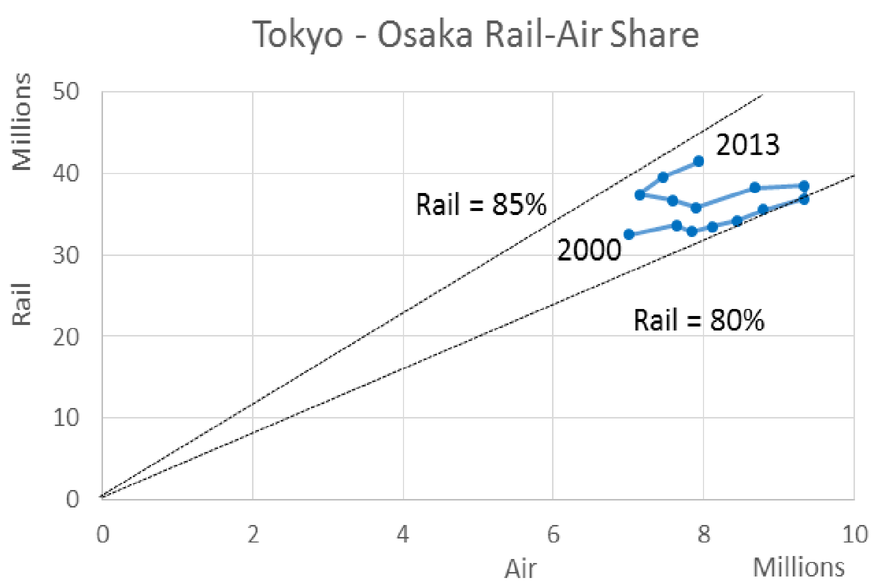


Figure 4.4 Rail-Air Share in Tokyo – Osaka Market

(Source: MLIT)

4.1.3 Air Transportation in the Tokaido Corridor

Figure 4.5 shows the daily frequency, the annual seat supply and the annual passengers in the Tokyo-Osaka air transportation system since 1992 [37]. In the Osaka metropolitan area, Osaka-Kansai international airport opened in 1994 and Kobe airport opened in 2005. Frequency, seat supply and passengers have increased since 1992, except in 2002 and 2007-2012 when economic recessions depressed travel demand. One note for the ridership data is that connecting passengers (e.g. ITM-NRT-JFK) are included in the number of riders, so the actual O-D demand between Tokyo and Osaka can be smaller than the ridership data in Figure 4.5.

The increase rate is larger in daily frequency than annual seat supply, which indicates that airlines have replaced large aircraft (e.g. Boeing 747) with smaller ones, and have provided more frequent services in each O-D. Indeed, the average seat supply per one flight has dropped from 487 in 1993 to 273 in 2014, as shown in Figure 4.6. The increased trend of seat supply and passengers are similar, which indicates that the average load factor has been relatively stable around 60%-70% (shown in Figure 4.6).

Regarding airports, more than half of the passengers in this market use the Tokyo Haneda-Osaka Itami shuttle services, while some passengers use distant international airports such as Tokyo Narita or Osaka Kansai. After the Kobe airport opened in 2005, some demand was induced or transferred from existing rail/air markets. Since 2011, new LCC entrants have been digging into the Tokyo Narita-Osaka Kansai market with lower fares than those of legacy carriers. In summary, there is robust air travel demand in the Tokaido Corridor, but it is coupled to passengers using the Tokyo, Osaka and Kobe airports for other domestic and international air travel.

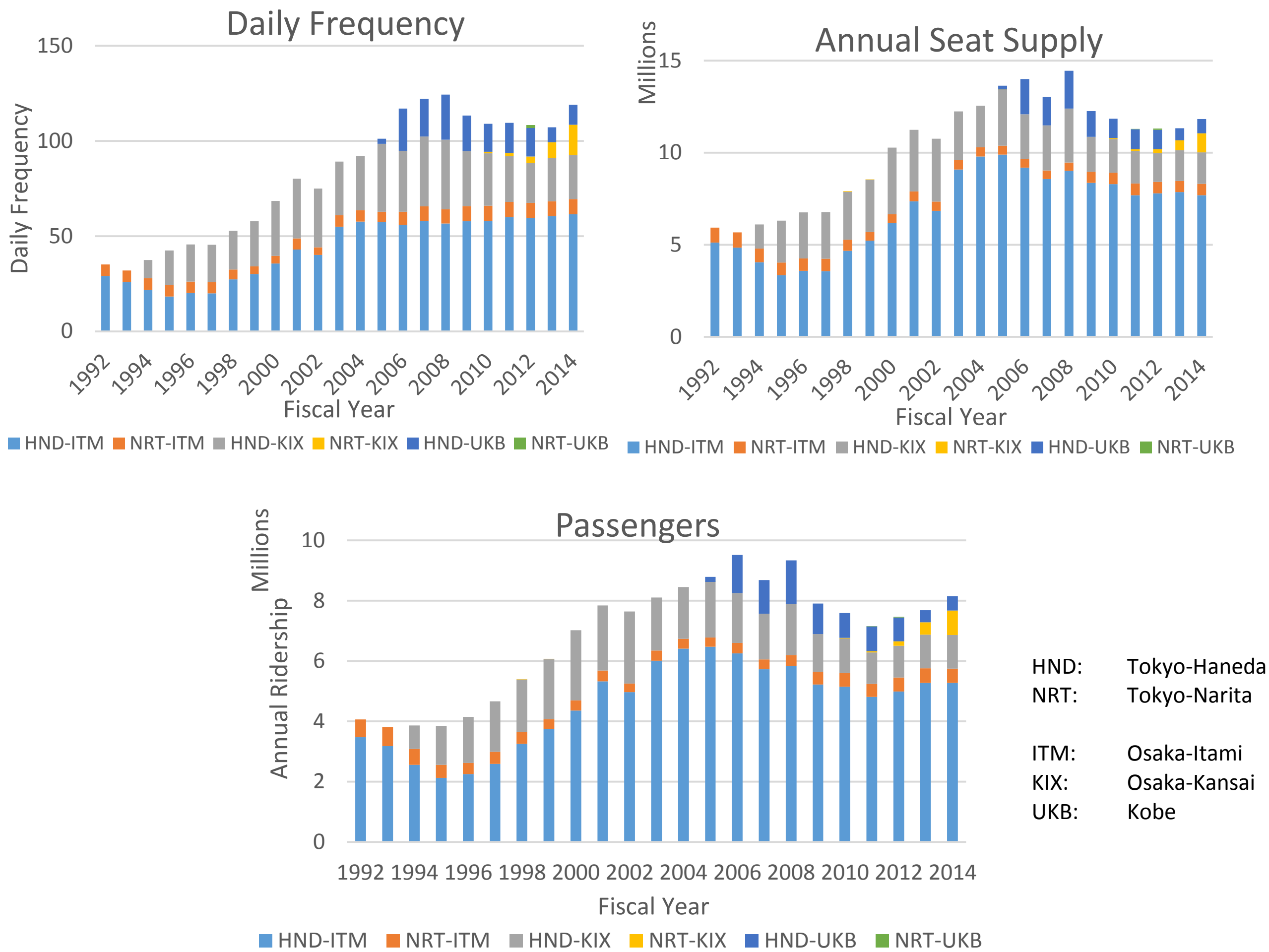


Figure 4.5 Air Transportation Trend in the Tokyo-Osaka Market

(Source: MLIT)

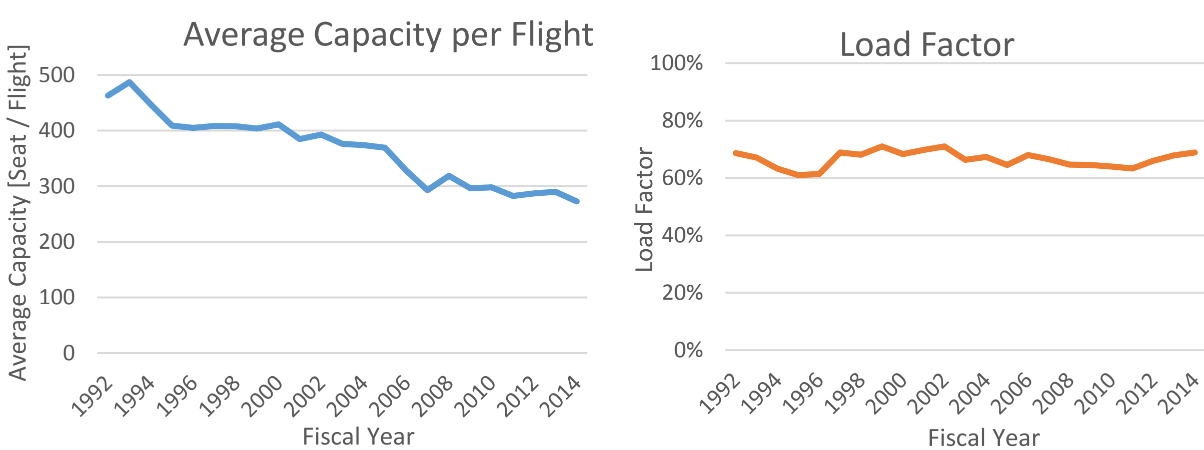


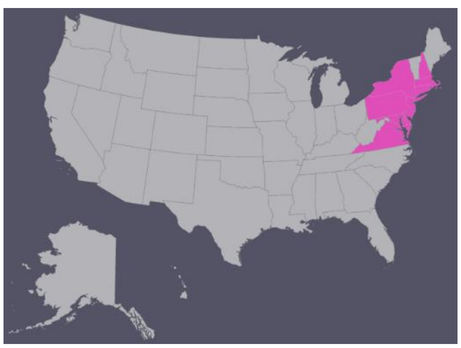
Figure 4.6 Average Capacity per Flight and Load Factor Trend

(Source: MLIT)

4.2 The Northeast Corridor

4.2.1 Overview

The Northeast Corridor (the NEC) is a fully-electrified 457-mile railroad line which connects several metropolitan areas in the northeastern US such as Boston, New York, Philadelphia, Baltimore and Washington DC. The NEC Region defined by the NEC Commission is shown in Figure 4.7 [38]. This region represents just 2% of US land area, but represents 17% of the entire US population and 20% of US GDP. In the NEC region, same as in the Tokaido Corridor case, multiple transportation modes such as highways, air transportation and HSR have served to fulfill increasing intercity travel demand as well as commuter demand.



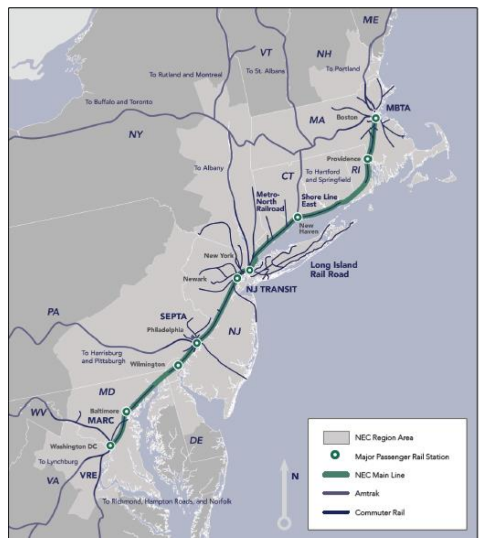


Figure 4.7 Geographical Location of the NEC Region

(Source: NEC Commission, 2014)

4.2.2 Modal Split of intercity travel on the NEC

The NEC Commission conducted an intercity travel study on the NEC, including a study on modal split in particular O-D markets, and a survey on demographics, trip purposes and stated preferences on mode choices [39]. In that report the NEC region is divided into 14 submarkets as shown in Figure 4.8, and intercity passenger travel conducted from one submarket to another is estimated. As main submarkets in the NEC region, Boston, New York and Washington DC areas are defined as Table 4.2.

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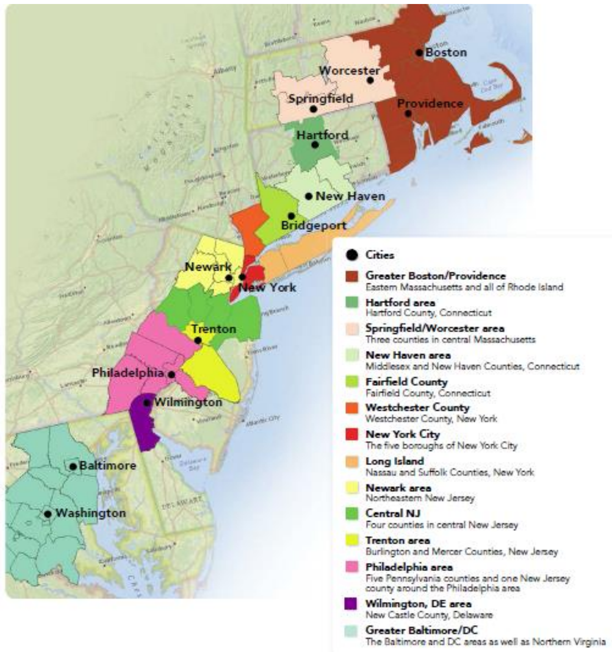


Figure 4.8 Geographical Location of Three Submarkets in the NEC

(Source: NEC Commission, 2015)

Table 4.2 Definition of Three Submarkets

Submarkets		**BOS**		**NY**		**DC**	
States	Cities Counties	**MA**	Barnstable Bristol Dukes Essex Middlesex Nantucket Norfolk Plymouth Suffolk	**NY**	Bronx New York Richmond Kings Queens	**MD**	Carroll Baltimore Baltimore city Howard Montgomery Prince George Anne Arundel Charles
		RI	All cities and counties			**VA**	Loudoun Fairfax Fairfax city Falls Church city Arlington Alexandria city Manassas Park city Manassas city Price William Fauquier Stafford
						DC	All areas
Area [$mile^2$]		4,552		587		5,200	
2010 Population [40]		5,977,483		8,175,133		7,426,123	
HSR Distance from NY [mile]		231.3 (Boston South)		0 (NY Penn)		225.3 (Washington Union)	

(Source: The US Census Bureau, 2010)

Figure 4.9 shows the estimated modal split among these three O-D markets. In all O-D markets, auto trips are dominant and has more than 50% share. In terms of public transportation, air transportation is the HSR's major competitor within the NEC region. Figure 4.10 shows the long-term trend of modal share between rail and air in the BOS-NY and the NY-DC market [41]. Before the introduction of Acela in 2000, air share was more than 50% in both markets, but after its introduction rail has gradually captured market share and now rail share exceeds air share. There is no equivalent data in the BOS-DC market, but from Figure 4.9, rail share seems to be still around as low as 10%, since rail travel takes much longer travel time than air in this market.

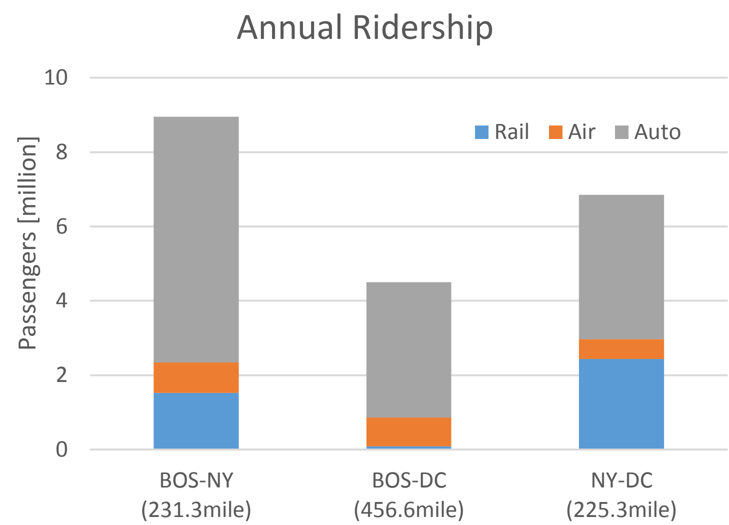


Figure 4.9 Annual Ridership in Three O-D markets

(Adapted from NEC Commission, 2015)

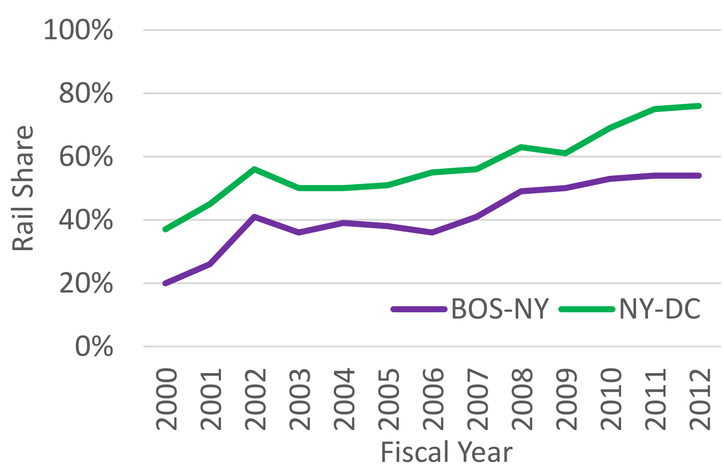


Figure 4.10 Rail-Air Share in the BOS-NY and the NY-DC Market

(Source: Kamga, 2015)

Figure 4.11 shows the comparison of normalized intercity travel demand in the Tokaido Corridor and in the NEC. Ridership is divided by population in O-D metropolitan areas as defined in Table 4.1 and Table 4.2. Therefore, the vertical axes in these figures represent the number of annual trips per one resident in each O-D pair.

First, the dominant travel modes in these two corridors are quite contrasting. JR, especially HSR is dominant in the Tokaido Corridor, while auto is dominant in the NEC. This is mostly due to the different utilities of each transportation mode. In the Tokaido Corridor, HSR connects downtowns in each market with quite short travel time, while the highway system charges significant tolls for long-distance travels (e.g. Tokyo-Osaka: approx. $80). In the NEC, in contrast, HSR has not achieved the international standard average speed, while auto travel costs much less than in the Tokaido case.

Second, the travel frequency is higher in the Tokaido Corridor than that of the NEC. This is primarily because these three markets (Tokyo, Osaka and Nagoya) represent a much larger fraction of domestic economic activities (62% of Japanese GDP) than that of the NEC (20% of the US GDP). In the US case, intercity travel to other economic blocks such as the Midwest and California account for significant portions of intercity travel in addition to travel within the NEC. Different attitudes toward intercity travel can be another reason for the difference of the travel frequency.

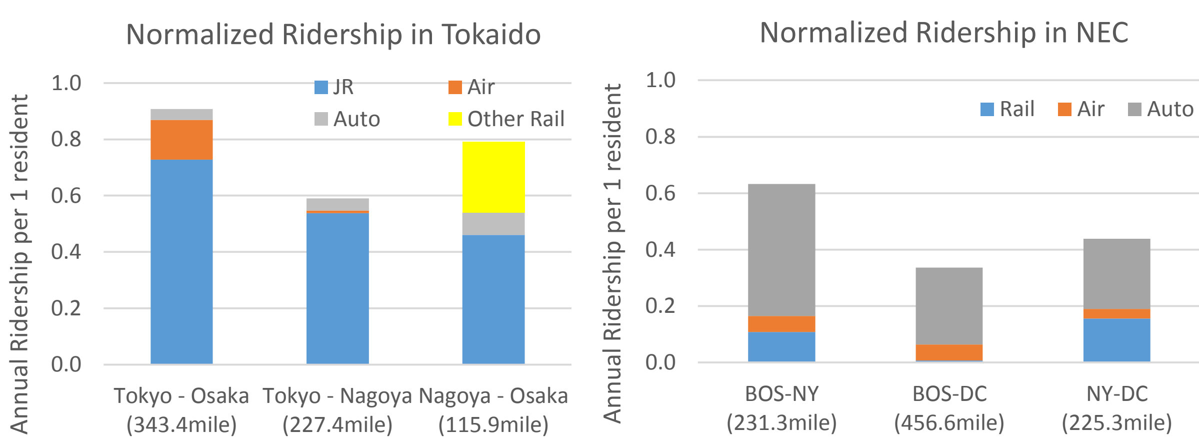


Figure 4.11 Normalized Ridership and its Comparison with the Tokaido Corridor (left) and the NEC (right)

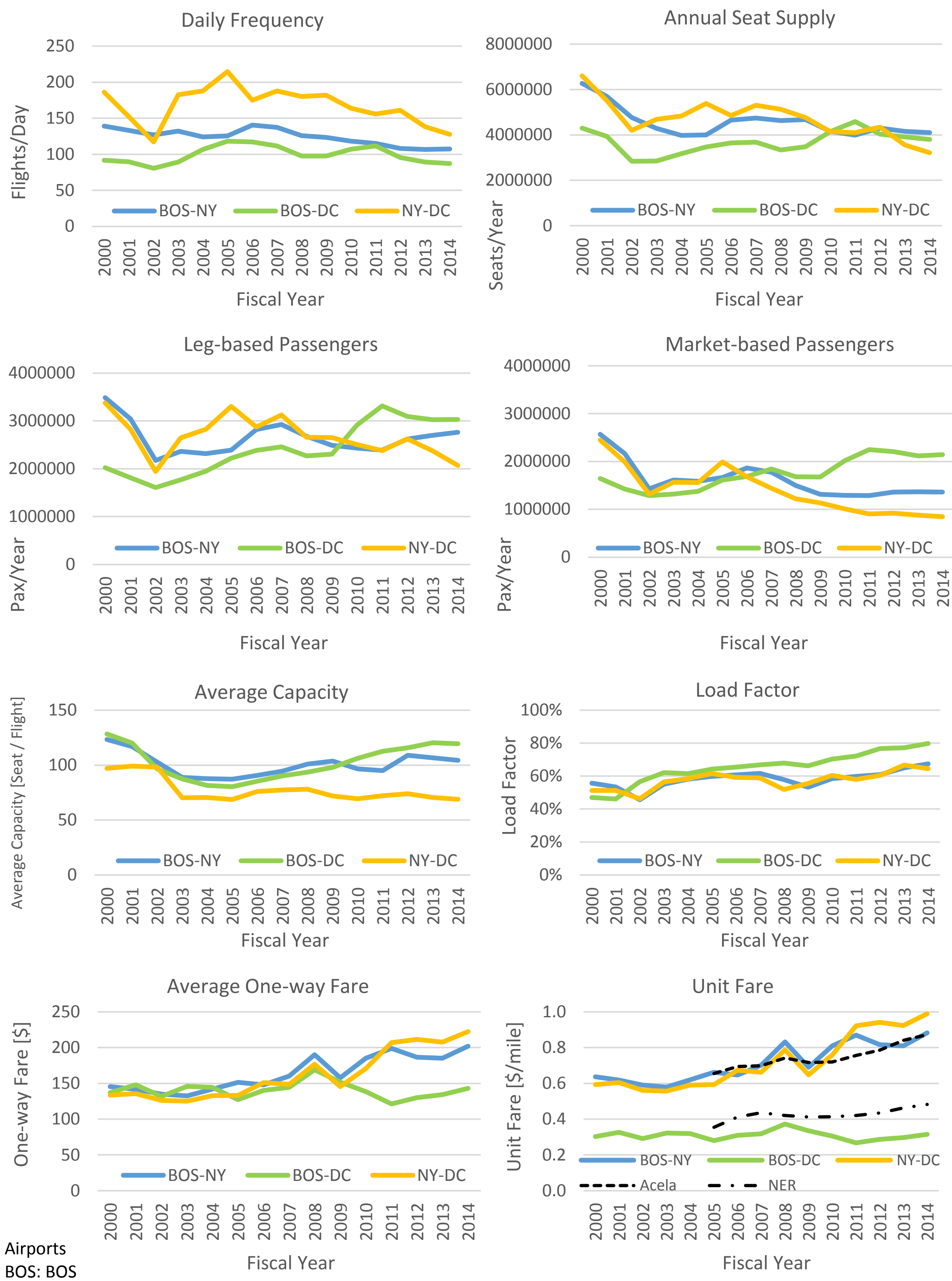
4.2.3 Air Transportation in the NEC region

In the US, air transportation data is available from the T-100 database [42] and the DB1B database [43] at Bureau of Transportation Statistics (BTS). The T-100 database provides flight-leg based data (Airport-to-Airport) such as frequency, supplied capacity and leg-based passengers. The DB1B database provides a 10% sample of market-based data (Origin-to-Destination) such as itineraries and fares. Leg-based data contains connecting passengers whose O-D pairs are different from their flight legs (e.g. BOS-NY-London passengers are counted in the BOS-NY and the NY-London legs, not in the BOS-London leg). On the other hand, market-based data contains connecting passengers within their itineraries (e.g. BOS-DC passengers and BOS-Chicago-DC passengers are both counted in the BOS-DC market). In the NEC region, there are many connecting passengers at airports such as JFK, while air travel within the NEC region is relatively short and non-stop flights are usually provided. Therefore, leg-based data accounts for more passengers than the actual O-D demand in the NEC region, while market-based data is quite close to that.

Figure 4.12 shows the long-term trend of air transportation in the NEC region. The frequency, the supply and the ridership in the BOS-NY and the NY-DC markets clearly reflects the loss of air share against rail, as shown in Figure 4.10. The fraction of market-based passengers out of leg-based passengers has also decreased in these two markets, and in 2014 it is less than 50%, which suggests that more than half of onboard passengers in these flight-legs are actually connecting passengers. In contrast, supply in the BOS-DC market is stable, and the ridership is even increasing. This fact, again, suggests that the rail share in the BOS-DC market has not been improved as much as in the BOS-NY and NY-DC markets.

The average capacity of aircraft used in these markets is stable around 100, smaller than the ones used in the Tokyo-Osaka market (Figure 4.6). The load factor, on the other hand, has steadily increased in these 15 years. In terms of fare, the BOS-NY and NY-DC markets have increased their fare, mainly due to shuttle services for business customers. On the other hand, the BOS-DC fare is stable, or has actually decreased given the inflation rate. Regarding the average fare per one passenger-mile (unit fare), unit fares in BOS-NY, NY-DC markets show a similar trend as Acela’s unit fare.

Figure 4.13 shows the trend of the ridership and the average fare on an airport-to-airport basis. In the BOS-NY and NY-DC markets, flight routes with shuttle services (BOS-LGA, LGA-DCA) have been dominant, but in these 10 years new LCCs have emerged and increased ridership in other pairs of airports (e.g. JetBlue entered JFK-BOS in 2006 have resulted from this increased competition). In the BOS-DC market, three airports are steadily used, and the overall ridership has increased. In terms of fare, routes with shuttle services are more expensive than other routes, since they mainly serve business customers.



Airports
BOS: BOS
NY: JFK, LGA, EWR
DC: DCA, IAD, BWI

Figure 4.12 Air Transportation Trends in the NEC Region

(Source: BTS)

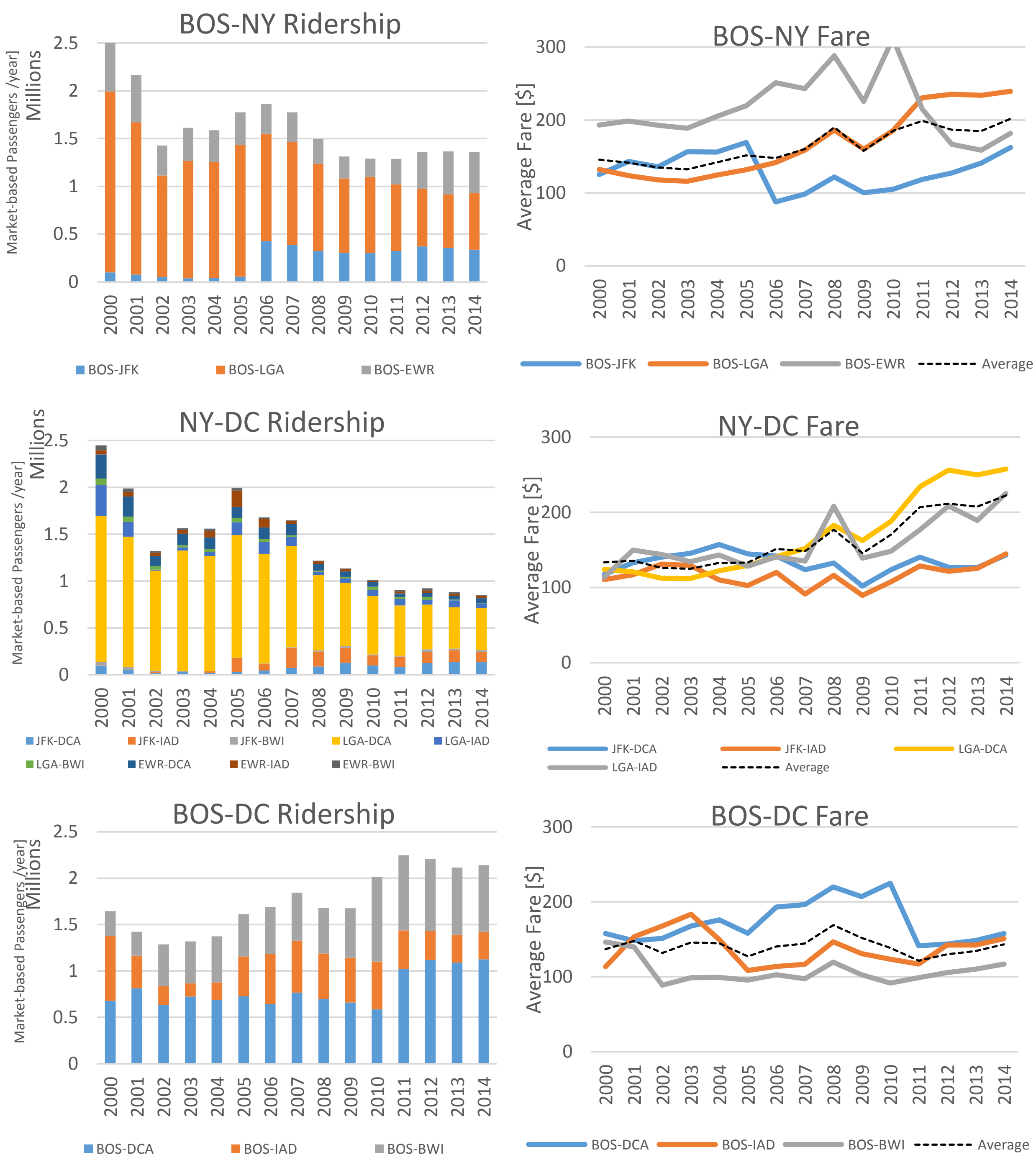


Figure 4.13 Air Transportation Trends in the NEC Region by Airports

(Source: BTS)

4.3 Conclusion

In this chapter, two intercity passenger travel markets (the Tokaido Corridor and the Northeast Corridor) are studied from the perspective of intermodal competition. Both corridors are busy business-oriented corridors and millions of passenger trips are conducted annually by different modes such as auto, air and rail. In the Tokaido Corridor, HSR is the dominant mode and captures about 80% market share in the Tokyo-Osaka market, and the rail-air share has been stable in 2000-2013. In the Northeast Corridor, on the other hand, auto is the dominant mode in every major O-D pair. After the introduction of Acela, rail has increased its market share gradually against air in Boston-New York and New York-DC markets, while air is still superior in the Boston-DC market.

As a main competitor to rail, the trend of air transportation in these two corridors is further studied. In the Tokaido Corridor (Tokyo-Osaka market), two new airports opened in the Osaka metropolitan area, and both supply and demand have steadily increased except during economic recessions. Since rail also has increased its ridership, the market share of air transportation has been stable around 15-20%. Airlines have reduced the unit capacity of aircraft and have increased their frequency, while maintaining their load factor. In the Northeast Corridor, airlines have reduced their supply and the demand has decreased accordingly in the Boston-New York and New York-DC markets. This trend corresponds to the increasing market share of rail. In the Boston-DC market, supply has been stable and demand has increased, which indicates that air is still doing better than rail in this market. In terms of fare, the average fares (fare per passenger-mile) in Boston-New York and New York-DC markets have synchronized with Acela's unit fare, suggesting these two services compete with each other to capture the same type of consumers (mainly business passengers).

In the next chapter, the Tokaido Corridor and the NEC are studied from the perspective of HSR operators. The Tokaido Shinkansen by JRC and Acela / NER services by Amtrak are the main scope, and their long-term performance relevant to the three key "ilities" (safety, availability and profitability) is considered.

Chapter 5 “Ilities” in HSR cases

Chapter 4 focused on the overview of intercity travel markets in Japan and in the US, and studied modal competition and trends in air transportation. In this chapter, the trend in HSR systems in these two corridors (the Tokaido Shinkansen in the Tokaido Corridor and Acela/Northeast Regional in the Northeast Corridor) is studied from the perspective of key “ilities” discussed in Chapter 3.

5.1 Tokaido Shinkansen

5.1.1 Overview

The Tokaido Shinkansen is a 343 mile-long HSR built in 1964, as the first HSR in the world. It connects Tokyo, Nagoya and Osaka, the three largest economic blocks in Japan. Before its launch, the transportation system in the Tokaido corridor, especially the conventional rail (the Tokaido Line) had been suffering from dealing with surging passenger travel demand. To ease the saturation of passenger demand, the Tokaido Shinkansen was designed as a dedicated, passenger-only HSR system. Originally, the Tokaido Shinkansen was constructed and operated by Japan National Railways (JNR), a government-owned public cooperation, but after the privatization and separation of JNR due to its bankruptcy in 1987, its ownership and operation was transferred[3] to JRC, a regional private railway company.

One characteristics of the Tokaido Shinkansen is that it runs in the most densely populated area in Japan. Wu et al. [44] introduced three HSR modes (Corridor Mode, Monocentric Radial Mode and Multicore Network Mode[4]) to understand their spatial influences on local development. He defined Corridor Mode as “a corridor of 480-560 km anchored by megacities at both ends, and often with other major enroute cities”, and cited the Tokaido Shinkansen as the typical example of this Corridor Mode. Figure 5.1 shows the distribution of population density by municipalities and Japanese HSR network with

[3] Strictly speaking, the HSR infrastructure was at first transferred to Shinkansen Holding Cooperation (SHC), a government-owned organization. At that time the Tokaido Shinkansen was vertically separated, since SHC leased HSR infrastructure to JRC, and JRC paid a leasing fee to SHC annually. In October 1991, JRC bought all infrastructure from SHC and vertically integrated HSR operation started. System Dynamics analysis in Chapter 6 is conducted with time horizon of 1992-current, because the conditions of assets, depreciations and capital investments are totally different before and after 1992.

[4] Monocentric Radial Mode is defined as “more than one HSR corridor converges on a single megacity, usually a financial and/or political center” [44]. The French TGV network is an example of this type (a single megacity = Paris). Multicore Network Mode is a newly emerging mode, in which the regional development is being created beyond a single HSR level. It is observed in Chinese dense HSR networks, particularly around Beijing, Shanghai and Chongqing.

route names and their train operators as of March 2016 [36] [45]. The Tokaido, Sanyo and Kyusyu Shinkansen by JR Central, JR West and JR Kyusyu operate as Corridor Mode at densely populated areas from Tokyo to Kagoshima, and the Tokaido is the most typical one. Not only the Tokyo and Osaka megaregions at endpoints, but also multiple municipalities whose population is more than 100,000 are aligned in the same corridor, constituting what is sometimes called “a string of pearls”. On the other hand, Tohoku, Hokkaido, Joetsu and Hokuriku Shinkansen by JR East, JR Hokkaido and JR West are rather close to Monocentric Radial Mode, since each HSR line originates from the same Tokyo metropolitan area.

Figure 5.2 shows the trend of annual ridership and Japanese real GDP since 1964 [46] [47]. The latest annual ridership is 157 million (FY2014), about five times that of the first full year (FY1965) which was 31 million. It is often said that the ridership of the Tokaido Shinkansen shows a correlation with GDP, since a large amount of economic activity is conducted within the Tokaido Corridor, as shown in Table 4.1. It is demonstrated in Figure 5.3 that the ridership and Japanese GDP mostly shows a positive correlation, except in 1975-1986. This exceptional period corresponds to the last decade of JNR operation, in which JNR suffered from large deficits and raised the HSR fare steeply as shown in Figure 5.4 [46] [47], resulting in losing numerous customers.

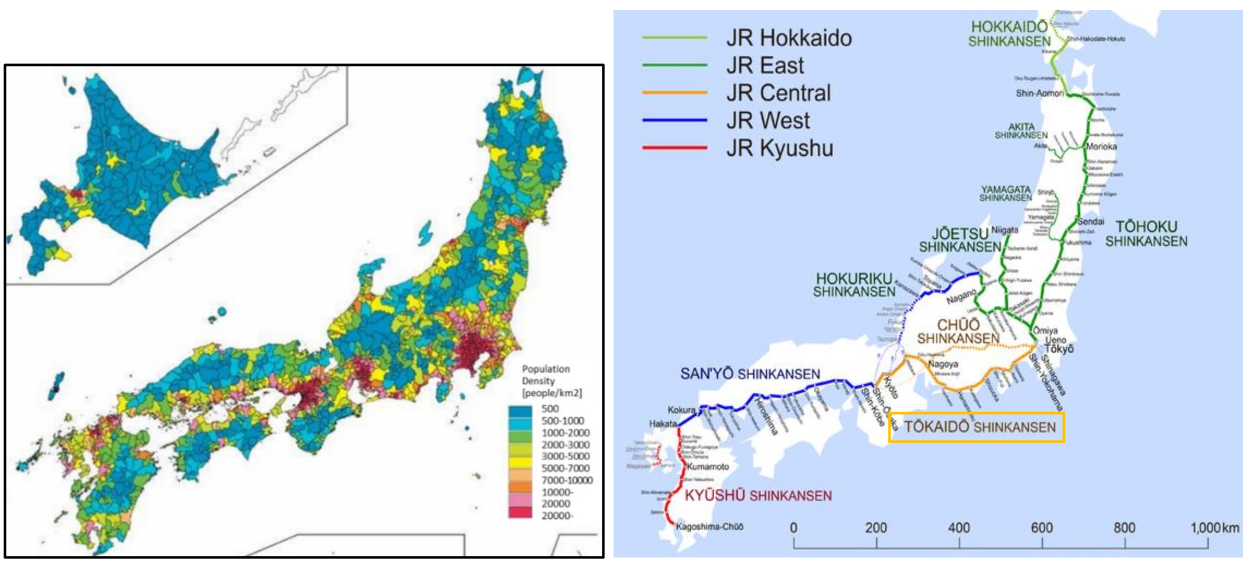


Figure 5.1 Distribution of Population Density and HSR Network in Japan

(Source: MIC, Wikipedia)

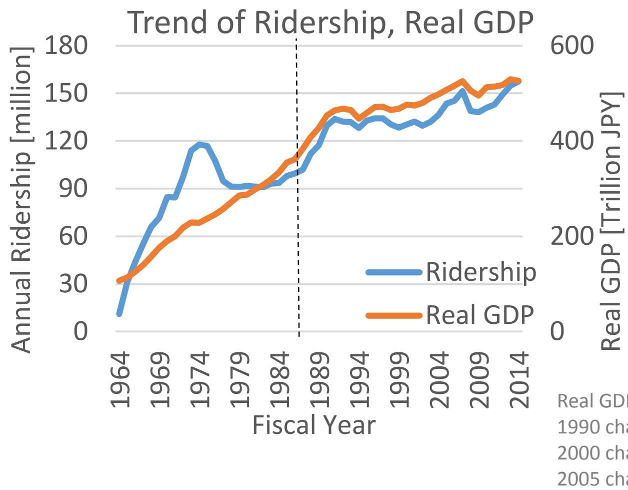


Figure 5.2 Ridership and Real GDP Trend

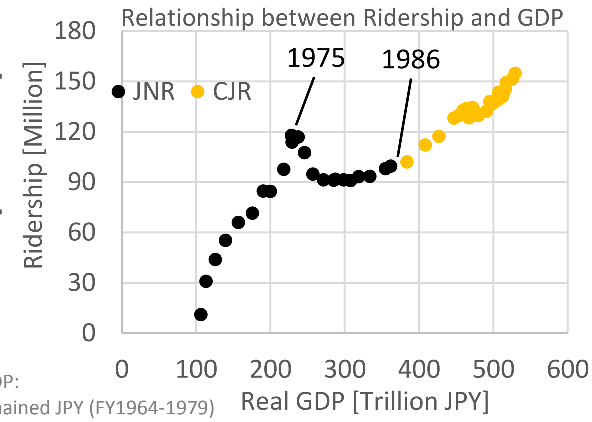


Figure 5.3 Relationship between Ridership and Real GDP
(Source: Cabinet Office, JRC)

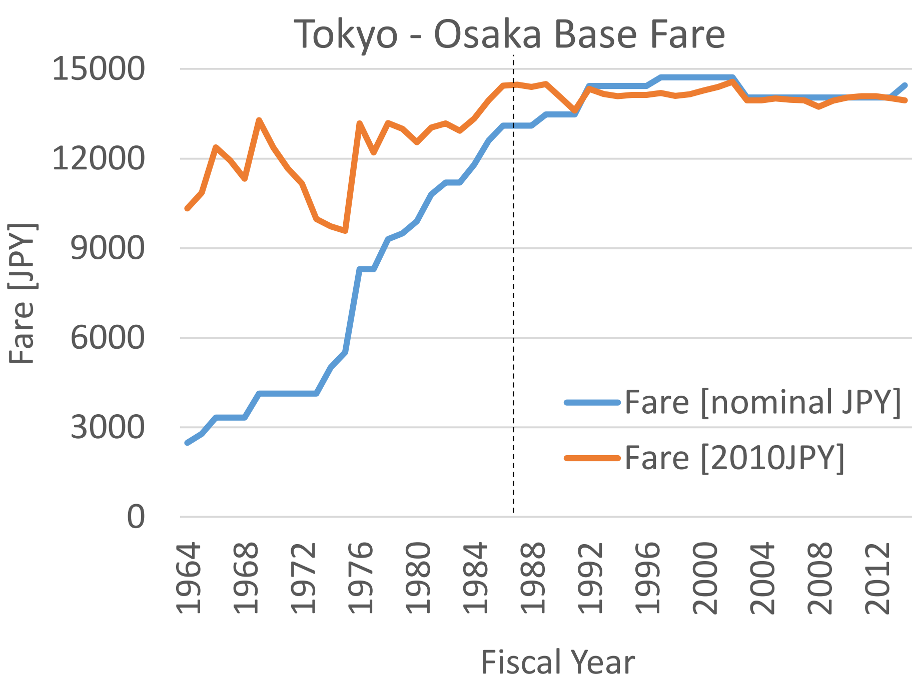


Figure 5.4 HSR Fare in Tokyo-Osaka Market
(Source: Cabinet Office, JRC)

Figure 5.5 shows the trend of the shortest travel time between Tokyo and Osaka, and the maximum operating speed [47]. The maximum speed had been 210kph (131mph) for a long time until it was raised to 220kph in 1986. The most drastic change occurred in 1992, when the maximum speed was increased to 270kph (168mph) by introducing new rolling stock. In 2003, Shinagawa station, a new station in Tokyo metropolitan area opened and every rolling stock was replaced to a new type which could run at 270kph. These two strategies contributed to a rapid increase of supply and demand, though the economic recession in 2007 depressed both. Currently, the fastest train is operated at 285kph (177mph), and the shortest travel time between Tokyo and Osaka (343mile) is 142 minutes. Thus, its average speed is about 145mph.

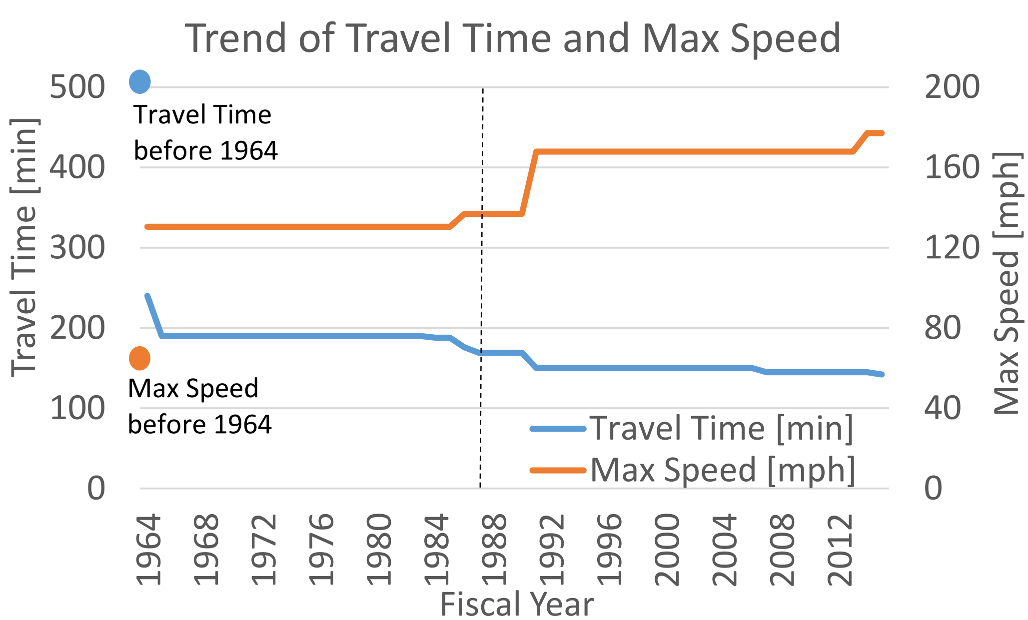


Figure 5.5 Travel Time (Tokyo-Osaka) and Maximum Operating Speed Trend

(Source: JRC)

5.1.2 Safety

As of 2016, JRC [47] states that there has been no accident in which onboard passengers were killed or injured due to train operator's liability in the 50-year-long history of Tokaido Shinkansen operation.[5] IHRA [48] explains that this strong safety record has been achieved by several factors shown below:

- "Crash Avoidance" Principle:
    - Dedicated tracks only for high speed passenger rail operation with full grade separation
    - Automatic Train Control (ATC) System to avoid collision and derailment
- Disaster-proof system
    - Earthquake: early detection, reinforcement of structures, facilities to prevent derailment and deviation
    - Countermeasures for wind, rain and snow
- Education of skilled professionals

MLIT [49] defines accidents in railway operation as shown in Table 5.1, and publishes the annual frequency of railway accidents by train operators since FY2006. Table 5.2 shows the frequency of train accidents in JRC operation (HSR and conventional rail) in FY2006-FY2014 [49]. Only one accident occurred in HSR as a fatality/injury category accident, and no accident occurred in other categories. In conventional rail, accidents have occurred mainly in the grade crossing category and the fatality/injury category. Accidents in grade crossing are prevalent also in other conventional rail operators, but they are totally eliminated in HSR due to its "crash avoidance" characteristics. Most accidents in the fatality/injury category are collisions of passengers and trains at tracks or platforms. In FY2014, 434 accidents of this pattern out of 449 accidents occurred as fatality/injury category accidents in the entire Japanese rail network. In HSR, all tracks are fully grade-separated and platform screen doors are introduced in most stations, so interference by passengers can be prevented much more easily than conventional rail, resulting in lower casualties.

[5] There are actually a few accidents where passengers are killed or injured, if this condition is loosened. In 1995, a passenger at a platform (not "onboard") tried to rush into a departing train, got his hand caught in the door, fell from the platform and was run over to die. In 2015, an onboard passenger conducted self-immolation (not "operator's liability"), and another passenger was killed due to carbon monoxide poisoning. Additionally, suicides are sometimes committed at stations, though they are not counted as accidents.

Table 5.1 Definition of Accidents in Railway Operation

	Categories	Definitions (Accidents in which…)
1	Train Collision	trains collide with other trains
2	Train Derailment	trains derail
3	Train Fire	fires occur in trains
4	Grade Crossing	trains collides with cars or humans at grade crossings
5	Trespassers	trains collides with cars or humans at roads other than grade crossings
6	Fatality / Injury	humans are killed or injured due to train operations (excludes accidents applied to categories 1-5)
7	Property Damage	properties worth more than 5M JPY are damaged due to train operations

(Source: MLIT)

Table 5.2 Railway Accidents in HSR and Conventional Rail under JRC Operation

High Speed Rail			Length	343mile						
Fiscal Year	Collision	Derailment	Fire	Grade Crossing	Trespasser	Fatality Injury	Property Damage	Sum	/million trainset mile	Train-set Mile [million]
2006								0	0	33.09
2007						1		1	0.03	33.89
2008								0	0	35.35
2009								0	0	36.06
2010								0	0	35.43
2011								0	0	35.18
2012								0	0	35.45
2013								0	0	36.70
2014								0	0	37.05

Conventional Rail			Length	881mile						
Fiscal Year	Collision	Derailment	Fire	Grade Crossing	Trespasser	Fatality Injury	Property Damage	Sum	/million trainset mile	Train-set Mile [million]
2006				6		10	1	17	0.58	29.16
2007				3		23		26	0.88	29.39
2008				5		15		20	0.68	29.46
2009				11		24		35	1.18	29.56
2010				8		16		24	0.82	29.35
2011				2		13		15	0.52	29.12
2012				7		10		17	0.58	29.39
2013				6		6		12	0.41	29.12
2014				6		8		14	0.48	28.97

(Source: MLIT)

5.1.3 Availability

5.1.3.1 Service Capacity

Since the intercity passenger travel demand in the Tokaido Corridor is quite high, the service capacity and frequency of HSR is also quite high. JRC is the only train operator and the infrastructure owner of the Tokaido Shinkansen, so JRC can utilize HSR to provide as much capacity as rolling stock, infrastructure and the market demands allow. In addition, it helps to control train frequency to respond to the short-term (weekly or seasonal) demand fluctuations. Figure 5.6 shows the trend of average daily frequency since FY1987. There are three kinds of train operations, namely Nozomi (Express), Hikari (Semi-express) and Kodama (Local). Daily frequency had been stable around 270[train/day] in the 20th century, but after Shinagawa station opened and all trains started 270kph operation in FY2003, the frequency has increased steadily to reach 349[train/day] in FY2014. Nozomi started its operation in FY1992 when a new rolling stock was introduced to operate at 270kph, and rapidly expanded its frequency after FY2003.

Figure 5.7 shows the trend of Revenue Passenger Mile (RPM), Available Seat Mile (ASM) and Load Factor over time [47]. The trend of ASM shows a similarity with that of daily frequency, and has grown since FY2003. RPM traces the change of ASM because the load factor is stable except in FY2009-2011, the recession period. This suggests that a HSR capacity increase has induced new demand or demand shifted from other modes given that economic conditions were stable.

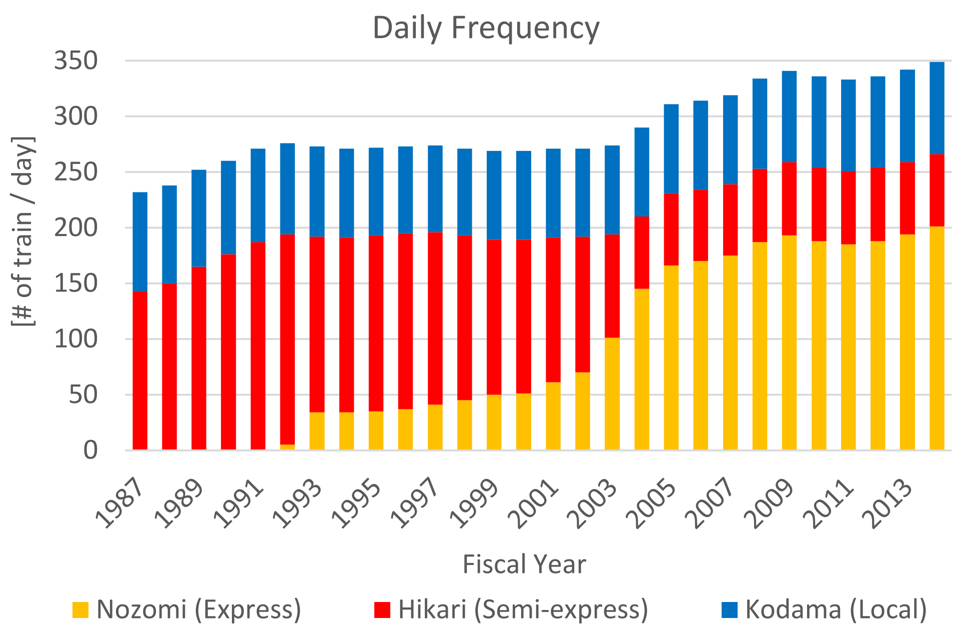


Figure 5.6 Service Frequency Trend in the Tokaido Shinkansen

(Source: JRC)

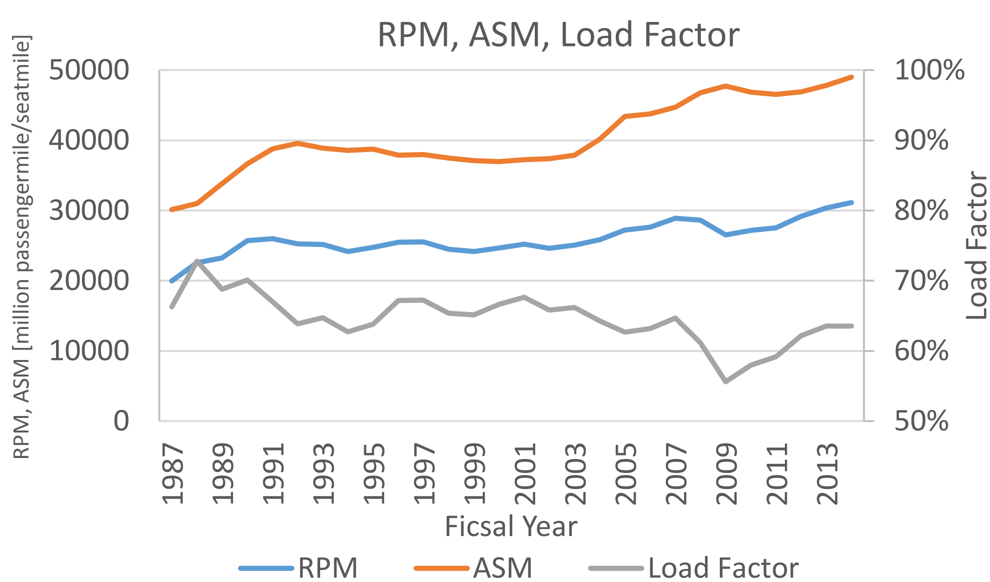


Figure 5.7 RPM, ASM and Load Factor Trend

(Source: JRC)

5.1.3.2 Service Reliability

As metrics to evaluate punctuality or service reliability[6], several indicators such as rate of cancellation, on-time performance and average delay-minutes are often used. In the Tokaido Shinkansen, average delay-minute per one train service is available, though on-time performance is not publicly open. Figure 5.8 shows the trend of average delay-minutes since FY1980. At JNR era the average delay was around 1-3 minutes, and it has been around 1 minute after JRC controlled the operation.

As an indicator to evaluate service reliability, MLIT [49] also publishes the annual frequency of service disruptions by train operators since FY2006, as well as accidents in railway operation. Service disruptions are defined as "situations which are not accidents in railway operation, but cause service cancellations or service delays (more than 30min in passenger trains, more than 60min in other trains)." One note in this definition is that it does not tell us how long trains are delayed or how many trains are delayed or cancelled in "one" service disruption, so it cannot directly related to the average delay or on-time performance. But at least this metric tells how railway systems are frequently disrupted by internal or external factors. Figure 5.9 shows the trend of service disruptions in JRC operation (HSR and conventional rail) in FY2006-FY2014 [49]. Out of 5 categories of causes, operation, rolling stock and infrastructure are responsible for train operators, and other 2 are responsible for third parties or environment. Conventional rail experiences about ten times as frequent service disruptions as HSR, which indicate that HSR meets less disturbances, or is more resilient to disturbances. The fraction of third party disruptions is higher in conventional rail, which suggests that interferences of cars, trespassers or animals at tracks, grade crossings and stations can be a dominant factor in this category.

[6] In the freight train industry, "punctuality" refers to "how train services can stick to the given timetables", while "reliability" refers to "how train services are operated in the same schedule". That is, train services which are always delayed 30 minutes are not "punctual" but are "reliable". In the passenger train industry, the sensitivity to train delay is much higher than that in the freight train industry, and "punctuality" and "reliability" are often interpreted in the similar way, which refers to "how passengers can use train services without disruptions or delays". This thesis focuses on the passenger rail and takes the latter interpretation.

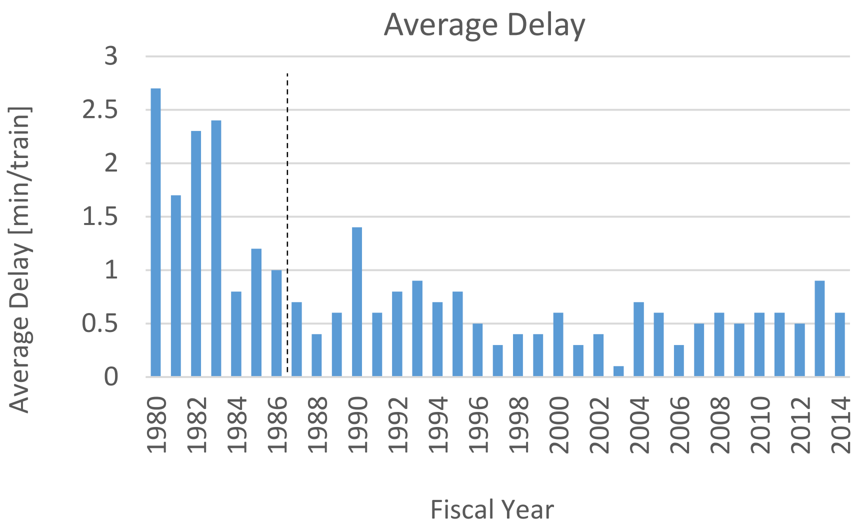


Figure 5.8 Average Delay per Train

(Source: JRC)

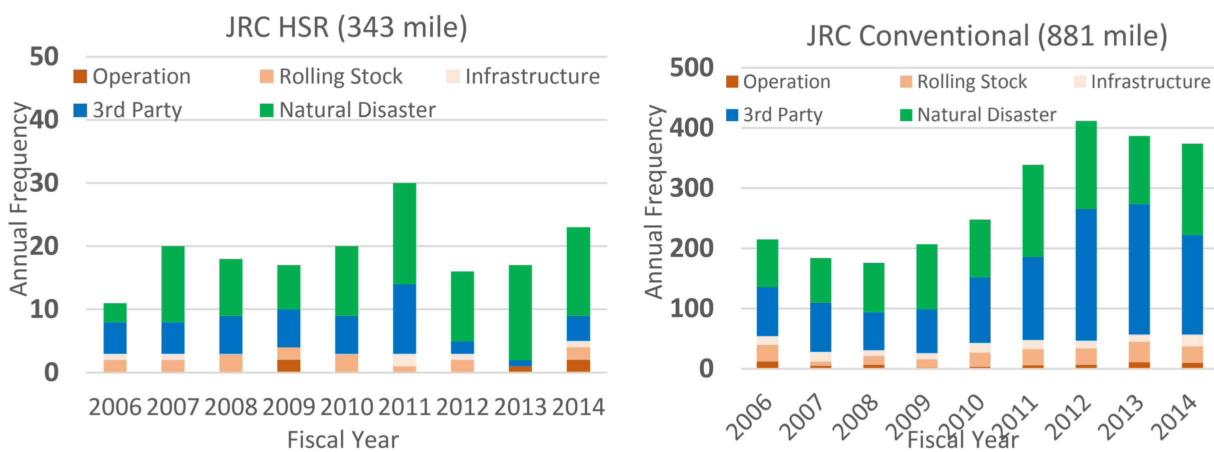


Figure 5.9 Service Disruption in HSR and Conventional Rail under JRC Operation

(Source: MLIT)

5.1.4 Profitability

In order to evaluate and compare profitability in different countries within the same time scale, the monetary metrics are evaluated in US dollars and the inflation is adjusted by the Consumer Price Index (CPI) in Japan [50] and the US [51]. In the US data, the revenue is adjusted by CPI for public transportation, and the cost is adjusted by CPI for general goods. FY2010 is used as the reference year. For simplicity, the exchange rate between the USD and JPY is assumed as 1USD = 100JPY.

5.1.4.1 Revenue Side

Figure 5.10 shows the trend of HSR revenue since FY1987 [47]. R-squared, or the correlation between HSR revenue (adjusted 2010USD base) and RPM is 90%, which means that HSR revenue has a strong correlation with the trend of RPM shown in Figure 5.7. This fact suggests that the average fare paid by each passenger has not changed much. Figure 5.11 shows the trend of average fare per one passenger-mile, and indeed it has been stable around 0.35-0.40 [2010USD]. The HSR base fare has not changed so much either as shown in Figure 5.4, so it can be said that JRC has not discounted tickets aggressively to attract more passengers.

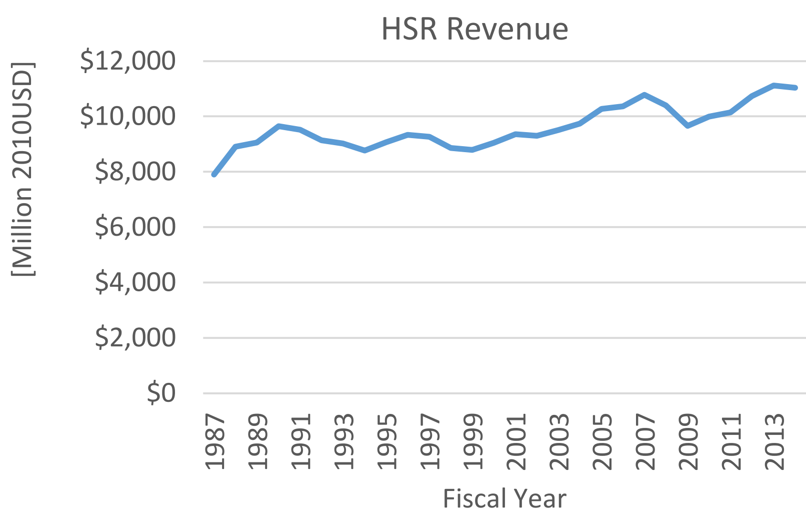


Figure 5.10 HSR Revenue Trend

(Source: JRC)

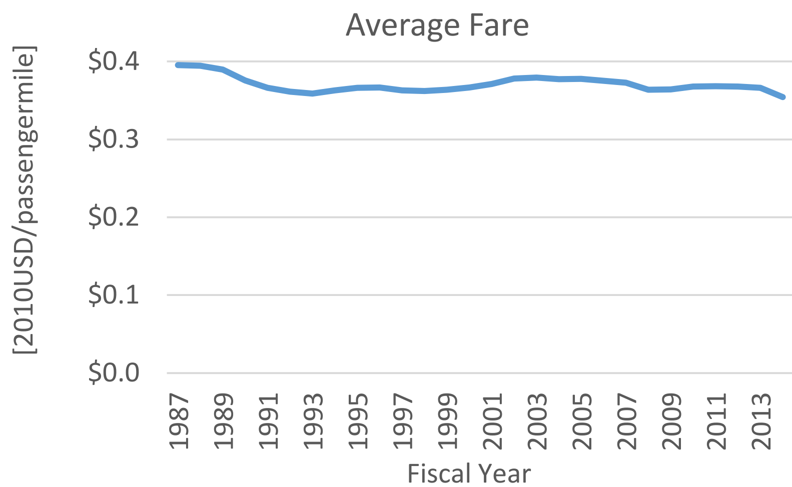


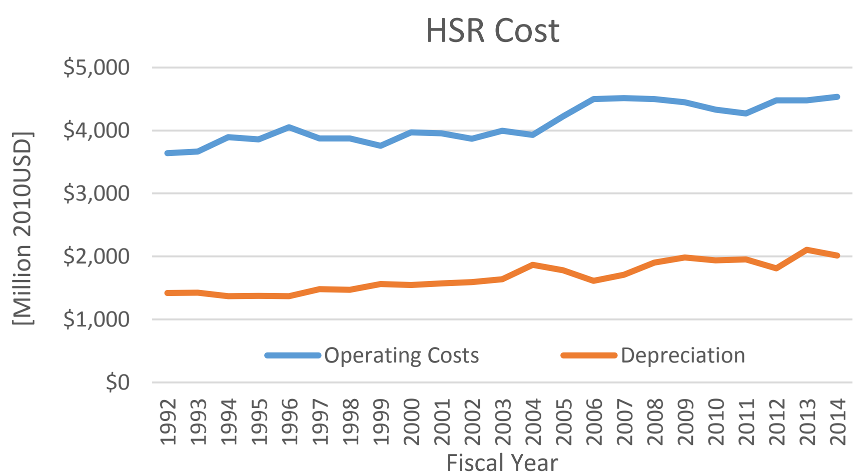
Figure 5.11 Average Fare Trend

5.1.4.2 Cost Side

The only publicly available data about the operating cost of JRC is the aggregated cost for the whole railway network, so here it is estimated that the cost for HSR and the cost for conventional rail are in proportion to train-miles in both categories. Figure 5.12 shows the trend of estimated operating cost and depreciation since FY1992 [47]. As explained in Section 5.1.1, before FY1992 JRC was paying the leasing fee of HSR infrastructure to Shinkansen Holding Co., and this leasing fee was included as a part of operating costs while JRC didn't cover depreciation of the HSR infrastructure. Thus, in the evaluation of costs, the period after FY1992 is taken into account, as the financial conditions are same. The magnitude of HSR operating cost is about half of the HSR revenue, which indicates that the HSR operation is quite profitable. After the increase of service capacity and frequency in FY2003, the operating cost have also increased. This is a similar trend to that of train frequency or ASM as shown in Figure 5.6 and Figure 5.7. R-squared between operating cost and frequency is 82%, and between operating cost and ASM is 78%.

Capital expenditure (CAPEX) is another metric to evaluate profitability, or financial capability to maintain HSR in the state of good repair (SOGR). Figure 5.13 shows the trend of capital expenditures since FY1992. This is the aggregated CAPEX of HSR and conventional rail, but most of it is estimated to be invested in HSR. More than half of total CAPEX is used in safety related investments such as the infrastructure replacement or the improvement of resilience to natural disasters. Other CAPEX includes procurement of rolling stock, construction of the new maglev HSR line, marketing, R&D, and so on. One note here is that this CAPEX comes from the cash flow of JRC, not from subsidies of government or municipalities. Thus, investments on railway assets have been stable and sustainable, keeping SOGR backlog small.

Although the stable CAPEX on infrastructure and rolling stock has enabled providing high service quality of HSR in the long-term, heavy usage of railway assets has led the deterioration of structures such as bridges and tunnels. CJR started the refreshment of such deteriorated structures in FY2013. The duration of this refreshment effort is 10 years, and the total cost is estimated as $7.3 billion, which is included as a part of CAPEX in each year.



※Operating cost does not include tax, CAPEX and depreciation

Figure 5.12 Estimated Operating Cost and Depreciation

(Adapted from JRC)

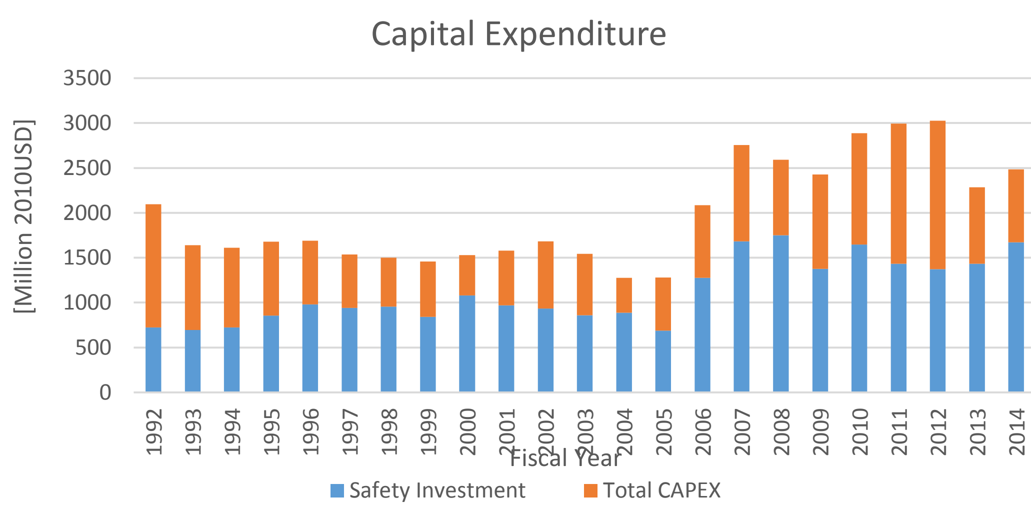


Figure 5.13 Capital Expenditure Trend

(Source: JRC)

5.1.5 Summary

The Tokaido Shinkansen has shown a moderate but steady growth after JNR was privatized and the ownership was transferred to JRC. In particular, after the opening of Shinagawa station and the speedup of all trains to 270kph in 2003, the frequency and the seat supply showed a rapid growth; then the ridership and revenue followed. The operating profit has been large enough to cover necessary capital investments on rolling stock and infrastructures, which enables to maintain them in a state of good repair. Services are sometimes disrupted by natural disasters or interference of external objects, but disruptions due to internal responsibility are relatively rare. In summary, from "ilities" standpoints, the characteristics of corridor (densely populated, medium distance etc.) and HSR competitiveness (safety, availability, travel time, accessibility etc.) enabled profitability, which in turn drives investments in safety and availability. That is, there seems to be a positive feedback loop among these "ilities", which makes HSR operation in this corridor successful.

5.2Amtrak Service in NEC

5.2.1 Overview

The current form of the NEC was incrementally built from the 19^{th} century to the beginning of the 20^{th} century. After several mergers of multiple railway companies, Penn Central took control of the entire NEC before it went bankrupt in 1970. This bankruptcy to led the enactment of the Rail Passenger Service Act in 1970, through which Amtrak was founded to provide intercity passenger rail services in the US, including the NEC. At first Amtrak did not own any tracks on which its trains were operated, but the Railroad Revitalization and Regulatory Reform Act (4R Act) of 1976 allowed Amtrak to acquire infrastructures in the NEC which had not been already taken over by states or local authorities.

Today, Amtrak owns 363 miles of track out of the 457-mile NEC main line between Boston and Washington DC. The New Haven Line (56 miles) between New Rochelle, NY and New Haven, CT is owned by New York Metropolitan Transportation Authority (MTA, 10miles) and Connecticut Department of Transportation (ConnDOT, 46miles), and it is controlled and maintained by Metro-North Railroad (MNR). The Attleboro Line (38 miles) between Boston, MA and MA/RI border is owned by the Massachusetts Bay Transportation Authority (MBTA), but Amtrak performs operation and maintenance of this line under an agreement. Not only intercity trains, but also multiple commuter trains and freight trains are operated in the NEC as a shared corridor. Figure 5.14 shows the current train operators and infrastructure owners in NEC. Such a situation where multiple operators coexist in one line with multiple ownerships requires negotiations with various stakeholders in operations management, and makes it difficult for Amtrak to coordinate intercity passenger train services flexibly.

The NEC can be defined as a Corridor Mode HSR, same as the Tokaido Shinkansen. Figure 5.15, the distribution of population density in the US in 2010, shows that the NEC is the most typical Corridor Mode region in the US. Along with large cities such as New York, Philadelphia, Baltimore, Washington DC and Boston, multiple cities with substantial population are aligned within this region, which makes the intercity passenger rail service competitive.

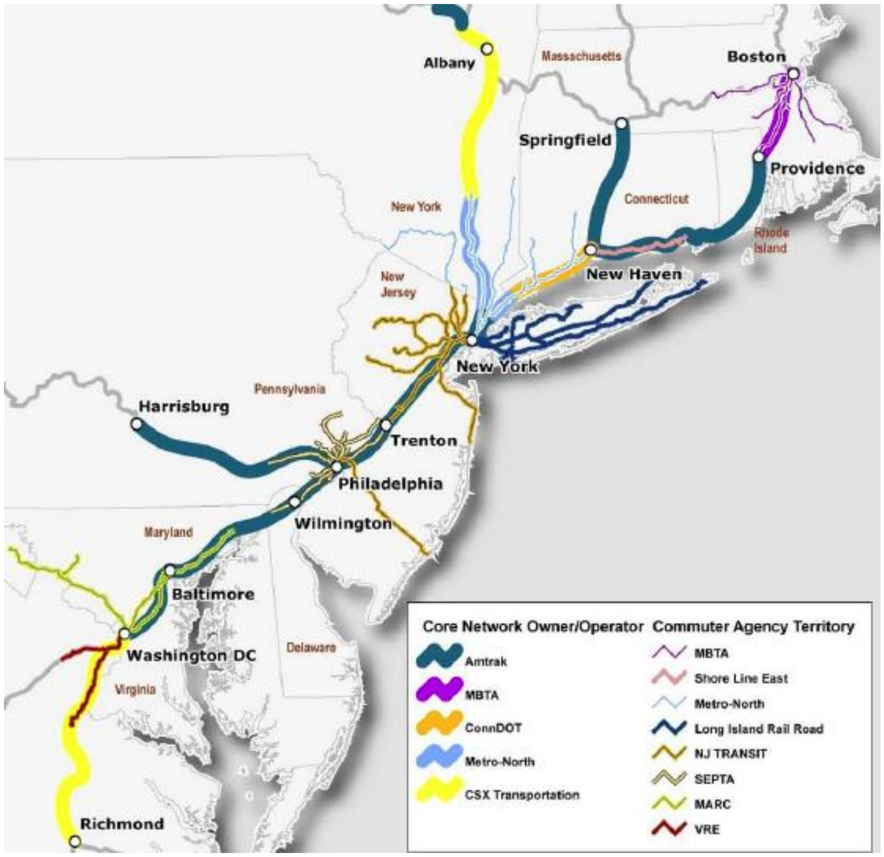


Figure 5.14 Train Operators and Owners in NEC

(Source: The NEC Master Plan Working Group, 2010)

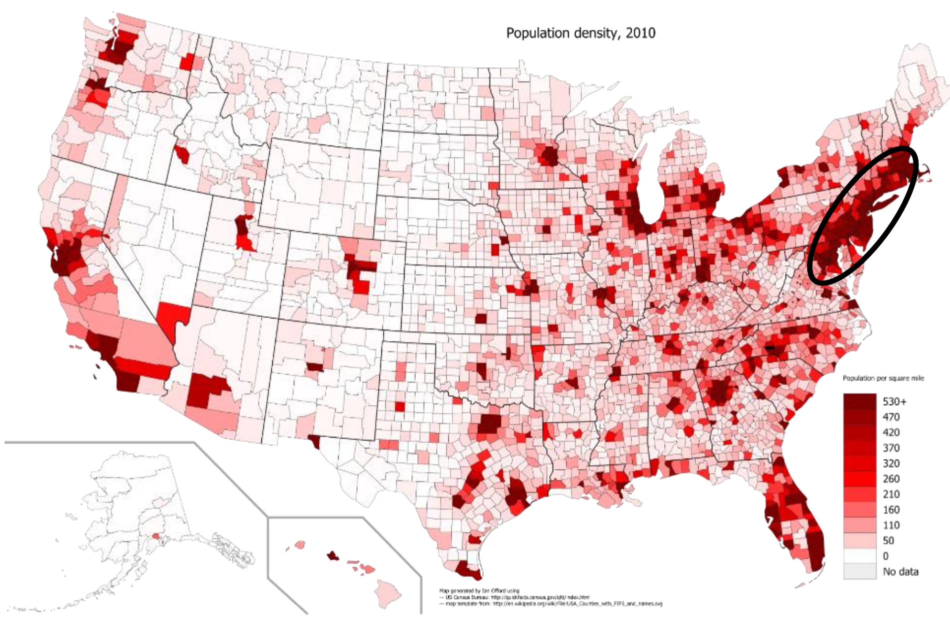


Figure 5.15 Distribution of Population Density in the US

(Source: The US Census Bureau, 2010)

Currently, Amtrak operates several intercity train services in the NEC. Acela Express (Acela) is the high speed rail service between Boston and Washington DC, with maximum speed of 150mph (240kph), though this max speed can be achieved only in small portions of the line due to constraints with the ground infrastructure. Acela started its operation in 2000 after the electrification of the northern part of the NEC (New Haven - Boston) was completed in 1999, and gradually replaced the former intercity service between New York and Washington, Metroliner, before its full replacement in 2006. As of November 2014 [52], Acela trains run between Boston and New York in 210-225min (average speed: 61-65mph), and between New York and Washington DC in 163-172min (average speed: 78-83mph). The daily frequency is 33 [train/day] during weekdays, 9 [train/day] on Saturday and 19 [train/day] on Sunday.

Northeast Regional (NER) is the so-called higher speed rail service between Boston and Washington DC, some of which extend their operation to cities in Virginia such as Lynchburg, Richmond, Norfolk and Newport News. It runs with a maximum speed of 125mph (201kph), and stops at more stations than Acela. As of 2014 [52], NER trains run between Boston and New York in 245-318min (average speed: 43-56mph), and between New York and Washington DC in 190-237min (average speed: 57-71mph). The frequency is 43 [train/day] during weekdays, and 34-35 [train/day] during the weekend. There are other Amtrak services which partially operate on the NEC. Table 5.3 shows the summary of train services running on the NEC as of 2014. The infrastructure capacity between New York and Philadelphia is the most highly utilized, since all these services run there.

Table 5.3 Train Services in the NEC

Train Service	Route	on NEC	Frequency (weekday)
Acela Express	Boston-DC	Boston-DC	33
Northeast Regional	Boston-Lynchburg/Newport News	Boston-DC	43
Vermonter	St. Albans-DC	New Haven-DC	2
Cardinal	NY-Chicago	NY-DC	2
Carolinian	NY-Charlotte	NY-DC	2
Crescent	NY-New Orleans	NY-DC	2
Silver Service/Palmetto	NY-Tampa/Miami	NY-DC	6
Keystone	NY-Harrisburg	NY-Philadelphia	19
Pennsylvanian	NY-Pittsburgh	NY-Philadelphia	2

(Source: Amtrak)

Figure 5.16 shows the trend of shortest travel time since FY1971 [53]. After the introduction of Acela, the travel time in BOS-NY has significantly improved thanks to speed-up and electrification. On the NY-DC line, since Metroliner had already served at the maximum speed of 125mph, and Acela runs this portion at most 135mph, not at its maximum speed of 150mph, the travel time has not improved much.

Figure 5.17 shows Amtrak's service frequency [53]. Train services running partial portions of regions (e.g. New Haven-NY, NY-Philadelphia) are also counted in the calculation of frequency. NY-DC shows much denser service than BOS-NY, but the overall frequency has not changed since the 1990s. Particularly, the frequency of express services (Metroliner and Acela) has been around 30-34 [train/day], or about 1 [train/hour/direction]. This stable frequency comes from several factors, such as difficulty in getting new slots in a congested shared corridor, and limited number of train sets (Acela).

Figure 5.18 shows the trend of ridership since FY2002 [54]. Except FY2009 when the economic recession depressed travel demand, the ridership of Acela and NER has been steadily increasing. This trend results in a market share increase in the BOS-NY and NY-DC markets as shown in Figure 4.10.

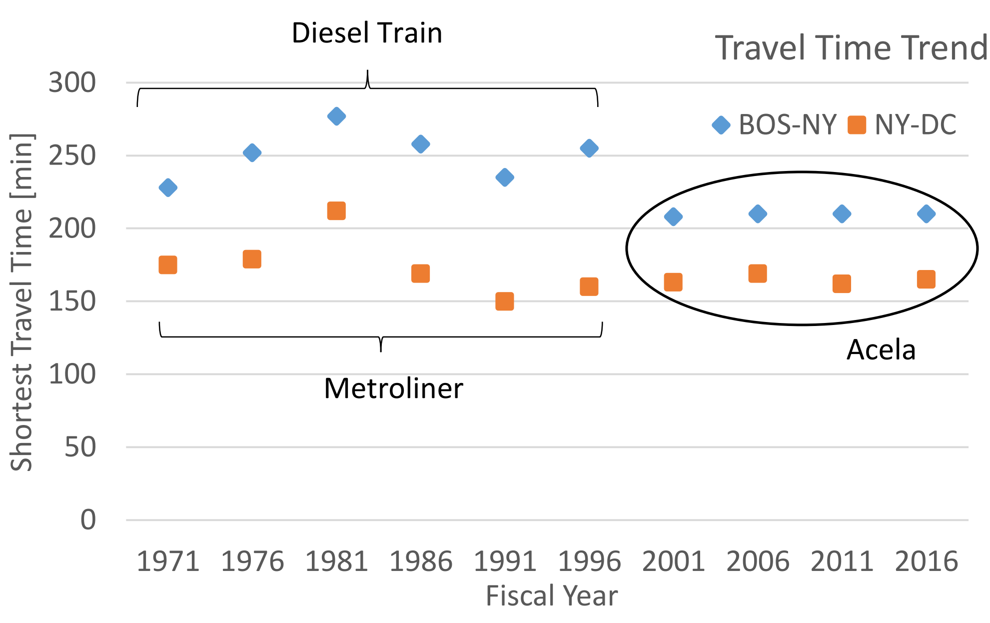


Figure 5.16 Travel Time in BOS-NY / NY-DC

(Source: The Museum of Railway Timetables)

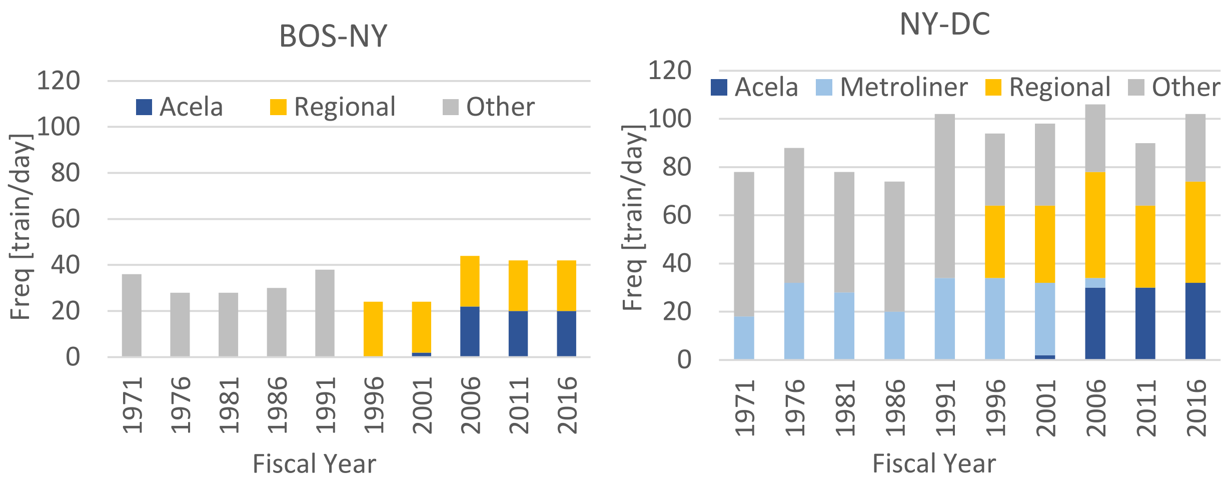


Figure 5.17 Weekday Service Frequency in BOS-NY / NY-DC

(Source: The Museum of Railway Timetables)

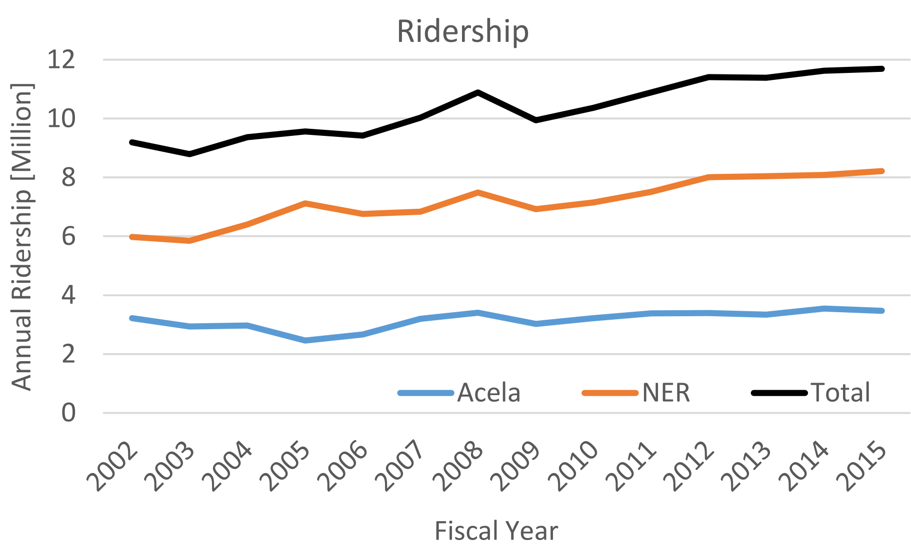


Figure 5.18 Ridership Trend in the NEC

(Source: Amtrak)

5.2.2 Safety

Under the Accidents Reports Act of 1910, FRA requires railroads to report accidents and incidents regularly. FRA [55] divides accidents/incidents into three categories (train accidents, highway-rail grade crossing incidents and other incidents), and defines train accidents as "safety-related events involving on-track rail equipment (both standing and moving), causing monetary damage to the rail equipment and track above a prescribed amount." When train accidents occur, railroads are required to submit FRA Form 6180/54 (Rail Equipment Accident / Incident Report) [56]. FRA publishes an online database [57] based on information collected from railroads. The "prescribed amount", or the monetary threshold to report train accidents or not has grown over time. It was $6,600 in 2000 and is $10,500 in 2016. Amtrak's accidents studied in this section follow this definition and threshold.

Figure 5.19 shows the frequency of Amtrak's train accidents (regardless of casualties) in the NEC by accident types. The annual frequency of train accidents reached 39 in FY2006, then gradually decreased and currently it is around 20. Serious accidents such as collisions, derailments and fires occur 1-5 times in almost all years, while most accidents are categorized as the "other" accident type. The right figure in Figure 5.19 shows its breakdown, which indicates that most accidents in the "other" category are pantograph-related accidents[7]. Pantograph-related accidents result from several causes such as defects of pantographs themselves, catenary fatigue, electric circuit failures and strikes of flying objects, and such accidents often yield damages more than the monetary threshold of accident reports. Indeed, Figure 5.20 shows the breakdown of primary causes of all accidents in FY2001-2015, and more than half of accidents result from either pantograph defects or catenary system defects. This figure also indicates that more than 80% of accidents result from failures in components of rolling stock (mechanical / electrical) or infrastructure (track / roadbed / structures), which suggests that poorly maintained subsystem components can be a driving factor of monetary losses in damaged properties, or even service suspensions and delays.

Figure 5.21 shows the trend of train accidents by train types (Acela, NER, Other). Acela and NER have experienced accidents with same level of frequency, but given that NER runs more train-miles than Acela, the frequency of accident per train-mile is higher in Acela. The fractions of pantograph defects and catenary system defects in Acela are 51% and 18%, respectively, while those in NER are 25% and 26%, respectively.

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[7] This is the author's definition. Pantograph is a subsystem of rolling stock which transfers electricity from catenary to rolling stock. The author judged an accident as "pantograph-related" if the accident description in the report referred to the word "pantograph".

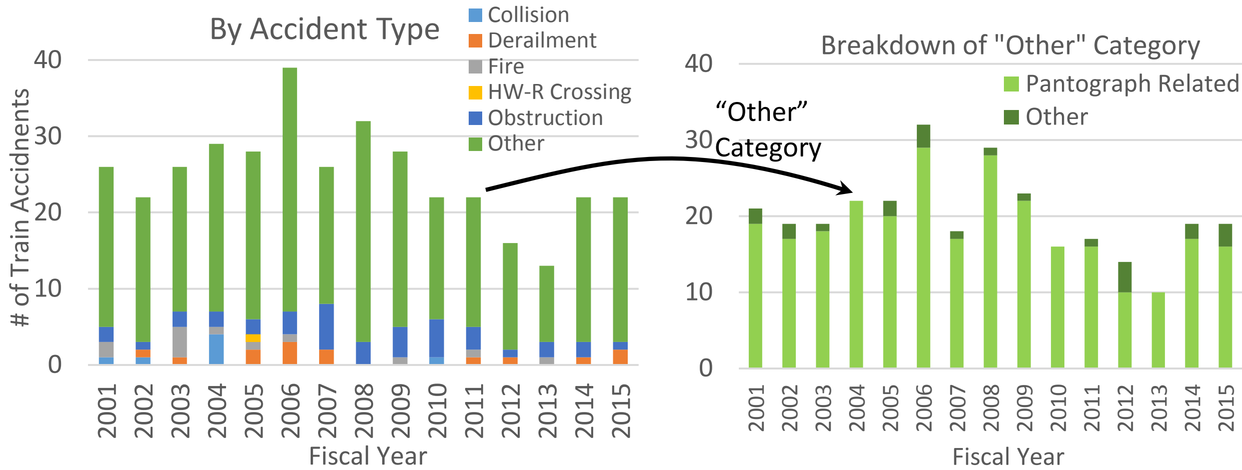

Figure 5.19 Train Accidents in the NEC by Accident Type

(Source: FRA)

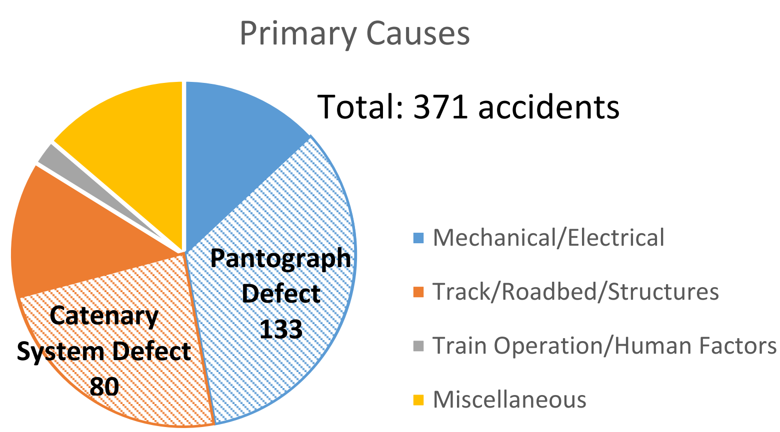

Figure 5.20 Primary Causes of Accidents

(Source: FRA)

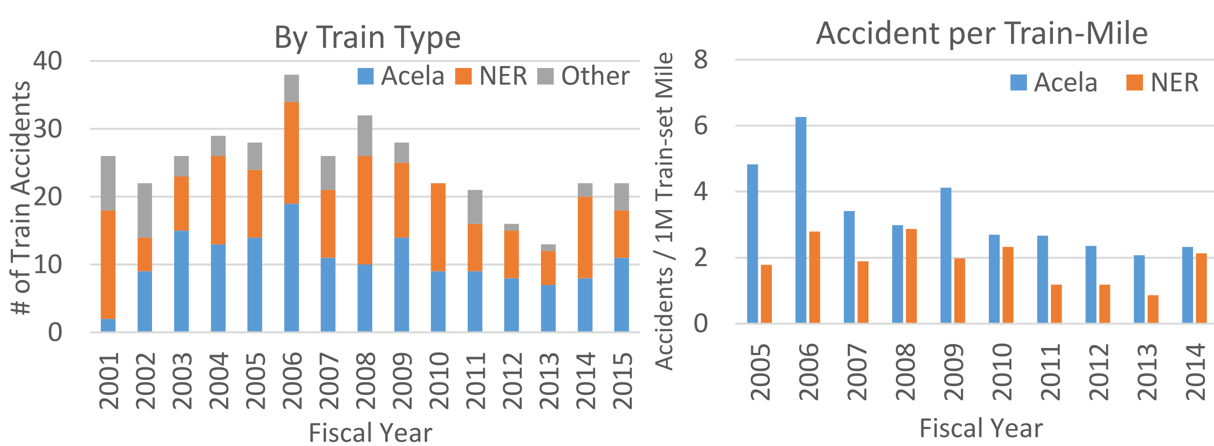

Figure 5.21 Train Accidents in the NEC by Train Type

(Source: FRA)

Table 5.4 shows the history of train accidents with fatalities or injuries in the NEC main line since FY2001. Out of 371 train accidents, 14 accidents caused casualties, and 6 accidents resulted in fatalities or injuries of onboard passengers. Out of 14 accidents with casualties, 7 resulted from the interference of external objects (trespassers, cars at grade crossings, stations and tracks), 5 resulted from human factors such as drivers' errors, and 2 resulted from technical failures of components. This breakdown is quite different from the overall breakdown of accidents shown in Figure 5.20, which suggests that serious accidents with casualties tend to involve causal factors other than hardware failures. In particular, regarding the interference of external objects, most grade crossings are removed in the NEC main line, but 11 still exist in Connecticut [58], which can be potential hazardous places in the future.

The only accident with onboard passengers' fatalities is the Amtrak 188 derailment at Frankford Junction, north of Philadelphia, in May 2015, in which 8 passengers were killed and 224 were injured. The direct cause of this derailment is the overspeed of the train at a steep curve, though the detailed investigation by the NTSB is still ongoing as of February 2016.[8] Acela Express experienced four accidents with casualties, and three of them were due to trespassers' interference and the rest was due to track deficiency in the MNR region.

Table 5.4 The NEC Accidents with Fatalities / Injuries (under Amtrak's Operation)

									Total		Passenger		
Date	Train No.	State	County	Infra Manager	Type	Primary Cause	Equipment Damage	Track Damage	Killed	Injured	Killed	Injured	Speed [mph]
2002.6.17	Amtrak 90 MARC 437	MD	Baitimore	Amtrak	Collision	Failure to comply signal	2,000,000	0	0	11	0	6	Amtrak 15 MARC 18
2003.9.30	Amtrak 2171	MD	Baitimore	Amtrak	Obstruction	Trespasser Interference at station	10,000	0	1	0	0	0	111
2004.4.19	Amtrak 183 LIRR 2099	NY	New York	Amtrak	Collision	Failure to comply speed restriction	50,000	5,000	0	31	0	27	Amtrak 10 LIRR 0
2004.10.28	Amtrak 2191	CT	New Haven	MNR	Derailment	Descrepancy of switch and running direction	150,000	0	0	1	0	0	5
2005.9.28	Amtrak 2153	CT	New London	Amtrak	HW-R crossing	Car interference at crossing	19,000	0	3	0	0	0	71
2006.5.20	Amtrak 66	NY	Westchester	MNR	Derailment	Switch point worn and chipped	97,000	0	0	3	0	3	15
2006.6.14	Amtrak 1662	MD	Baltimore	Amtrak	Obstruction	Car left foul	300,000	150,000	0	3	0	0	35
2006.9.26	Amtrak 819	DE	New Castle	Amtrak	Derailment	Broken switch	22,000	15,000	0	1	0	0	26
2006.10.29	Amtrak 163	RI	Washington	Amtrak	Obstruction	Interference of track car	2,000	1,000	0	2	0	0	37
2010.2.25	Amtrak 2151	PA	Delaware	Amtrak	Obstruction	Trespasser Interference at station	21,585	0	2	1	0	1	108
2010.5.6	Amtrak 2153	MD	Anne Arundel	Amtrak	Other Impacts	Trespasser Interference on track	25,000	0	1	0	0	0	108
2014.6.22	Amtrak 132	MA	Bristol	Amtrak	Obstruction	Car left foul	39,312	0	3	2	0	1	107
2015.4.18	Amtrak 65	RI	Washington	Amtrak	Obstruction	Car interference at interlocking	477,617	0	1	0	0	0	92
2015.5.12	Amtrak 188	PA	Philadelphia	Amtrak	Derailment	Under Investigation - Overspeed at curve?	27,140,000	3,630,962	8	224	8	216	106

Yellow cells represent the Acela Express

(Source: FRA)

[8] The author conducted an analysis of this accident using a system-theoretic approach (STAMP) to consider system-level factors beyond a single driver's human error. It is inserted in the Appendix A of this thesis.

5.2.3 Availability

5.2.3.1 Service Capacity

Figure 5.22 shows the trend of ASM, RPM and Load Factor in Acela (FY2005-2006: sum of Acela and Metroliner) and NER since FY2005 [54]. Except in FY2005 and FY2006 when Acela experienced technical problems in its braking system and train sets were taken out of service for emergency repairs, ASM of Acela is quite stable around 1 billion seat-miles per year. Acela's capacity is constantly 304 seats/trainset, so this suggests that the service frequency of Acela service has not changed much since FY2007. Whereas RPM and LF has steadily increased after the drop in FY2009. NER shows higher ASM and RPM, since its frequency and operation distance is higher than those of Acela. In addition, NER has experienced more fluctuation in ASM and steady increase of RPM.

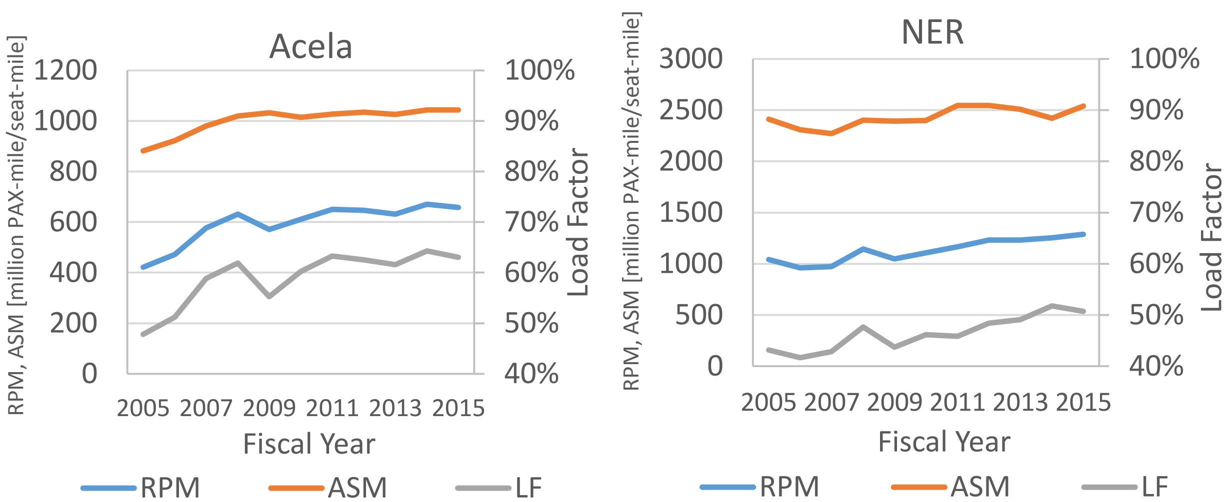

Figure 5.22 ASM, RPM and Load Factor Trend

(Source: Amtrak)

5.2.3.2 Service Reliability

In 2008, the Passenger Rail Investment and Improvement Act (PRIIA) was enacted to improve services, operations and facilities in intercity passenger rail services in the US. In PRIIA, Section 207 required FRA, Amtrak and other stakeholders to develop uniform metrics and standards to evaluate service quality of intercity passenger train operations, which was previously interpreted differently by different stakeholders. As a result, on-time performance and train delay-minutes were utilized as metrics to indicate service reliability.

On-time performance (OTP) is the fraction of trains achieving "on-time" service out of all trains served. There are two types of OTP: endpoint OTP and all-stations OTP. Endpoint OTP focuses only on the endpoint terminal station to judge whether the train arrived at that station "on time" or not. All-stations OTP focuses also on intermediate stations to see the arrival times on these stations as well. In this thesis, endpoint OTP is used as the metric of on-time performance. The definition of "on time" differs by train services in NEC. Acela is considered as "on time" if it arrives at a station with less than 10 minutes delay. The threshold for NER depends on its travel distance; 10 minutes for less than 250miles, 15 minutes for 251-350 miles, and 20 minutes for 351-450 miles.

Train delay-minutes is the sum of delays of all trains against their scheduled arrival times, regardless of whether they arrive "on time" or not. In Section 207, this metric is normalized by train-miles, and the average delay-minute is expressed as the delay-minutes per 10,000 train-miles. In NEC, the average delay-minutes are calculated separately in Amtrak-host regions (401mile) and MNR-host regions (55mile), and in MNR-host regions the causes of delays are divided into host (MNR)-responsible delays and Amtrak-responsible delays.

Figure 5.23 shows the trend of OTP in Acela and NER service since FY2005 [59]. Both show similar trends except the FY2005, though Acela's OTP is relatively getting worse compared to that of NER. Acela and NER achieved its best OTP in FY2012, and their OTP has rapidly dropped to the worst level in these 10 years in FY2014-2015. One main reason for this deteriorating trend is that MNR has imposed additional speed restrictions at several curves and bridges on the New Haven Line after its deadly derailment at Spuyten Duyvil station in December, 2013 [60]. Figure 5.24 shows Acela's average delay in the MNR region in FY2011-2015 [61]. After the derailment, particularly MNR-responsible delays shows a significant surge by more than 1000 [minutes / 10000 train-mile] after FY2014Q4, and more than 80% of these delay-minutes are categorized as "slow order delays" or "commuter rail interference". In the Acela service, train-miles in the MNR region account for about 10% of total train-miles in NEC[9], so the 1000 [minutes / 10000 train-mile] increase of MNR-responsible delay is reflected as about 100 [minutes / 10000 train-mile] increase of overall Acela's average delay.

Figure 5.25 shows the delay-minutes of Acela and NER, normalized by train-miles and train frequencies. Train frequencies are estimated from the Amtrak timetable in 2014 [52]. It reflects the surge of delay-minutes in the MNR region in FY2014 as explained above. Also, the average delay shows a negative correlation with OTP, which is intuitive in that better on-time performance leads to fewer delay-minutes.

[9] Author's estimation from published timetable in FY2014. Given no cancellation, train-miles on Amtrak region and MNR region are estimated as 3.2 [million mile], 0.33 [million mile] respectively, from the daily frequency on weekdays, Saturday and Sunday. Estimated total train-miles are 3.6 [million mile] and the actual train-miles were 3.4 [million mile], so this estimation can be said to be realistic.

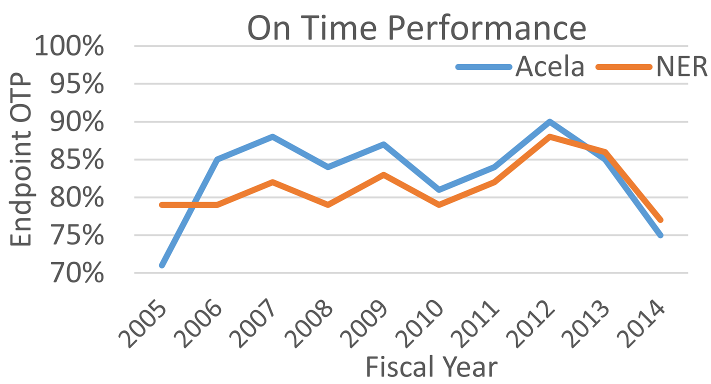

Figure 5.23 On-time Performance Trend

(Source: Ogunbekun, 2015)

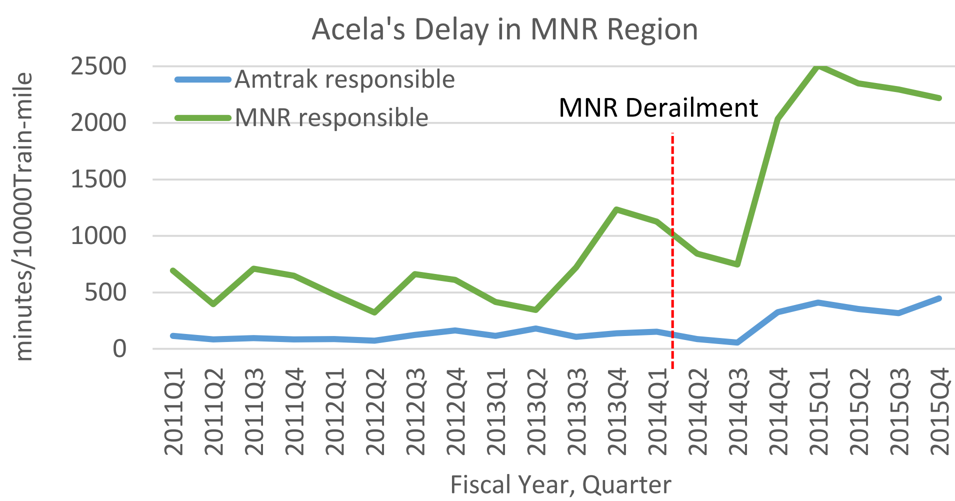

Figure 5.24 Acela's Delay in MNR Region

(Source: FRA)

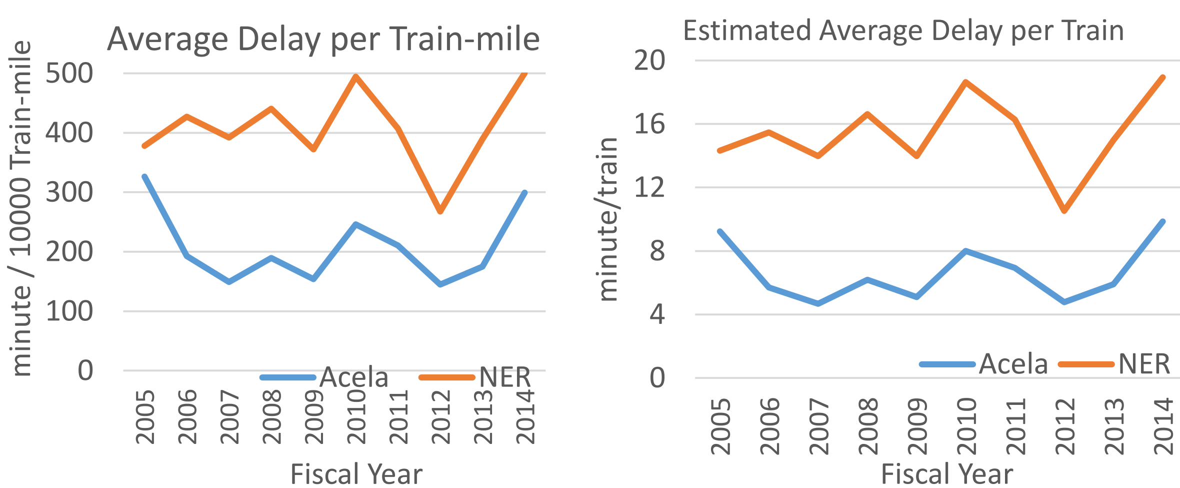

Figure 5.25 Average Delay per Distance / Train

(Source: Ogunbekun, 2015)

5.2.4 Profitability

5.2.4.1 Revenue Side

Figure 5.26 shows the trend of operating revenue in the NEC since FY2002 [54]. Even if the revenue is adjusted by inflating US CPI, the operating revenue has been steadily increasing after the recession period in FY2009. Acela's RPM is about half as large as that of NER as shown in Figure 5.22, but the revenue level is same as NER because the average fare per one passenger-mile ride is much higher on Acela. R-squared between the aggregated operating revenue and aggregated RPM is 66%, which means that the revenue shows a weaker correlation with the trend of RPM than that of the Tokaido Shinkansen (R^2 = 90%). This fact suggests that the average fare paid by each passenger has not been constant. Figure 5.27 shows the trend of average fare per one passenger-mile, and indeed it shows some oscillating trends. Also, as discussed in Section 4.2.3, the average fares of air transportation in the BOS-NY, NY-DC markets have shown similar trends to Acela's average fare, since they are the direct competitors for business-oriented passengers in these markets.

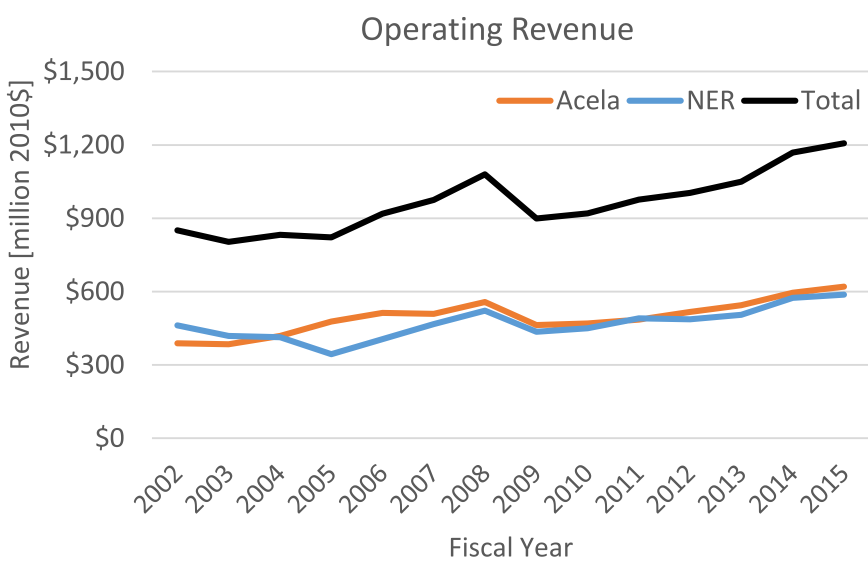

Figure 5.26 Operating Revenue Trend

(Source: Amtrak)

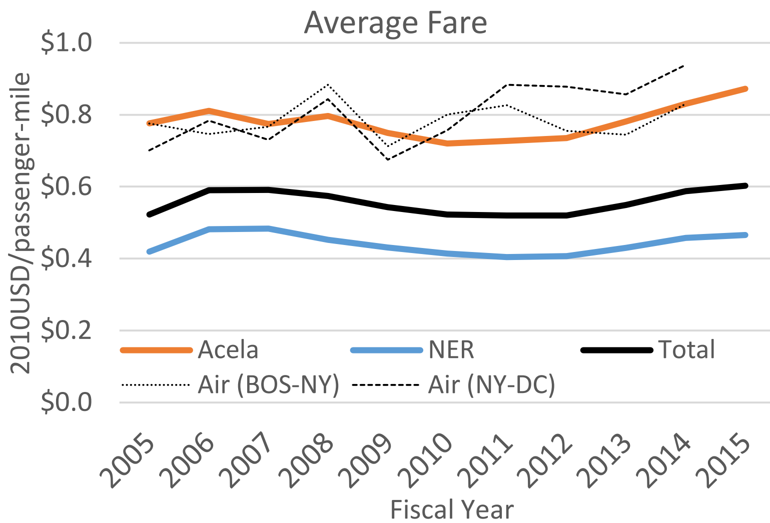

Figure 5.27 Average Fare Trend

5.2.4.2 Cost Side

Amtrak publishes operating cost data of individual lines or train names by allocating costs into specific routes or train services. However, the system to frame and calculate the cost allocation has been upgraded several times, and the definitions and schemes for operating costs have changed accordingly. Therefore, operating costs calculated under different systems are not directly comparable. The good thing is that there are always comparisons of costs between the current year and the previous year under the same, latest cost allocation system in every annual report, so that a one-year incremental change of operating costs under the same definition is traceable. In this thesis, operating costs calculated under the latest system (Amtrak Performance Tracking System, available from FY2009 data) is set as reference data, and operating costs prior to FY2008 are estimated by using the changing ratio of costs between current years and previous years under definitions valid at that time.

Figure 5.28 shows the trend of operating cost (FY2008: estimated, FY2009-: actual) in the NEC. The discontinuity in FY2005 is due to the temporary service suspension of Acela fleets, and costs have increased until 2010 and started decreasing since then, even though ASM has been stable. R-squared between the aggregated operating cost and aggregated ASM is only 10%, which suggests that these two metrics are not strongly correlated. Also, the operating cost is not affected by the recession in FY2009.

From Figure 5.27 and Figure 5.28, Acela and NER can be said to be profitable services. However, operating costs do not account for capital investment or depreciation, and such expenses need to be taken into account in the evaluation of sustainable profitability in the long term operation. Originally, operating profits in the NEC were used as cross-subsidies for unprofitable state supported lines and long distance services, and Amtrak received an operating grant to cover CAPEX in the NEC and OPEX + CAPEX in other routes. However, PRIIA Section 212(c) required Amtrak and other agencies to standardize the way to allocate operating and capital costs among multiple stakeholders (e.g. train operators and infrastructure owners), and restricted cross-subsidizations between intercity passenger, commuter and freight rail services in order to increase transparency of this cost allocation scheme. After this policy, "The Northeast Corridor Commuter and Intercity Rail Cost Allocation Policy", was approved by the NEC Commission in 2014, Amtrak started to utilize the NEC operating profit as an internal funding resource for capital investments only in the NEC from FY2016. This change of financial scheme is illustrated in Figure 5.29.

Figure 5.30 shows the trend of capital expenditures invested on the NEC main line. Amtrak and state agencies have invested about 4 billion dollars on the NEC main line from FY2004-2013, and the American Recovery and Reinvestment Act (ARRA) and High-Speed Intercity Passenger Rail Program (HSIPR) have supplemented CAPEX since FY2008. However, the level of capital investments is far smaller than what is needed to return the NEC infrastructure to the state of good repair (SOGR), whose total backlog is now estimated to be $21.1billion [62] due to a long-term deferred maintenance. The NEC commission [63] estimates that more than $1billion is annually required to be invested to reduce SOGR backlog, and states that additional $1-3billion is necessary to improve capital levels in the NEC. Amtrak and other stakeholders have requested additional funds from federal and state budgets, but not all projects have been funded. Figure 5.31 shows the projection of the total NEC capital needs (including New Haven Line and connecting corridors) in the next 5 years, with a status of funded vs unfunded. Less than half of projected capital needs are funded after FY2017, so it is still uncertain whether SOGR backlogs can be steadily eliminated or not.

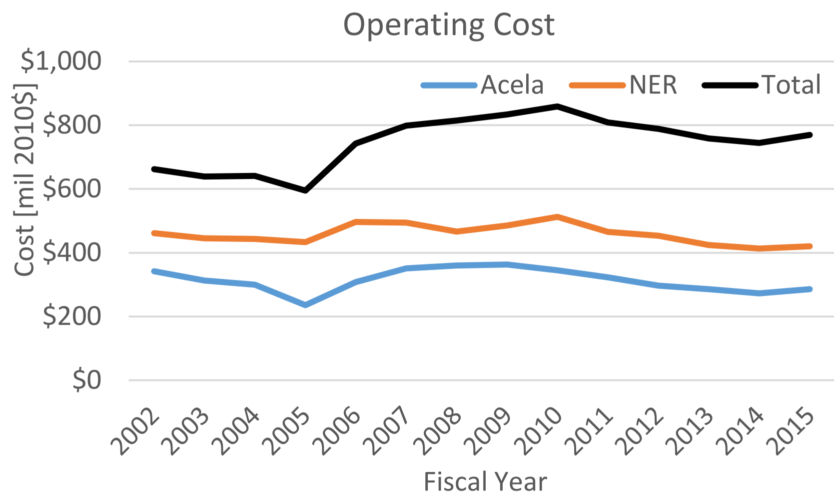

Figure 5.28 Estimated Operating Cost

(Source: Amtrak)

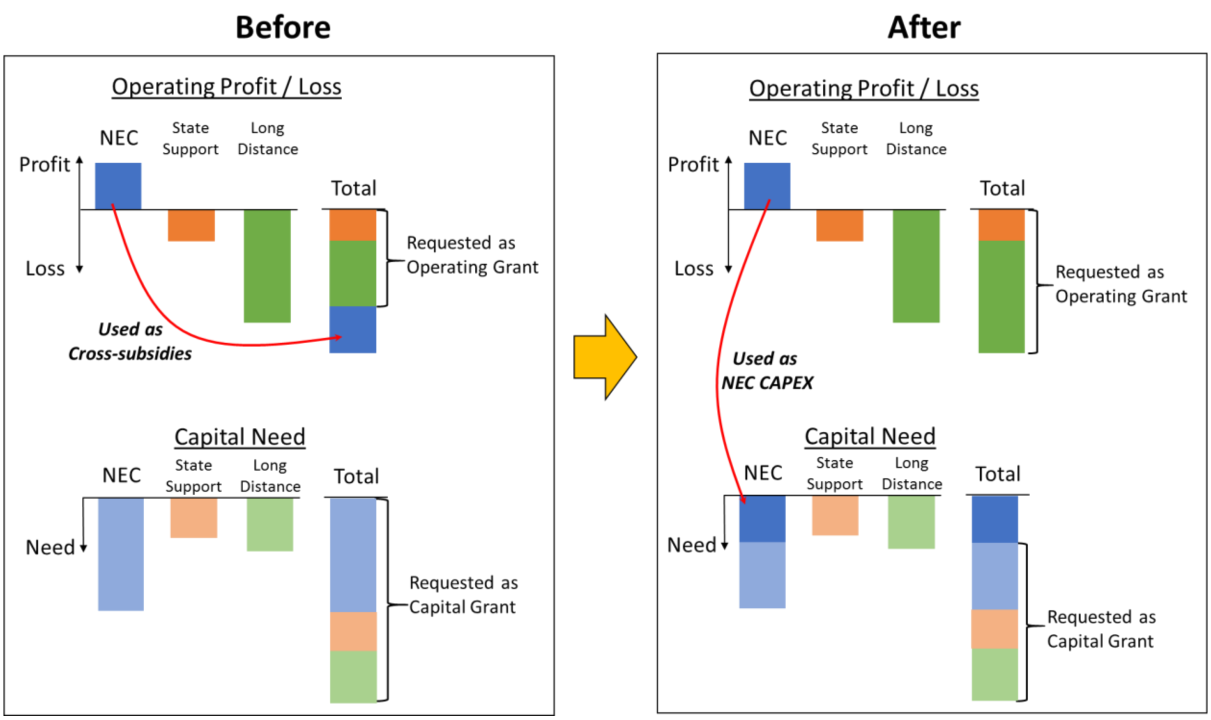

Figure 5.29 Scheme Change in Amtrak's Request for Operating and Capital Grant

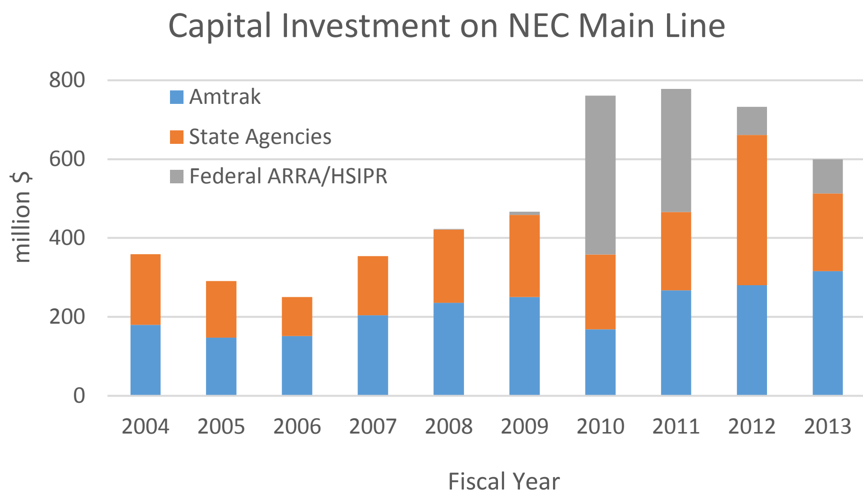

Figure 5.30 Capital Investment on the NEC Main Line

(Source: NEC Commission, 2014)

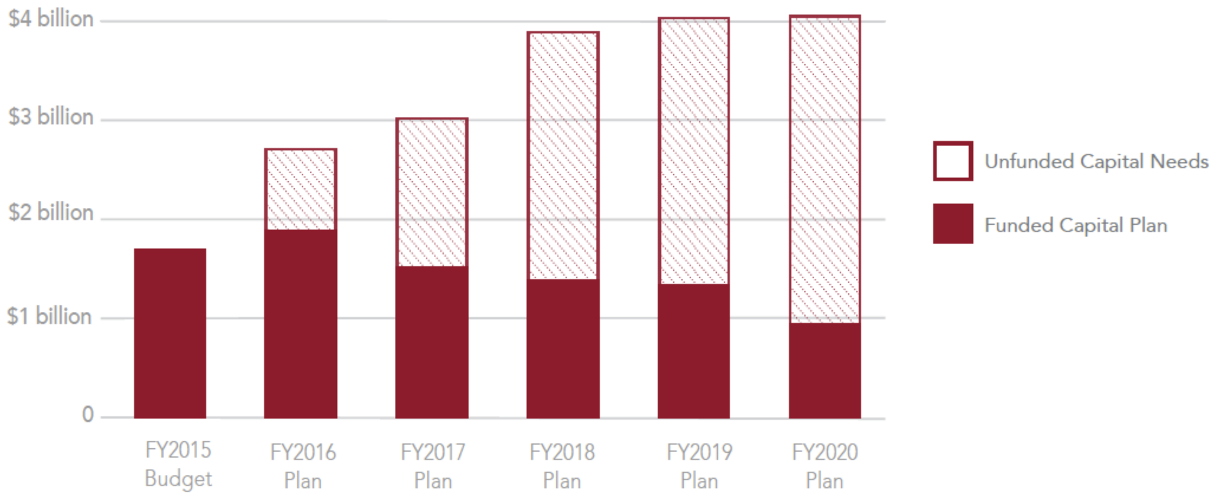

Figure 5.31 The NEC Capital Needs in FY2015-2020: Funded vs Unfunded

(Source: NEC Commission, 2015)

5.2.5 Summary

In the NEC, Amtrak started Acela's operation in 2001, which has been the only HSR service in the US under the HSR definition of USDOT [64]. Acela and NER have been the main intercity passenger rail services provided in NEC, and since 2001 the ridership has steadily increased, capturing market share mainly from air transportation. The service frequency, however, has not changed much, due to capacity constraints of the shared, highly utilized corridor. This characteristic of shared operation / ownership has also heavily influenced the service reliability of Acela and NER, particularly in their on-time performance and average delay-minutes. In terms of safety, most accidents result only in property damages on tracks or equipment, and such accidents are often due to defects of subsystem components such as pantographs or catenaries. Accidents with casualties mostly result from trespassers' interference or human factors. From the perspective of profitability, the NEC service has yielded a fair amount of profits, but they had been transferred as cross-subsidies to other unprofitable Amtrak lines before FY2015. Since FY2016, the NEC profits are used in the NEC capital investments, but because of long-term deferred maintenance, the state of good repair backlog in the NEC cannot be covered only by the NEC profits, and external grants are not sufficient so far. In summary, although Amtrak service yields profitability in operation, its performance in safety and availability is limited by multiple factors, and such limitations prevent boosting the NEC revenues further. In other words, if limiting factors can be eliminated, a positive feedback loop like the Tokaido Shinkansen case could potentially be activated. However, the degree to which the NEC investments can be further increased is primarily a policy issue, further complicated by a large number of stakeholders and competing interests.

5.3 Conclusion

In this chapter, three "ilities" (safety, availability and profitability) in two HSR cases (the Tokaido Shinkansen and Acela/NER services in the NEC) are studied. In the Tokaido Shinkansen, profitable operation due to sufficient demand has yielded affordable capital expenses on its own assets. This investment and the characteristics of the corridor (dedicated, HSR only line) has enabled to achieve high safety and availability. In the NEC, the introduction of Acela has contributed to increases in ridership and revenues in HSR operation. The NEC operation has become profitable, but the cross-subsidization scheme, deferred maintenance in the past decades and the lack of government support have prevented Amtrak from investing enough in its deteriorated infrastructure. As a result, safety and availability have not improved much, which hinders Amtrak's further growth in this market.

The main scope of this chapter was to illustrate the trend of key "ilities" one by one, by using several performance indicators. These indicators tell us several insights shown below:

<u>Baseline level of "ilities"</u>

The magnitude of "ilities" are determined by several conditions, such as

- Historical backgrounds of HSR
- Strategic alternatives of HSR operation (e.g. vertically integrated vs separated, dedicated vs shared, public vs private)
- The overall travel demand in markets and HSR competitiveness among multiple modes

Such conditions differ by countries or corridors, and they are not easy to be controlled in the short run. It is important to consider what kind of factors contribute to decide the baseline levels of "ilities".

<u>Dynamic change of "ilities" from the baseline</u>

"Ilities" have been continuously altered from their baselines by several factors such as

- Internal factors: companies' strategy (e.g. investment plan), quality of assets, cost structures
- External factors: economic conditions (e.g. GDP, CPI), competitors' actions, regulations, subsidies

These factors alter "ilities" and other variables in various time scales. How these factors contribute to such changes is the key issue to understand and model the dynamic behaviors of "ilities" in the long-term HSR operation.

Although "ilities" and contributing factors became clear by the study in this chapter, the relationship among different "ilities" and other variables have not yet been shown explicitly. In the next chapter, the implicit relationship of "ilities" and other key variables in HSR operation is studied qualitatively and quantitatively by using System Dynamics as a modeling methodology.

Chapter 6 Application of System Dynamics

6.1 Overview of System Dynamics

The original idea of System Dynamics (SD) was developed by Forrester [65] at MIT in the 1950s. SD was originally used in the business and management domain, but due to its broad applicability, SD has expanded into various disciplines such as policy analysis, healthcare, the automotive industry, urban development, and so on. [66] In the transportation domain, Abbas and Bell [67] discussed the suitability and appropriateness of SD in transportation policy planning, and listed 12 strengths and 5 limitations in the SD application to transportation modeling as shown in Table 6.1. Shephard [68] categorized papers in the transportation domain with SD application published in 1992-2014, and showed the wide capability of SD in transportation analysis.

The main objective of SD is to construct models of complex systems and understand their dynamic behaviors by using computer simulation [67]. The basic idea of SD comes from control theory, which considers feedback structures among variables. This characteristics enables SD to capture complex, non-linear behaviors in systems, which are difficult to be understood by human's intuition.

In qualitative analysis, causal loop diagrams (CLD) are designed to model causal relationship among relevant variables. In CLD, variables with causalities are connected by arrows with polarities ("+" or "-"). The "+" sign represents that the effect is positively related to the cause; the increase/decrease of the cause result in the increase/decrease of the effect. The "-" sign represents the opposite; the increase/decrease of the cause results in the decrease/increase of the corresponding effect.

When multiple variables and arrows compose closed loops, they become feedback loops. There are two types of feedback loops: reinforcing loops (represented as "R" in the model) and balancing loops (represented as "B" in the model). In reinforcing loops, the increase of one variable leads to the increase or decrease of other variables, which in turn further increases the original variable. Thus, the system behavior is amplified and can lead to an exponential growth. In balancing loops, in contrast, the variables behave to oppose change, and the system behavior is mitigated. Figure 6.1 shows a simple example of a reinforcing loop, a balancing loop and their interaction. In the left reinforcing loop, when the population grows, the birth rate increases and again the population grows more. In the right balancing loop, the growth of population induces more deaths, which in turn reduces the population. The overall behavior of the population depends on the relative magnitude of birth rate and death rate.

In the real world, where multiple feedback loops are coupled and interact, the system behavior becomes complex. Qualitative SD analysis hypothesizes multiple feedback loops in the system and obtains insights of the system behavior from them, but when it is difficult to predict the system behavior intuitively, quantitative analysis is used to simulate the model behavior [66].

In quantitative analysis, variables are divided into three types: stocks, flows and auxiliary variables. Stocks represent the accumulated levels of variables of interest, while flows represent either inflow rates or outflow rates of stocks. Stocks are time integrals of flows, and flows are time derivatives of stocks. Thus, the units of flow are always the units of stock per time period. For example, if the stock is the current number of students in a university (measured in persons), the flow can be the number of new students (inflow) or graduating students (outflow) (measured in persons/year). Auxiliary variables are other variables in the model, which are used in the model formulation, such as parameters or constants.

Stocks and flows are the driver to generate dynamics in the system [66].

1. Stocks are the state of the system, and are the basic information for decision makers.
2. Stocks can store inertia and memory of past events.
3. Accumulation in stocks causes delays.
4. Different rates of inflow and outflow cause disequilibrium dynamics.

These characteristics are critical to understand complex, dynamic behaviors in the system, and they are difficult to capture by CLD. Figure 6.2 shows the example of a stock-flow diagram, which represent the same idea as Figure 6.1. In Figure 6.2, "Population" is a stock, while "Birth" and "Death" are flows. "Birth Rate" and "Life Expectancy" are auxiliary variables. The population can be calculated by solving a differential equation shown below:

$$Population(t) = \int_{t_0}^{t} [Birth(s) - Death(s)]\, ds + Population(t_0)$$

where

$$Birth = Population * Birth\ Rate \qquad Death = \frac{Population}{Life\ Expectancy}$$

In the computer simulation, the differential equation is discretized by a certain time step, and solved numerically.

In this thesis, both qualitative and quantitative SD modeling is considered. In Section 6.2, a qualitative model with CLD is represented to capture the overall dynamics in HSR operation. In Section 6.3, a quantitative model is crafted to evaluate the relationship among variables and "ilities".

Table 6.1 Strengths and Weaknesses of SD in Transportation Planning

Strengths	
1	SD represents complex systems like transportation logically, systematically and in detail.
2	SD clearly accounts for dynamic interactions between supply and demand, which cannot be dealt with by conventional methodologies.
3	SD provides a holistic view in which feedbacks between transportation and other sectors are incorporated.
4	Data requirements in SD modeling clarify necessary data for the development of future transport models.
5	Dynamic, causal feedback interactions as well as empirical data based approaches explicitly represent nonlinearities and time delays among components of the model.
6	SD enables the construction of hypothetical models to test multiple alternatives or assumptions.
7	Conceptual working environment on SD modeling enables modelers to utilize their modeling capability, and provides a platform on which different stakeholders in transportation can discuss.
8	Experimental tools developed in SD modeling can be used to assess different transport policy alternatives and scenarios.
9	Time-dependent behaviors (short, long) in transportation systems can be traced by SD, which implies their dynamic natures and possible adjustments.
10	SD is low-cost, transparent, transferrable and easy to update.
11	SD identifies controlling structures in transportation models, which enables policy makers to consider factors to lead better performance of systems.
12	SD structures the way to consider and understand transportation problems and their solutions.
Limitations	
1	Spatial aspects and distribution effects are difficult to take into account, since SD focuses mainly on the time dimension.
2	SD usually provides approximate outputs and general guidance of policies. Refinement is required to provide numerically precise outputs.
3	SD is usually deterministic.
4	Manual, heuristic optimization in SD is sometimes difficult. Computer-aided optimization algorithms are to be considered together when needed.
5	There are no universal, well-established ways to validate SD model results.

(Adapted from Abbas et al., 1994)

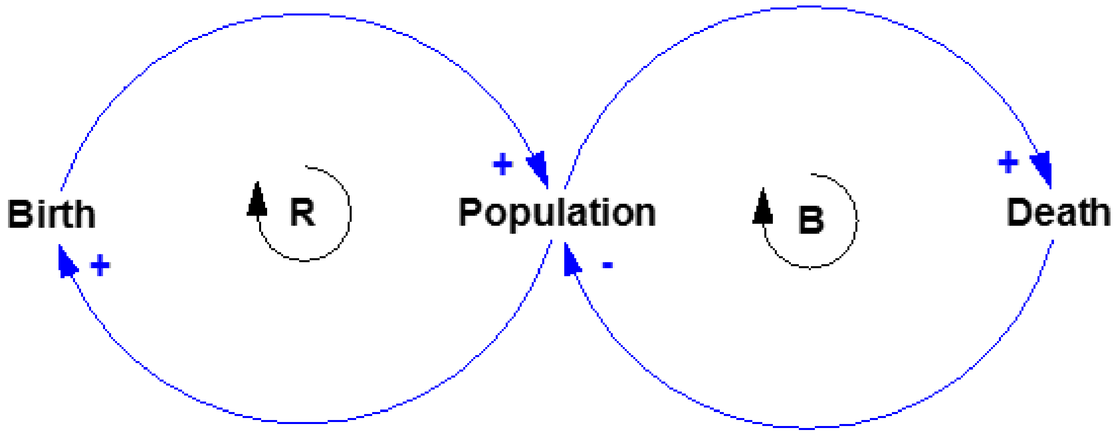

Figure 6.1 Systems with Multiple Feedback Loops

(Adapted from Sterman, 2000)

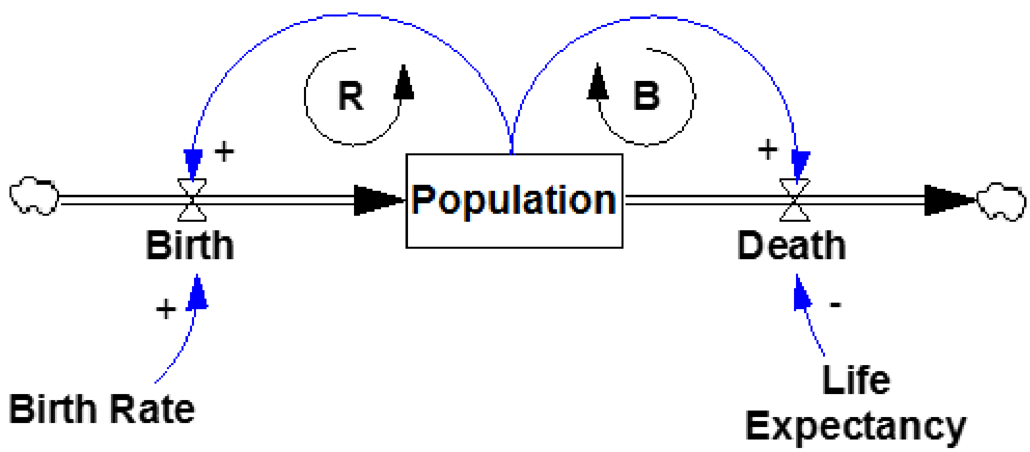

Figure 6.2 Example of the Stock-Flow Diagram

6.2 Causal Loop Diagram Modeling

6.2.1 SD Modeling Process

There are several frameworks to show the process of SD modeling. Figure 6.3 shows two examples to frame the SD modeling process [66] [67]. Although the detailed steps are described differently in these two figures, the overall flow of the modeling process is similar. Also, they share a common notion that the SD modeling process is an iterative process, not a sequential one. In this thesis, the SD modeling process is shown with the following steps:

1. Problem definition, system boundary setting
2. Conceptual SD modeling
3. Model formulation and programming
4. Model simulation
5. Analysis, evaluation

In Section 6.2, the first and second steps are conducted. The third, fourth and fifth steps are followed in Section 6.3 and Section 6.4.

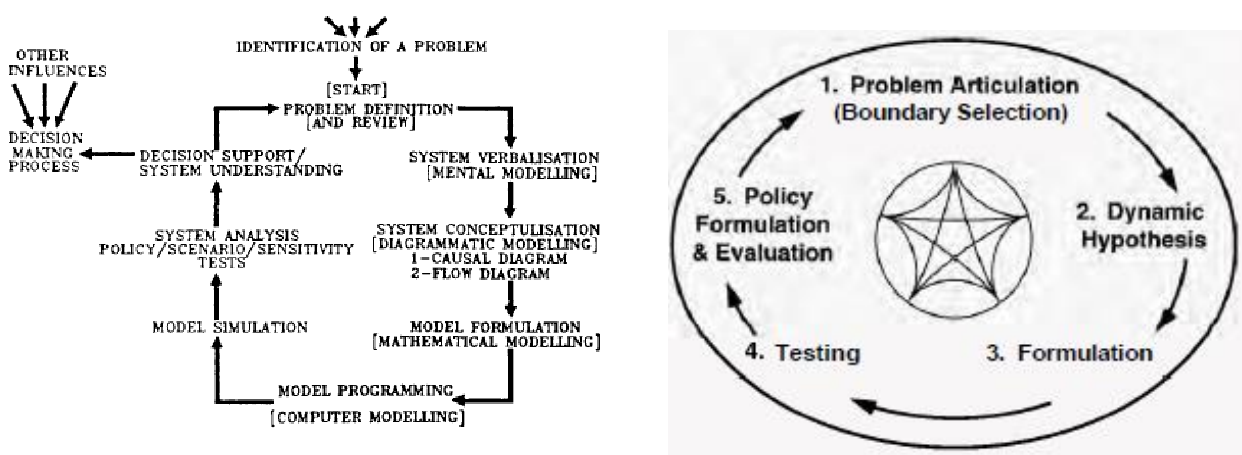

Figure 6.3 SD Modeling Process

(Source: Abbas et al., 1994 (Left) / Sterman, 2000 (Right))

6.2.2 Problem Definition

The initial step of SD modeling is to define the problem of interest, and to select the boundary of the system. Clear problem definition is essential for model builders to choose appropriate variables used in the model, and to exclude irrelevant ones. Also, the design of the system boundary differentiates exogenous variables and endogenous variables. In SD modeling, exogenous variables are ones which cannot be controlled by other variables in the model. Endogenous variables are influenced by other variables in the model, and thus the components in feedback loops are only endogenous variables.

The main scope of this thesis is the dynamic behavior of relevant "ilities" in the long-term HSR operation. Since HSR is a CLIOS system as described in Section 2.3.2, the full picture of HSR operation involves multiple stakeholders in various domains. For example, Sussman et al. [69] detected 23 stakeholders relevant to the NEC. Consideration of all stakeholders in the SD modeling is "just as complex as the system itself and just as inscrutable" [66]. In this thesis, as shown in Chapter 5, HSR operation is mainly considered from the perspective of HSR operators and infrastructure managers. Thus, we set the system boundary at the enterprise level, and the influence of other stakeholders is treated as external factors.

Figure 6.4 shows the causal relationship of basic variables in HSR operation at the enterprise level. Exogenous variables are omitted here, but they are considered in Section 6.2.3. In vertically integrated HSR operation, train operation and infrastructure / rolling stock management are conducted within the same enterprise, so the system boundary corresponds to one enterprise. In vertically separated HSR operation, however, train operation and infrastructure / rolling stock management are controlled by different companies or departments, and also there may exist multiple train operators in one corridor. In this thesis, since the Tokaido Corridor and the NEC are adopted as case studies, the vertically integrated model is mainly considered.

Strictly speaking, Amtrak's HSR operation in the NEC is not perfectly vertically integrated, since part of the NEC infrastructure is controlled by different institutions (owned by MTA, ConnDOT and MBTA, managed by MNR, see Chapter 5). Also, there exist other train operators in the same corridor, which pay access fees to Amtrak and other infrastructure owners. However, Amtrak is the only passenger rail operator which operates trains in the entire NEC, and controls more than 85% of the infrastructure. Also, Amtrak takes the initiative to improve HSR operation in the NEC. Thus, in this thesis, Amtrak is considered as the enterprise which controls both HSR train operation and infrastructure / rolling stock management in the NEC. The effect of other train operators and infrastructure owners are considered as exogenous variables.

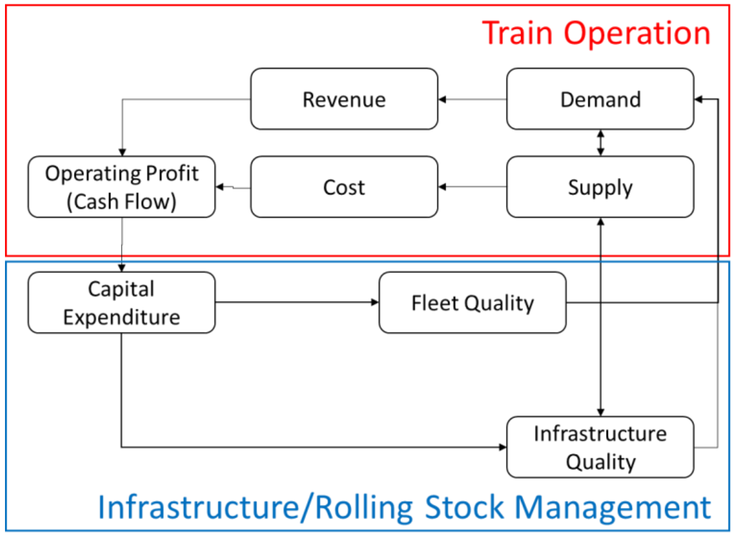

Figure 6.4 Causal Relationship in HSR Operation at Enterprise Level

6.2.3 Conceptual SD Modeling

In this section, the causal loop diagram (CLD) of HSR operation is developed. At first, a CLD of the train operation part and of the infrastructure / rolling stock management part is designed separately; then they are integrated to reveal emergent feedback loops in the entire system. The difference between the Tokaido Corridor and the NEC is considered with CLD, based on the insights obtained in Chapter 4 and Chapter 5. Explanatory notes of symbols used in CLD are shown in Table 6.2.

Table 6.2 Explanation of Symbols in CLD

Symbols	Explanation
Cause + Result	The result changes in the same direction (increase/decrease) as the cause, given all other variables stay constant.
Cause - Result	The result changes in the opposite direction (increase/decrease) as the cause, given all other variables stay constant.
Cause ‖ Result	The result changes with a certain time delay after the cause changes.
R	Reinforcing loops. The arrow direction depends on the flow of causalities.
B	Balancing loops. The arrow direction depends on the flow of causalities.

6.2.3.1 Train Operation

The train operation part is the interface between the train operator and passengers. The balance between demand and supply and pricing strategies are the main drivers for operating revenue, cost, and profit. In this section, CLDs in three subparts (Demand/Revenue, Supply/Cost and Pricing) are developed first, then they are integrated into one CLD.

6.2.3.1.1 Demand / Revenue

The ridership of HSR is obtained from the overall passenger travel demand in O-D markets, and the market share of HSR in these markets. "The size of the pie (market)" in which HSR exists depends on economic factors, such as GDP or income. The market share of HSR in such markets is a function of its relative utility or competitiveness, which is determined by various factors such as average unit price[10], travel time, service capacity, service quality, safety and reliability. Also, the response of competitive modes such as airlines influence the HSR attractiveness. The increase of HSR demand results in the increase of operating revenue and usually profit. Also, when the increased demand approaches the capacity limit, the train operator may increase the supply (train capacity or frequency), if the condition of infrastructure and equipment allow it. Increased capacity drives the increase of the operating cost, and potentially negatively affects the operating profit. Figure 6.5 shows the partial CLD in this subpart.

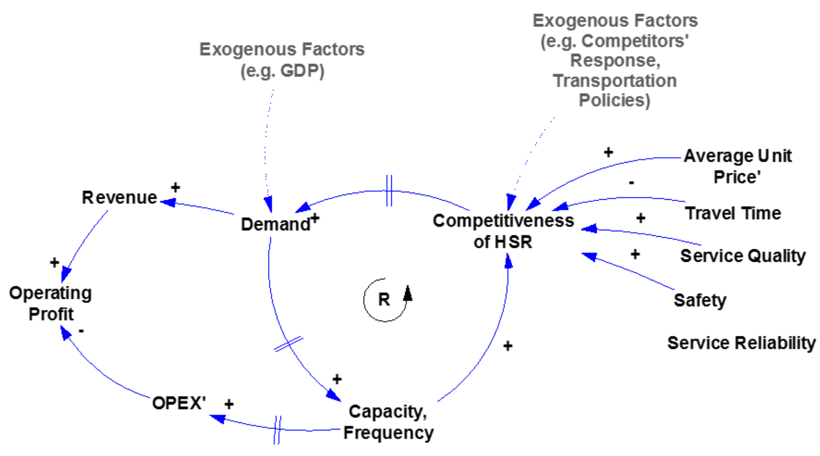

Figure 6.5 CLD in Demand / Revenue Subpart

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[10] In this thesis, unit price means "ticket price/mile" in one itinerary, and average unit price represents the weighted sum of unit prices in all itineraries, which can be represented as "Total Ticket Revenue / Total RPM". In reality, HSR tickets show different unit prices, based on their O-D pairs, travel distances, fare classes, and so on. In the SD modeling in this section, for simplicity, such diversities and distributions of unit prices are aggregated and only the average unit price is used to represent the price level of HSR services.

6.2.3.1.2 Supply / Cost

The amount of supply is driven mainly by the demand, as explained in the Demand/Revenue subpart. How the supply changes in accordance with the demand change depends on the possibility of capacity expansion as well as the agility of management decisions. Particularly, in the shared corridor such as the NEC, the arrangement of capacity expansion may be more inflexible than in a dedicated corridor since it requires negotiation with other stakeholders. The change of supply is reflected in ASM (Available Seat Mile), and it influences the operating cost and profit. Also, the amount of supply affects the infrastructure and rolling stock usage, since more train operations lead to more deterioration. Figure 6.6 shows the partial CLD of this subpart.

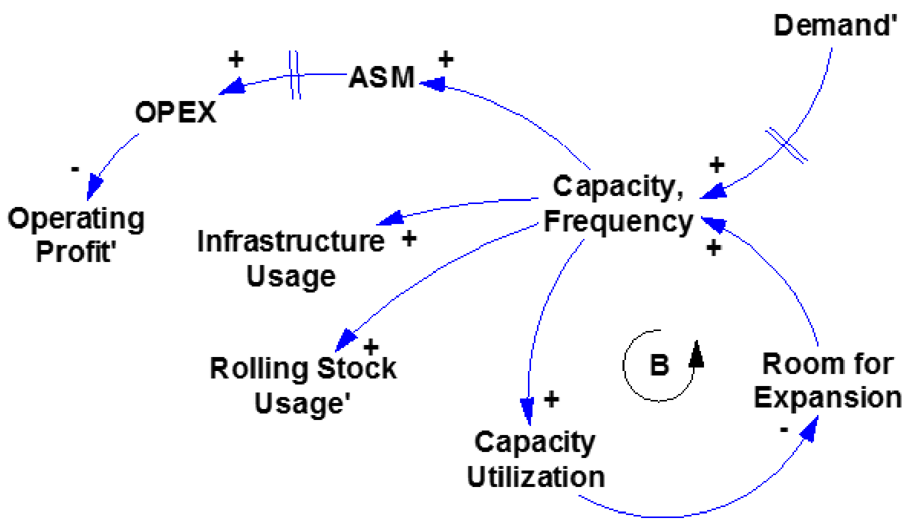


Figure 6.6 CLD in Supply / Cost Subpart

6.2.3.1.3 Pricing

The pricing strategy in HSR differs by country. In Japan, as shown in Figure 5.4, there exists a HSR base fare and most passengers buy tickets with the same price, though there exist several discount tickets. European HSR operators apply more aggressive revenue management strategies like the airline industry, such as price discrimination (e.g. cheap but non-refundable vs expensive but refundable) or dynamic pricing by seasons, days or even trains, based on demand forecasts. In the NEC, Amtrak also applies its own revenue management strategies, though they are not as aggressive as the European ones.

In this thesis, the detailed pricing strategies are not studied, and only the aggregated average unit price [$/passenger-mile] is considered as the variable to evaluate HSR price. The average unit price is total HSR ticket revenue divided by RPM. That is, the average unit prices across all O-D pairs in the HSR line are aggregated with weights of their distance and ridership. The load factor and the operating expense are assumed to be the main drivers to alter the average HSR price level. The change of price affects operating revenue and HSR competitiveness. Figure 6.7 shows the partial CLD in this subpart.

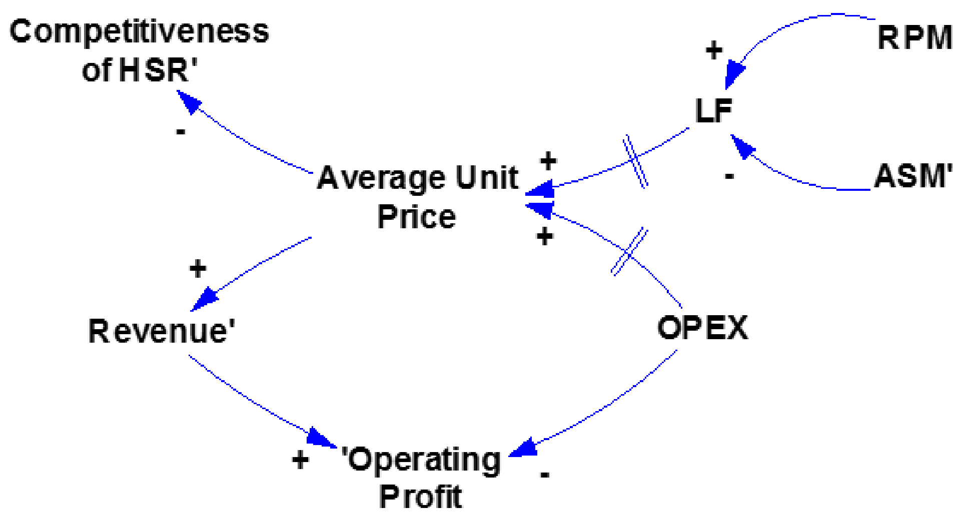


Figure 6.7 CLD in Pricing Subpart

6.2.3.1.4 Integrated Model

Figure 6.8 shows the CLD of the train operation part, which integrates Figure 6.5, Figure 6.6 and Figure 6.7. By integrating them, there emerge several feedback loops explained below:

- Service Opportunity (Reinforcing Loop)

Improvement in HSR operation (e.g. ticket fares, service quality/reliability/frequency, safety and travel time) or external factors (e.g. GDP growth, airlines' withdrawal from markets) contribute to an increase in HSR competitiveness, and the demand for it. Increased demand pushes the supply in the long term if HSR infrastructure and equipment allows, and the capacity expansion again increases the HSR competitiveness. This loop can act as a vicious circle as well. The lack of HSR competitiveness leads to the decline of demand and supply, and the competitiveness deteriorates even more.

- Dynamic Pricing (Balancing Loop), Capacity Expansion (Reinforcing Loop)

The increased demand initially pushes up the load factor, which raises the average HSR price. This price adjustment make some passengers deviate from HSR to other modes, and the demand goes down. At the same time, the increased demand results in the capacity expansion with time delay, which stabilizes the increased load factor. This reduces the average price and recovers HSR competitiveness. Thus, the balance between the demand and the supply affects the price and HSR competitiveness, which again influences the demand.

- Capacity Limit (Balancing Loop)

There exists a certain limit of train capacity on corridors, which is determined by several factors such as infrastructure conditions, fleet size, train speed, interference with other train operators, and so on. The increase of capacity utilization rate suppresses the room for further capacity expansion, which slows down the increase rate of capacity.

- Cost Variation (Balancing Loop)

The capacity expansion driven by increased demand results in the increase of operating costs, since it costs more for the operation and maintenance of rolling stock and infrastructure. The increased OPEX leads to raising the average price with time delay, which reduces HSR competitiveness and the demand.

The operating profit and the infrastructure and rolling stock usage are used as inputs to the infrastructure / rolling stock management part. In turn, several input variables for HSR competitiveness are derived from the infrastructure / rolling stock management part.

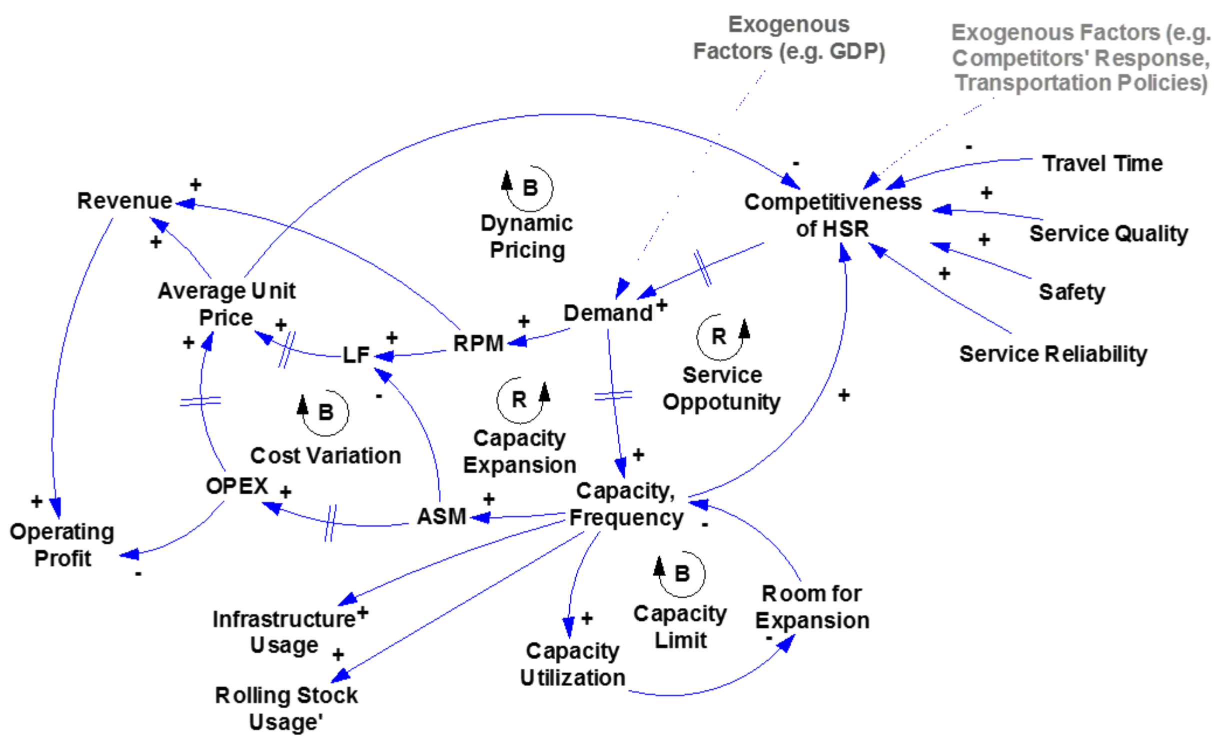


Figure 6.8 CLD in Train Operation

6.2.3.2 Infrastructure / Rolling stock Management

The Infrastructure / Rolling Stock Management part represents how capital expenses are used to rehabilitate or replace or expand equipment and infrastructure. Infrastructure represents tracks, power supplies, signaling systems, structures, and so on. Rolling stock includes passenger cars and locomotives. In this section, CLDs in two subparts (infrastructure, rolling stock) are developed; then they are integrated into one CLD.

6.2.3.2.1 Infrastructure Management

The driver for the infrastructure management is the allocated capital investment budget (CAPEX) for infrastructure. This budget comes from either the operating profit of the train operation, or external funds such as public subsidies or access charges from other train operators. CAPEX for infrastructure is divided into two categories: the normal replacement and the backlog elimination. The budget for normal replacement is used to keep the infrastructure in a state of good repair, such as replacing ties, rails, catenaries and so on. Meanwhile, the usage of infrastructure by train operation drives the required level of infrastructure replacement. If the budget for normal replacement is insufficient compared to the requirement, some infrastructure is not properly maintained, and becomes part of the maintenance backlog. The budget for backlog elimination is used to remove such maintenance backlog. The amount of maintenance backlog indicates the condition of infrastructure, and affects service reliability and safety. Figure 6.9 shows the partial CLD in this subpart.

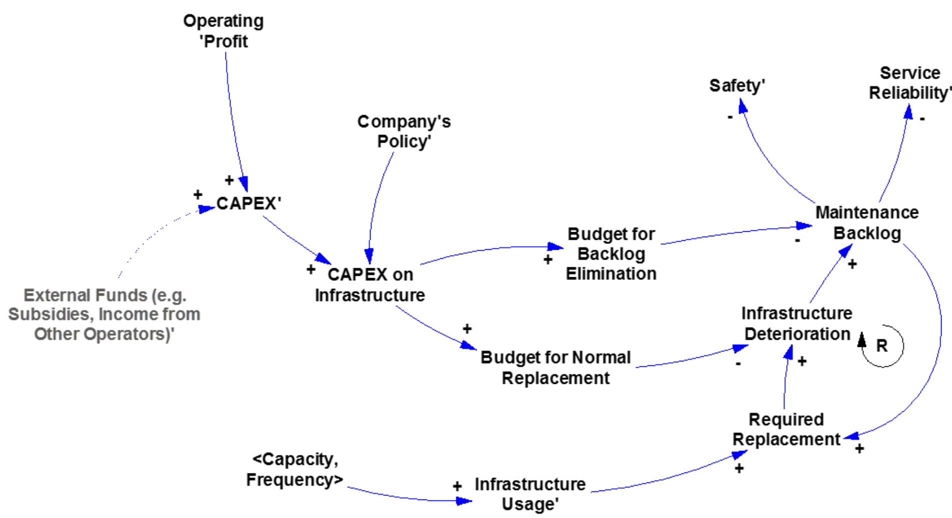


Figure 6.9 CLD in Infrastructure Management Subpart

6.2.3.2.2 Rolling Stock Management

Capital Expense (CAPEX) for rolling stock derives from the overall CAPEX. The allocation of CAPEX into infrastructure and rolling stock depends on company policy, based on their condition. CAPEX on rolling stock represents the overhaul and renewal of old fleets into new ones. Such investment increases the quality of fleet, and positively affects factors in the train operation. Meanwhile, the usage of rolling stock causes the deterioration of fleet quality, and negatively influences the train operation. Figure 6.10 shows the partial CLD in this subpart.

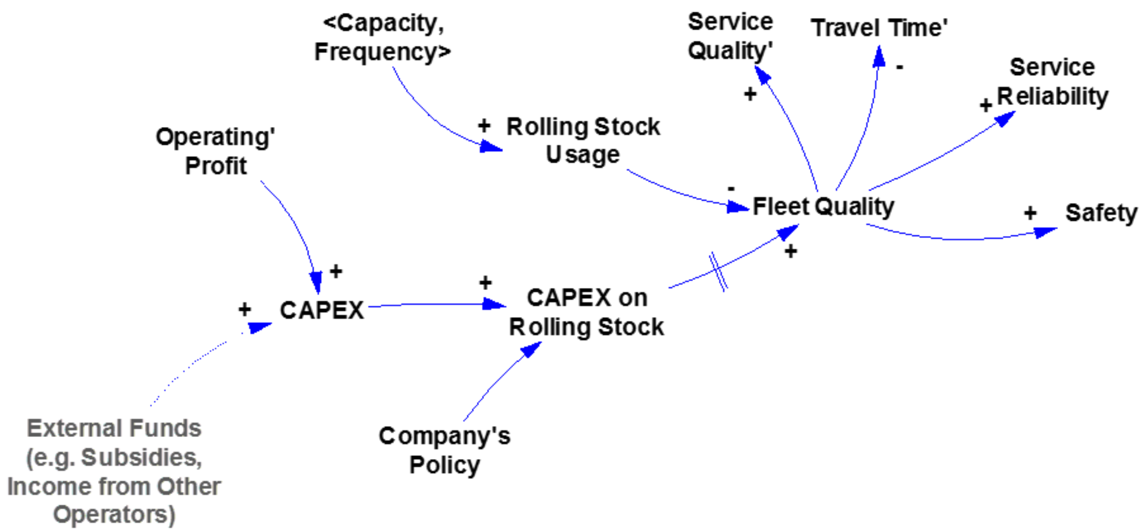


Figure 6.10 CLD in Rolling Stock Management Subpart

6.2.3.2.3 Integrated Model

Figure 6.11 shows the CLD in the infrastructure / rolling stock management part, which integrates Figure 6.9 and Figure 6.10. There exist one feedback loop explained below:

- Deferred Maintenance (Reinforcing Loop)

Accumulated maintenance backlog in the infrastructure requires more investment to maintain it. Unless the budget for normal replacement is sufficiently allocated, the deterioration rate of existing infrastructure accelerates and the maintenance backlog increases more and more.

In Figure 6.11, several variables are added to supplement safety and service reliability. Safety and service reliability are emergent properties in HSR operation, so systemic factors (e.g. organizational structures, human factors, deficiencies in design/manufacturing) and external factors (e.g. regulation, weather, interference of other train operators) as well as the maintenance backlog influences them. Such factors are sometimes difficult to quantify, so there are no polarities shown in these arrows.

In summary, in the infrastructure / rolling stock management part, CAPEX is used as the input to manage infrastructure and rolling stock, and the management result is reflected in several factors influencing HSR competitiveness in the train operation part. In the next section, the train operation part and the infrastructure / rolling stock management part are integrated into one CLD.

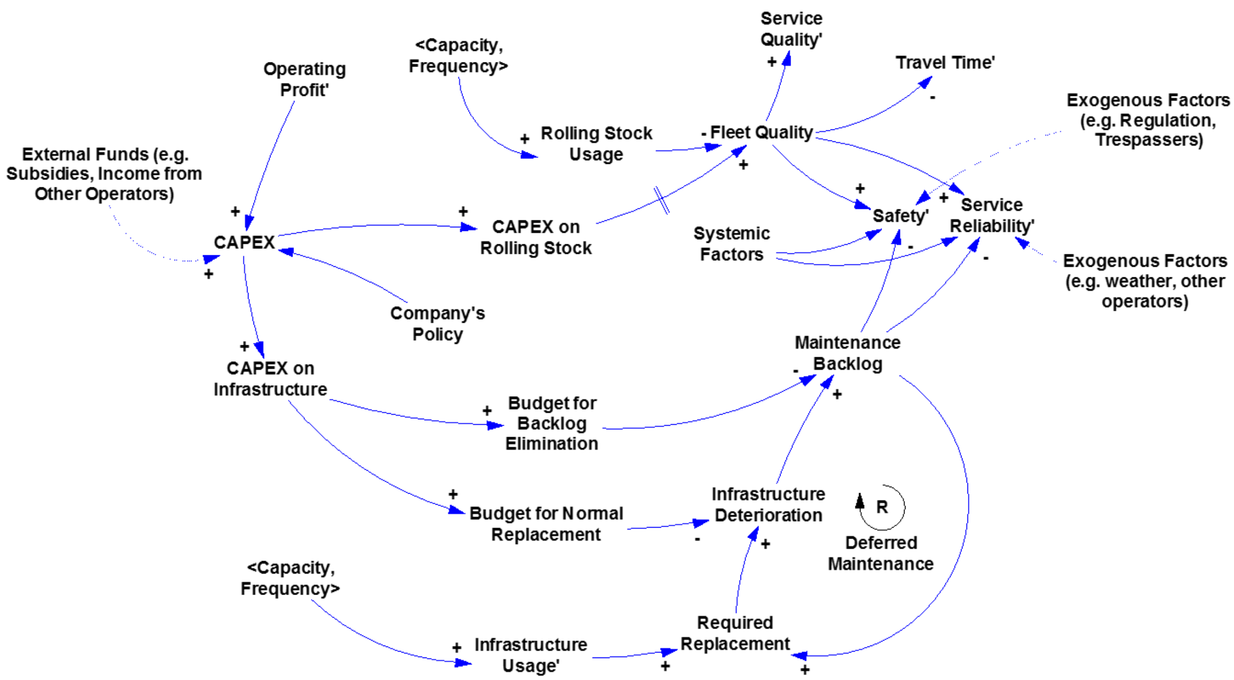


Figure 6.11 CLD in Infrastructure / Rolling Stock Management

6.2.3.3 Integrated CLD

Figure 6.12 shows the overall CLD in HSR operation, which integrates Figure 6.8 and Figure 6.11. The red square shows the area of the train operation part, and the blue square shows the area of the infrastructure and rolling stock management part. By integrating them, there emerge several additional feedback loops explained below:

- Infrastructure Quality, Rolling Stock Quality (Reinforcing Loop)

Sufficient operating profit or external funding enable HSR operators to dedicate CAPEX for infrastructure and rolling stock. The capital investment on infrastructure reduces the maintenance backlog, which contributes to safe and reliable train operation. In the same way, the capital investment on rolling stock improves the fleet quality, which positively affects the train operation. Such positive influence again ensures HSR attractiveness and the operating profit. These loops can also work viciously. The lack of capital investment in infrastructure and rolling stock leads to their insufficient quality, which impactts negatively on HSR competitiveness. This leads the further reduction of operating profit.

- Infrastructure Utilization, Rolling Stock Utilization (Balancing Loop)

High frequency, high capacity utilization causes the intensive usage of infrastructure and rolling stock, which results in the increase of their deterioration rates. If not properly maintained or replaced, deteriorated facilities negatively affect the train operation, and eventually lead to a decrease of demand and supply.

The combination of the “Infrastructure Quality” loop and the “Deferred Maintenance” loop can be strong vicious reinforcing loops if HSR operation is underfunded. Figure 6.13 shows these vicious loops in underfunded HSR operation (highlighted in red). These loops proceed as follows:

1. The lack of the operating profit or external funds lead to insufficient CAPEX on the infrastructure.
2. Insufficient CAPEX causes the infrastructure manager to defer necessary investment.
3. Deferred maintenance policy increases the maintenance backlog, which accelerates the deterioration rate of the infrastructure. This leads to the further increase of the maintenance backlog.
4. Poorly maintained infrastructure impacts safety and service reliability, which negatively affects HSR competitiveness.
5. Low HSR competitiveness causes passengers to use other modes, and thus the operating revenue decreases. This leads to a further reduction of the operating profit.

Figure 6.12 suggest that the train operation part and the infrastructure / rolling stock management part are integrated with each other via some measures of key "ilities", such as operating profit, safety and service reliability. In order to make HSR operation sustainable, HSR operators need to

1. At first make "Infrastructure Quality, Rolling Stock Quality" reinforcing loops virtuous cycles
2. Then control "Infrastructure Utilization, Rolling Stock Utilization" balancing loops when facilities are heavily utilized

That is, after the service is expanded, HSR operators need to ensure sufficient CAPEX to maintain facilities in a state of good repair, so that HSR service is competitive enough to attract passengers and generate operating revenue/profit while keeping accident/incident rates as low as possible.

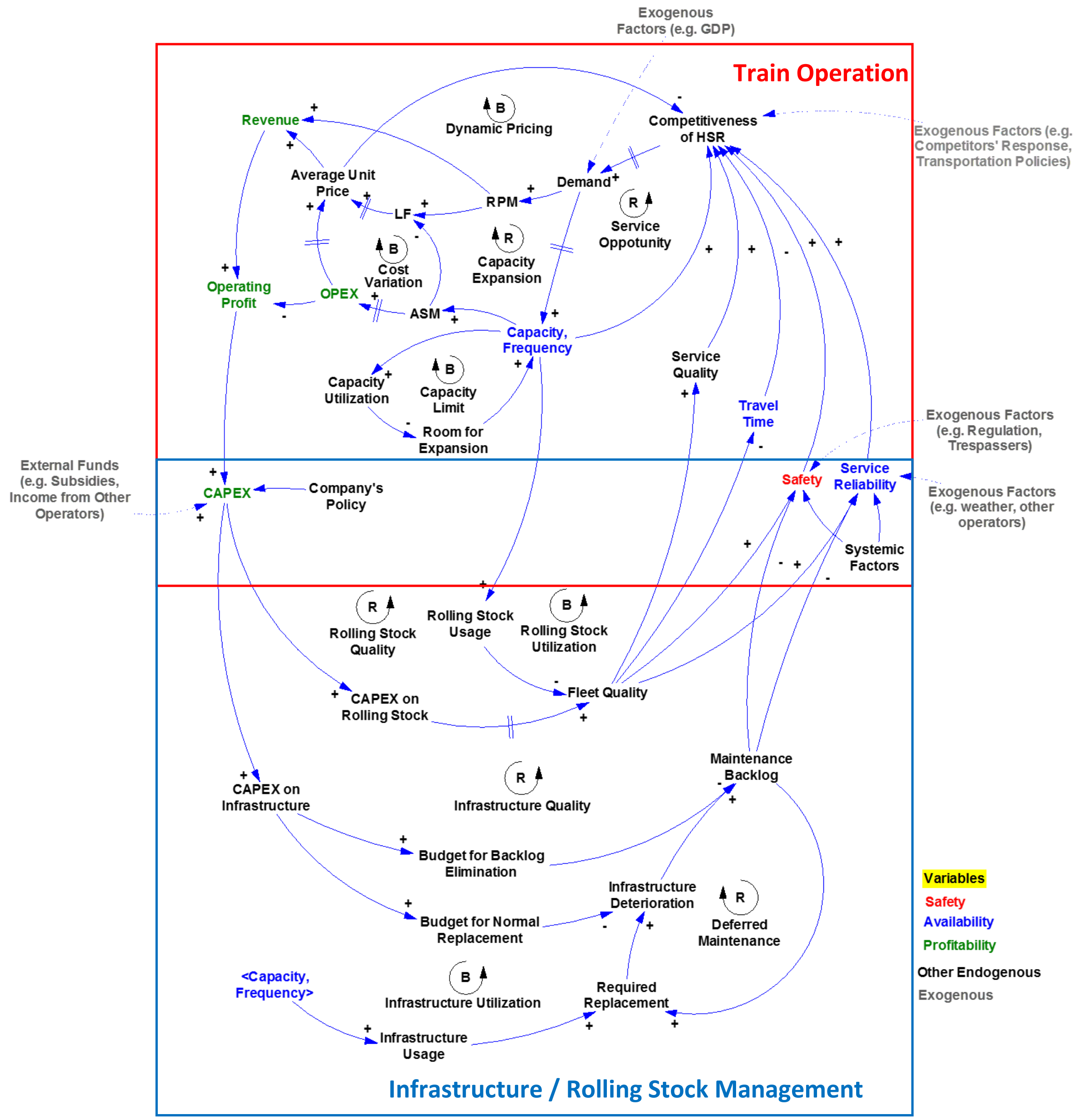


Figure 6.12 Conceptual System Dynamics Model of HSR Operation

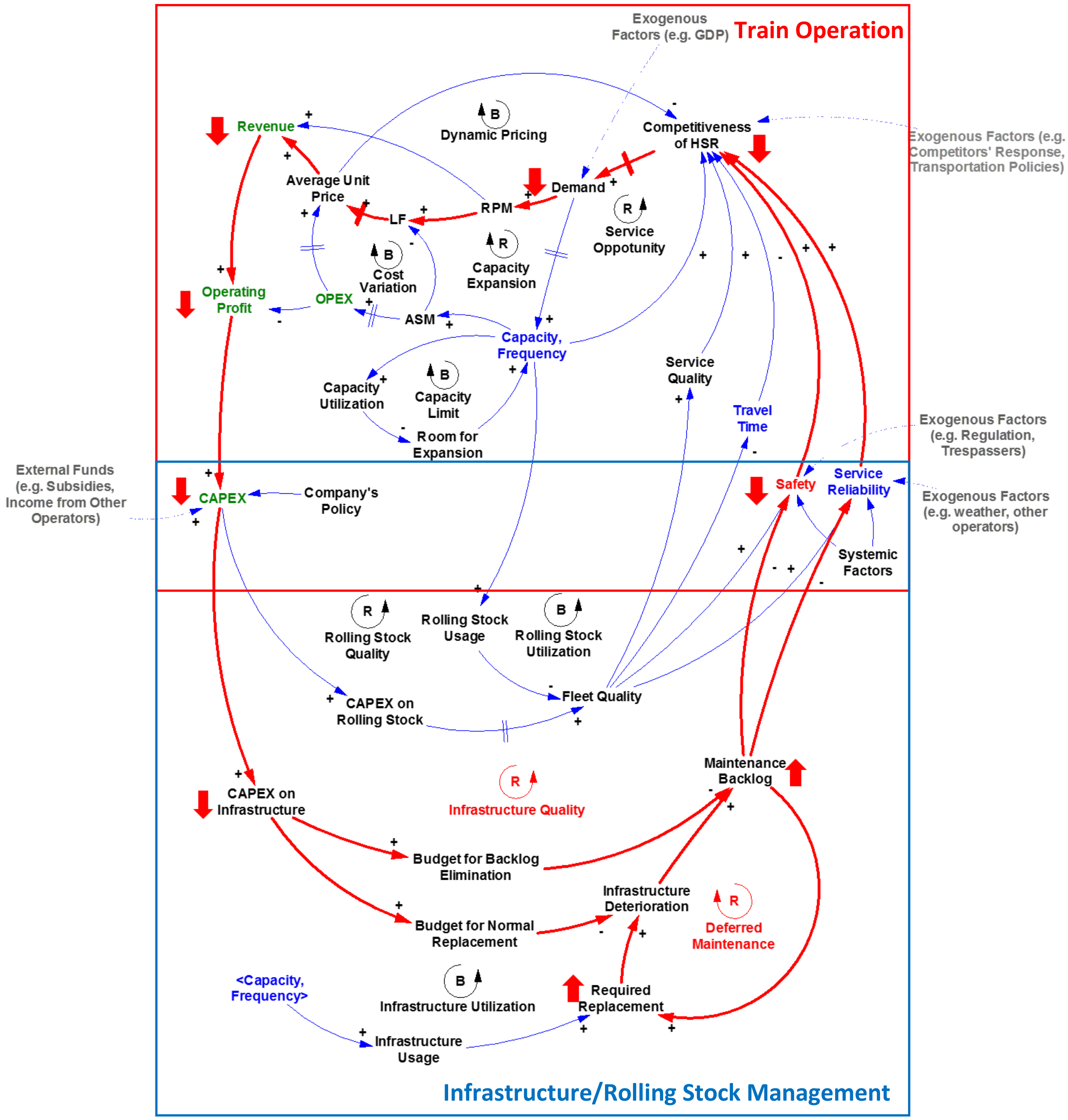


Figure 6.13 Vicious Loops in Underfunded HSR Operation

6.2.3.4 Application of Causal Loop Diagrams to two HSR cases

Figure 6.12 represents a general idea showing a causal relationship among variables in vertically integrated HSR operation. The existence itself, or the strength of each causal arrow differs for various HSR systems. In this section, two cases studied in Chapter 4 and Chapter 5 (the Tokaido Shinkansen and Amtrak' service in the NEC) are considered again, to see how some of their specific operating conditions can be reflected in this CLD. Several causal arrows shown in Figure 6.12 are covered in this section, and some of other arrows are quantitatively evaluated in Section 6.3.

6.2.3.4.1 The Tokaido Shinkansen

- Relationship between the operating profit and CAPEX

The operating profit is used for various purposes such as cross-subsidization for conventional lines and debt repayment, as well as CAPEX for HSR. In other words, CAPEX for HSR is fully covered by the operating profit, and no external funds are supplied.

- Pricing Strategy

As stated in Section 6.2.3.1, the pricing strategy of the Tokaido Shinkansen is relatively static. The base fare, or the upper-bound fare has been fixed, while several discount tickets have been introduced to attract passengers. In this sense, the sensitivities of the average price with respect to the change of the load factor and the operating costs would be small (small price elasticity of demand). The quantitative evaluation of these sensitivities is conducted in Section 6.3.

- Renewal of rolling stock

JRC has continuously introduced new fleets to the Tokaido Shinkansen. When JNR operated the Tokaido Shinkansen, it introduced two types of rolling stock in 23 years: Series 0 and Series 100. After JRC succeeded its operation, it introduced 4 types of rolling stock in 28 years: Series 300, Series 700, Series N700 and Series N700A. Some technical characteristics of these rolling stocks are shown in Appendix C. Figure 6.14 shows the fleet composition over time. Every 7-10 years new types of rolling stock have been introduced to replace obsolete train sets. This policy has required substantial capital investment on rolling stock, but has enabled JRC to keep the fleet quality high. In particular, in 2003, all train sets became able to run at 270kph, compared with 220kph in some train sets before that. This change not only improved the fleet quality, but also increased the maximum capacity limit in the line, since uniform speed of fleet removed potential queues in the line. This contributed to the growth of supply and demand after 2003.

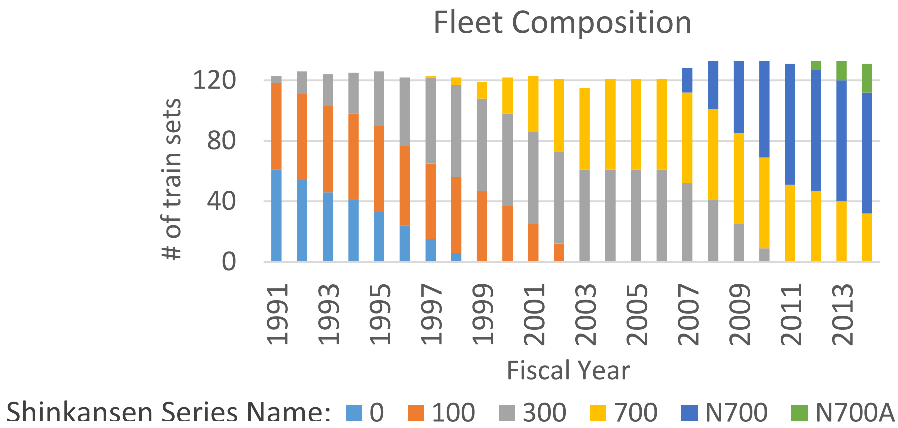


Figure 6.14 Trend of Fleet Composition in the Tokaido Shinkansen

Figure 6.15 shows the CLD for the Tokaido Shinkansen, which is adapted from Figure 6.12. Red signs, arrows and variables represent specific factors in this HSR system described above.

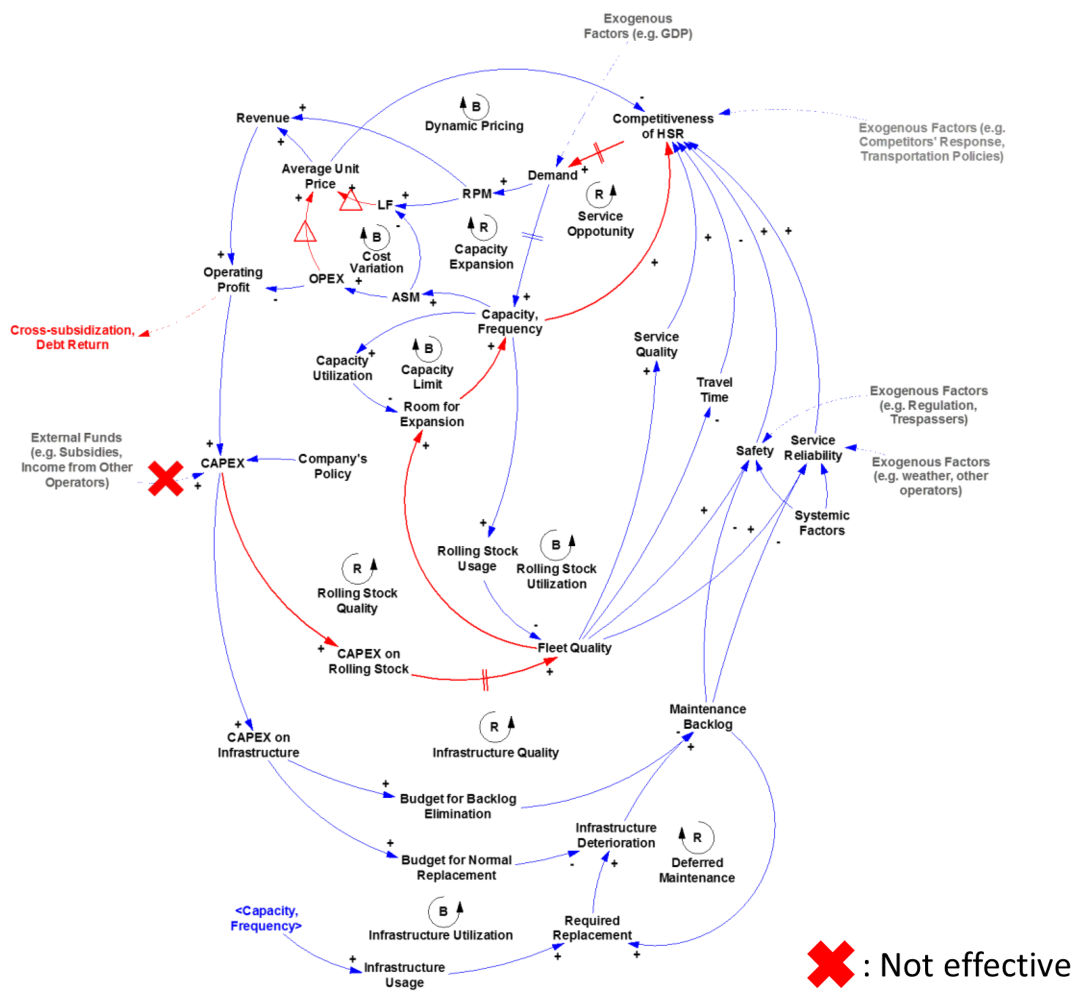


Figure 6.15 CLD for the Tokaido Shinkansen

6.2.3.4.2 Amtrak Service in the NEC

- Increase of HSR competitiveness

After the introduction of Acela in 2001, HSR market share in the NEC has dramatically increased, as shown in Figure 4.10. This is because HSR competitiveness has improved, compared to other modes such as air transportation. Particularly, BOS-NY service has significantly improved in fleet quality (from diesel trains to Acela), frequency and travel time after the electrification. In addition, the deterioration of utility in other modes such as congestion of highways or longer security checks at airports after 9.11 are the contributing factor for HSR growth in this market.

- Barrier for Capacity Expansion

The NEC is a shared corridor of intercity HSR, commuter railroads and freight railroads. The frequency of commuter rails is much higher than that of HSR services. Indeed, the NEC Commission [38] reports that there are over 2,000 intercity and commuter trains per day on the entire NEC, while Amtrak's intercity trains account for only about 100 of them. The intercity HSR train service interferes with all eight commuter rails in the NEC, so the time table coordination of HSR requires an extensive, complex negotiation with them. This hinders Amtrak from expanding HSR capacity flexibly.

- Relationship between operating profit and CAPEX

As discussed in Section 5.2.4, the operating profit in the NEC had been used to cross-subsidize the unprofitable Amtrak lines throughout in the US, and CAPEX for infrastructure and rolling stock were covered by subsidies from federal governments and states. Thus, the arrow between the operating profit and CAPEX was not active, which made "Infrastructure / Rolling Stock Quality" reinforcing loops inactive. This fact means that there is little flexibility in making decisions about how to maintain facilities from internal funding resources. It makes it difficult for Amtrak to design a sustainable, long-term investment plan for its infrastructure and rolling stock.

- Long-term deferred maintenance

From a historical perspective, the infrastructure in the NEC has been used for decades, over the 19th, 20th and the 21st Centuries. The NEC Commission [62] indicates that several bridges or catenary wires were constructed in the 19th Century or the beginning of the 20th Century, and now they require immediate rehabilitation or reconstruction. The replacement of large structures such as movable bridges had been deferred by successive infrastructure managers, due to the large capital requirement and the lack of funding. Now the maintenance backlog is too large to be recovered by current level of federal grants for

CAPEX, or by the operating profit. In summary, in terms of the SD model, the "Deferred Maintenance" loop is working strongly, and as shown in Figure 5.31, the increase of capital investment is necessary to mitigate this vicious cycle.

Figure 6.16 shows the CLD for Amtrak operation in the NEC, which is adapted from Figure 6.12. Red signs, arrows and variables represent specific factors in this HSR system described above.

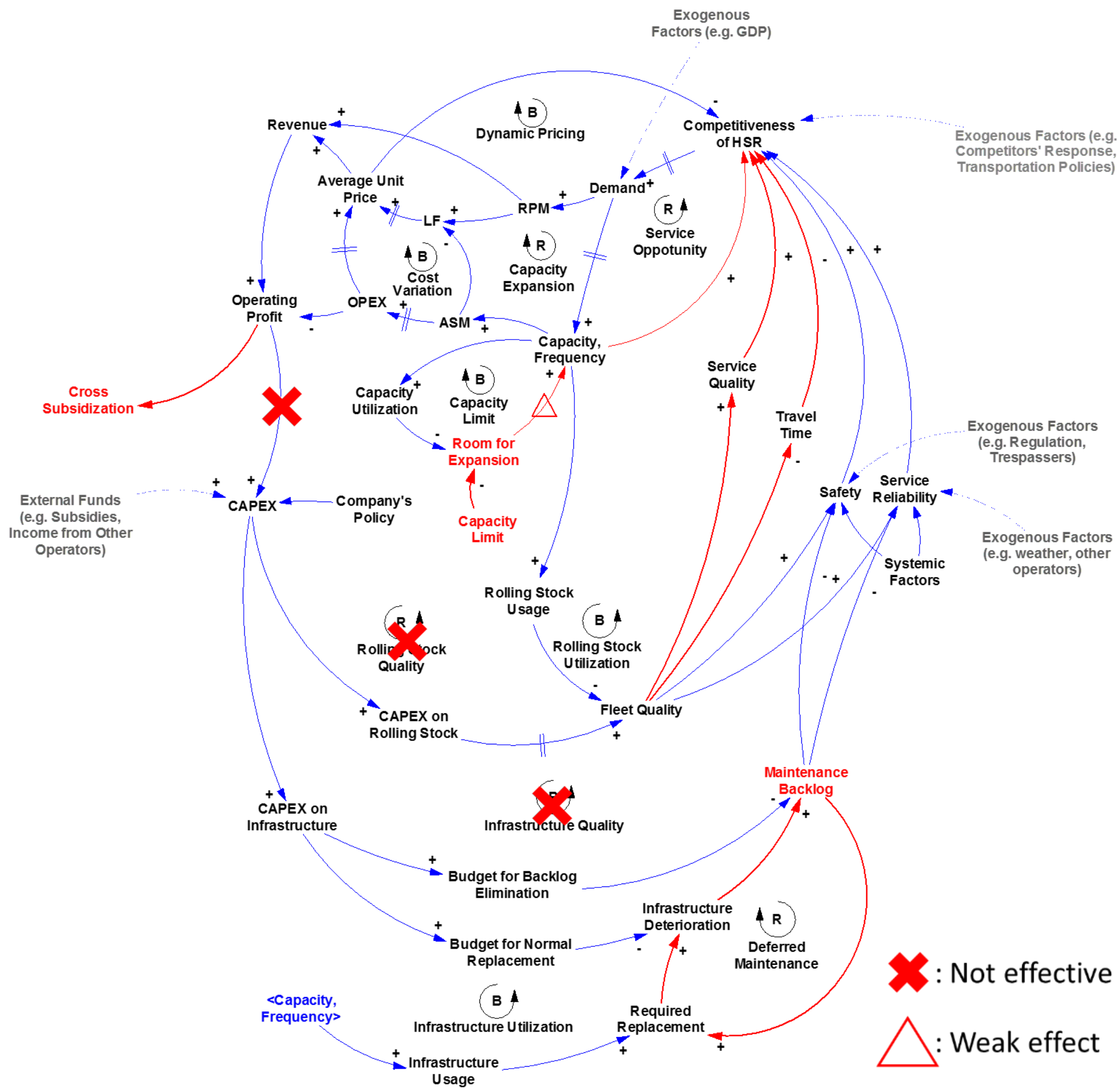


Figure 6.16 CLD for Amtrak Operation in the NEC

6.3 Numerical SD Modeling

In this section, the CLD developed in Section 6.2.3 is converted to a numerical model, and the strength of causalities is quantitatively evaluated. One note here is that the validity of SD is interpreted as the usefulness of the model, rather than the preciseness of numerical values [67]. That is, the objective of numerical SD modeling in this section is to validate structures of the CLD presented in the last section, and to deepen understanding about causal relationships among the variables of interest.

In numerical SD modeling, empirical data is used to estimate unknown parameters in the model, so the time horizon of SD modeling depends on the availability of reference data. In this thesis, time horizons in the two cases (the Tokaido Shinkansen and Amtrak service in the NEC) are set as Table 6.3.

Table 6.3 Time Horizon in Numerical SD Modeling

Case	Time Horizon (Fiscal Year)	
	Fiscal Year	Calendar Year, Month
The Tokaido Shinkansen	FY1992-FY2014	1992.4 – 2015.3
Amtrak Service in the NEC	FY2005-FY2015	2004.10 – 2015.9

6.3.1 Model Formulation and Programming

In this section, the relationship of variables in the numerical SD models are discussed, and several important formulations are shown. In the SD model, variables shown in red letters represent unknown parameters, whose values are estimated in the simulation. The list of variables used in numerical SD models are shown in Appendix D.

6.3.1.1 Train Operation

6.3.1.1.1 Demand / Revenue

- Ridership

In the demand modeling, the Cobb-Douglas function is used to estimate the ridership as shown below:

$$\ln(Ridership) = \alpha + \sum_{i=1}^{n} \beta_i \ln(x_i)$$

Here α is a constant, x_i are inputs for demand, and β_i are elasticities of ridership with respect to x_i. When the reference value[11] of ridership and x_i are introduced, the above equation can be written as

$$\ln\left(\frac{\text{Ridership}}{\text{Reference Ridership}}\right) = \sum_{i=1}^{n} \beta_i \ln\left(\frac{x_i}{x_{iREF}}\right)$$

Or by using E_i (effects of inputs),

$$\text{Ridership} = \text{Reference Ridership} \times \prod_{i=1}^{n} E_i \quad where \ E_i = \left(\frac{x_i}{x_{iREF}}\right)^{\beta_i}$$

GDP, average unit price, ASM, travel time, service reliability, safety and airlines response are used as x_i. There are delays in the perception of ASM (supply), reliability and safety, so time constants are inserted to adjust delays. Reference values of x_i are historical data in the initial year of the simulations.

- RPM

RPM is the product of ridership [passenger/year] and average travel distance per passengers [passenger-mile/passenger]. In this section, 191.0 for the Tokaido and 161.7 for the NEC are used as average travel distance, which are the average value in their time horizon.

[11] In the numerical modeling in this section, the ridership in the initial year of the time horizon is chosen as the reference value of ridership.

- Operating Revenue

HSR operating revenue is composed of ticket revenue and ancillary revenue. Ticket revenue is obtained from RPM and average unit price. Ancillary revenue refers to additional income such as onboard food services. In the Tokaido, corridor ticket revenue and ancillary revenue are not distinguished[12], only ticket revenue is considered. In the NEC, ancillary revenue is estimated as 2.8% of ticket revenue, which is the average value in FY2005-2015.

Figure 6.17 shows the overview of SD formulation in Demand/Revenue subpart. Variables with red letters are unknown parameters inserted to formulate equations, and their values are estimated in the next section by comparing simulation results and historical data.

Figure 6.17 SD Formulation in Demand / Revenue Subpart

[12] Food service in the Tokaido Shinkansen is conducted by an associated company, and its revenue is not counted as the non-consolidated revenue of CJR.

6.3.1.1.2 Supply / Cost

- ASM

The design of ASM is modeled as "Adjustment to a Goal" [66]. Target load factor (unknown parameter) and current RPM decide target ASM, and the discrepancy between target ASM and actual ASM drives its adjustment. ASM change rate can be expressed as

$$\text{ASM Change Rate} = \frac{\text{RPM} \times \text{Target Load Factor} - \text{ASM}}{\text{Time Lag in Changing ASM}} + \text{ASM Change by External Policy}$$

In the Tokaido, the replacement of fleets and service expansion of Nozomi trains (shown in Figure 5.6) in FY2003 has significantly increased ASM, so the variable "ASM Change by External Policy" is inserted to reflect this non-routine policy. Also, the target load factor is split into "pre-2003" and "post-2003" to reflect the steep increase of ASM in 2003.

In the NEC, there is a capacity limit due to congestion, so the ASM limit is considered as the upper limit. From empirical data, the ASM limit is set as 3.6B [seat-mile/year].

- Train-Miles

Once ASM is obtained, train-miles can be calculated by using average seats per one trainset. In the Tokaido, the capacity of one trainset is consistently 1323 [seat/train]. In the NEC, Acela and NER are taken into account, and their average capacity is estimated as 381.4 [seat/train][13]. The reflection of train-miles on the operating cost has a time lag, so a time constant (1 year) is inserted to calculate the variable cost.

- Operating Cost

Operating cost is modeled as the sum of variable cost and fixed cost. Variable cost is assumed to change in proportion to train-miles. Thus, operating cost can be formulated as

$$\text{Operating Cost} = \text{Fixed Cost} + \text{Unit Variable Cost} \times \text{Train Mile Reflected on OPEX}$$

Figure 6.18 shows the overview of SD formulation in the Supply / Cost subpart.

[13] The average number of seats per one trainset is 310 for Acela and 430 for NER. The average seat per one trainset in the NEC is estimated as the weighted sum of both services, in proportion to their frequency.

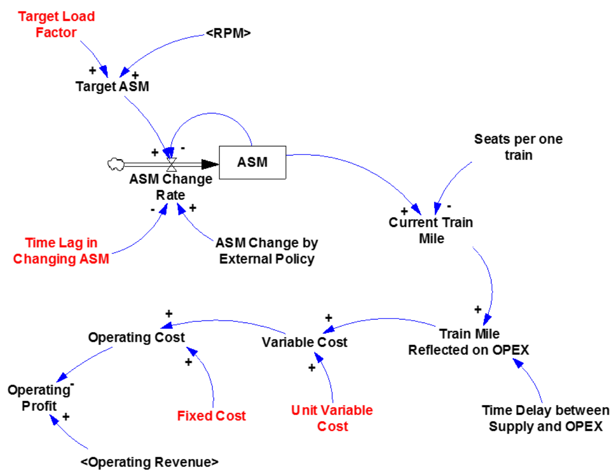


Figure 6.18 SD Formulation in Supply / Cost Subpart

6.3.1.1.3 Pricing

The adjustment of average unit price is modeled as a "Hill-Climbing Optimization" [66]. The goal for the price (target average unit price) is influenced by the current ticket price and the effect of load factor and operating cost.

$$\text{Unit Price Change Rate} = \frac{\text{Average Unit Price}(\text{Effect of Demand} \times \text{Effect of Cost} - 1)}{\text{Time Lag in Changing Price}}$$

$$\text{Average Unit Price} = \int_0^t (\text{Unit Price Change Rate})dt$$

Figure 6.19 shows the overview of the SD formulation in Pricing subpart.

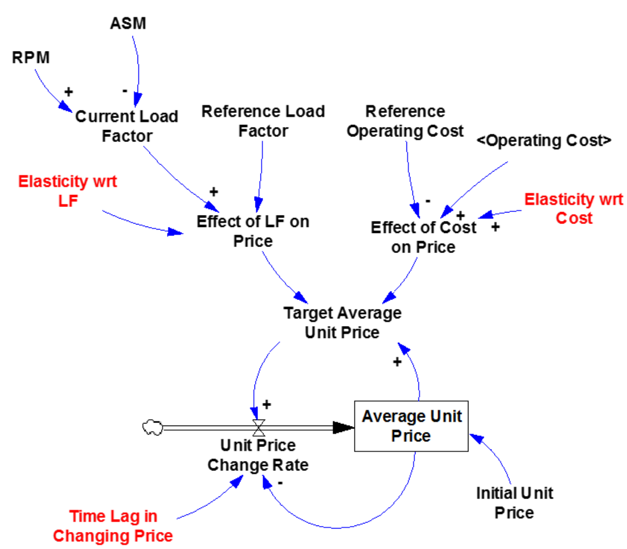


Figure 6.19 SD Formulation in Pricing Subpart

6.3.1.2 Infrastructure / Rolling Stock Management

6.3.1.2.1 Infrastructure Management

- Budget Allocation

CAPEX derives from operating profit or external funding, or both. The allocation of CAPEX is divided between infrastructure and rolling stock, and between normal replacement and backlog elimination. In each step the fraction of CAPEX into each category is defined.

$$\text{CAPEX for Infrastructure} = \text{Total CAPEX} \times \text{Fraction of CAPEX for Infrastructure}$$
$$\text{Budget for Normal Replacement} = \text{CAPEX for Infrastructure} \times \text{Fraction of CAPEX on Normal Replacement}$$

- Normal Replacement

Normal replacement of infrastructure is conducted to keep currently healthy infrastructure as it is. The usage of infrastructure drives the required investment on normal replacement. If the allocated budget for normal replacement is smaller than the required amount, some infrastructure is not maintained in a timely manner, resulting in generating new backlog. The growth of the maintenance backlog can be a trigger for deterioration in the service reliability, safety and ridership in the future, as explained in Figure 6.13.

$$\text{Required Investment} = \text{ASM} \times \text{Unit Investment per ASM}$$
$$\text{Budget Shortage} = \min(0, \text{Required Investment} - \text{Budget for Normal Replacement})$$

- Backlog Elimination

Investment in backlog elimination is used to refresh already deteriorated infrastructure. It often refers to a large project such as the replacement of a bridge or tunnel. Thus, the stock-flow diagram is applied in the evaluation of backlog elimination so that the time delay between initial investment and completion of projects can be reflected. When the project is partially or fully completed, it reduces the amount of current maintenance backlog.

$$\text{Current Stock of Investment on Backlog Elimination} = \int_0^t (\text{Budget for Backlog Elimination} - \text{Project Completion Rate})dt$$

$$\text{Project Completion Rate} = \frac{\text{Current Stock of Investment on Backlog Elimination}}{\text{Average Duration of Backlog Elimination Projects}}$$

- Maintenance Backlog

Maintenance backlog is formulated as a stock. The outflow of backlog derives from the completion of backlog elimination projects. The inflow of backlog can be divided into two types: newly generated backlog and further deterioration of existing backlog. The former derives from the budget shortage in normal replacement, as explained above. The latter reflects the idea that facilities with maintenance backlog usually deteriorate faster than other facilities in good condition [70]. In the model, a penalty rate is used to estimate the deterioration from existing backlog.

$$\text{Maintenance Backlog} = \int_0^t (\text{Budget Shortage} + \text{Additional Deterioration from Backlog} - \text{Backlog Elimination})dt$$

$$\text{Additional Deterioration from Backlog} = \text{Maintenance Backlog} \times \text{Penalty Rate}$$

Figure 6.20 shows the overview of SD formulation in the infrastructure management subpart.

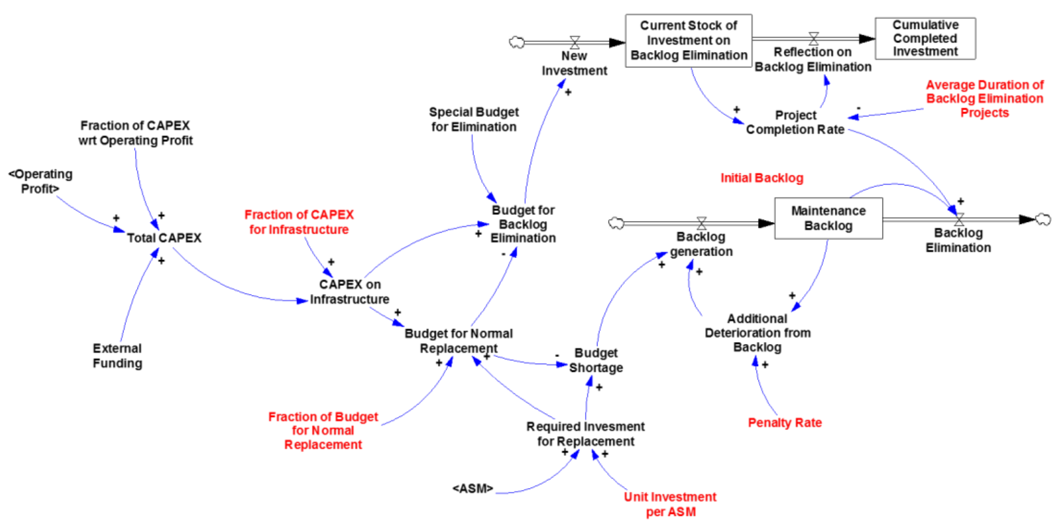


Figure 6.20 SD Formulation in Infrastructure Subpart

6.3.1.2.2 Rolling Stock Management

- Purchase

CAPEX not invested in infrastructure is assumed to be used for new rolling stock purchase. The amount of purchase is determined from CAPEX and the unit price of trainsets.

- Obsolescence

Rolling stock is divided into three categories: new, intermediate and old. Transitions from new to intermediate, and from intermediate to old occurs with a certain time delay. This time delay depends on the average lifespan of rolling stock. Here, the time delay of obsolescence is set as one-third of the average lifespan, which assumes that the average duration in three stocks (new, intermediate and old) is the same.

$$\text{New Rolling Stock} = \int_0^t \left(\text{New Purchase} - \frac{\text{New Rolling Stock}}{\text{Average Lifespan of Rolling Stock / 3}}\right) dt$$

$$\text{Intermediate Rolling Stock} = \int_0^t \left(\frac{\text{New Rolling Stock} - \text{Intermediate Rolling Stock}}{\text{Average Lifespan of Rolling Stock / 3}} - \text{Early Retirement}\right) dt$$

$$\text{Old Rolling Stock} = \int_0^t \left(\frac{\text{Intermediate Rolling Stock}}{\text{Average Lifespan of Rolling Stock / 3}} - \text{Retirement}\right) dt$$

- Retirement

The retirement of rolling stock usually comes from old rolling stock. Similar to the obsolescence rate, the retirement rate depends on the amount of old rolling stock and its average lifespan. The time delay of retirement is set as one-third of the average lifespan, same as that of obsolescence. There are several exceptions to this general rule. When the fleet size reaches the upper bound, additional old rolling stock retires to keep fleet size within the allowable size range. On the other hand, when the fleet size reaches the lower bound, the retirement is deferred. In addition, when there is no old rolling stock, intermediate rolling stock retires.

$$\text{Retirement} =$$

$$\frac{\text{Old Rolling Stock}}{\text{Average Lifespan of Rolling/3}} \qquad \text{(General)}$$

$$(\text{Total Rolling Stock} - \text{Max Fleet SIze}) + \frac{\text{Old Rolling Stock}}{\text{Average Lifespan of Rolling Stock/3}} \qquad (\text{Fleet Size} > \text{Upper Bound})$$

$$0 \qquad (\text{Fleet Size} < \text{Lower Bound})$$

$$\frac{\text{Intermediate Rolling Stock}}{\text{Average Lifespan of Rolling Stock/3}} \qquad (\text{Old Rolling Stock} = 0)$$

Figure 6.21 shows the overview of the SD formulation in the rolling stock management subpart. In Amtrak's case, since Amtrak fleet served in the NEC is composed of Acela trainsets, NER locomotives and NER coach cars, separate stock-flow diagrams are designed for each fleet category.

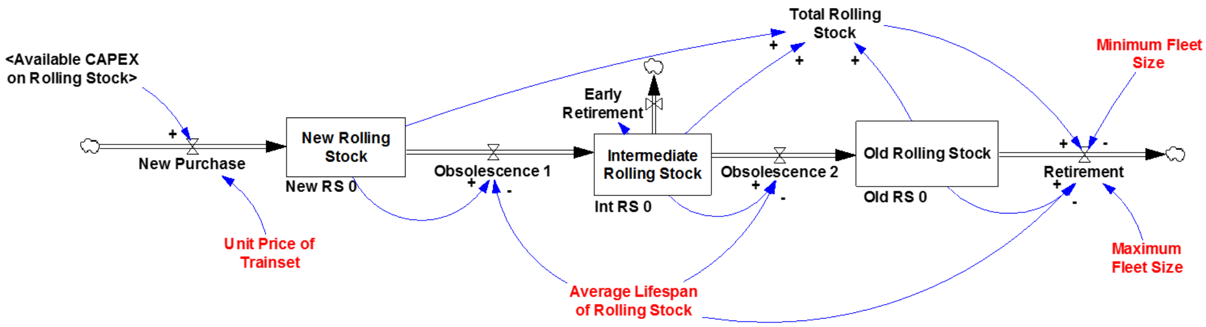


Figure 6.21 SD Formulation of Rolling Stock Management

6.3.2 Model Simulation

In this section, unknown parameters in the numerical model shown in Section 6.3.1 are estimated considering the strength of causal relationship among variables. In the train operation part, unknown parameters are estimated so that they minimize the weighted sum of squared errors between simulated data and historical data in variables of interest (ridership, operating cost and average unit price). As the weight to normalize squared errors of different variables, root mean squared errors (RMSE) between simulation and reference data in each variable are used [71]. Doing so assures that the total error becomes a chi-squared distribution, given that errors in individual variables are normally distributed.

For the error minimization, Markov chain Monte Carlo (MCMC) method is used [71]. In each step in the MCMC algorithm, unknown parameters walk randomly from their previous points, and the new set of parameters is chosen as the best dataset if the total error decreases. The MCMC method also estimates the confidence interval (CI). In this thesis, a 95% CI is estimated along with the estimated values of unknown parameters.

In the infrastructure / rolling stock management part, since annual data for several items is not available, parameters are estimated to show possible scenarios which comply with available reference data. Estimated parameters are used in the sensitivity analyses shown in Section **Error! Reference source not found.**.

6.3.2.1 Train Operation

6.3.2.1.1 Tokaido Shinkansen

Table 6.4 shows the estimated parameters with 95% confidence intervals in the train operation of the Tokaido Shinkansen. Figure 6.22 shows the comparison between simulation and historical data in ridership, operating cost and average unit price, along with goodness-of-fit measures such as R-squared and the root mean squared error (RSME) of simulated data over the mean value of historical data. In all three variables, the overall trend is well traced.

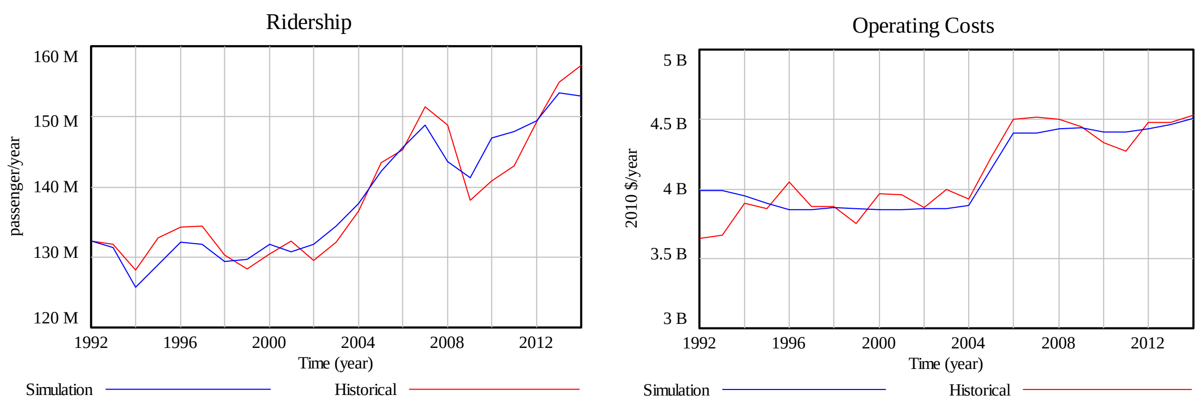
In the derivation of demand, ridershio shows a close to linear relationship with GDP. This result validates the argument in Section 5.1.1 (Figure 5.3), which states that there is a positive correlation between them. Average unit price negatively influences ridership. Supply, or ASM slightly contributes to ridership, with a certain time delay. Travel time, reliability (average delay minutes) and airline response shows almost no impact on ridership. In terms of travel time and reliability, it can be because they didn't change much in the given time horizon. Travel time changed from 150min to 145min in 2007. Reliability, or average time delay has fluctuated within the range of 1 [min/train]. If there were drastic changes in these variables, these elasticities could take other values. Small elasticity with respect to airlines' response means that the loss of HSR passengers to air transportation is small. This can be explained from the fact that the market share between these two modes has stabilized as shown in Figure 4.4. Safety is not considered in the Tokaido Shinkansen, since there have been almost no accidents as shown in Table 5.2, and it seems that time-dependent change of customers' perception in terms of safety does not exist.

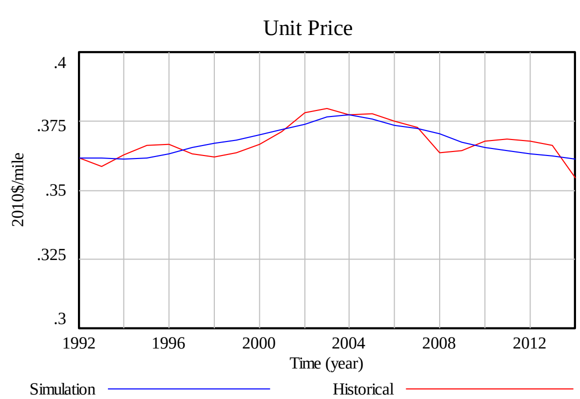
On the supply side, the target load factor decreased after 2003, because the total ASM significantly increased due to the service expansion of Nozomi trains after 2003. The steep increase of ASM is reflected in the increase of operating cost, and these changes are dominant factors to calculate unit variable cost and fixed cost.

In pricing, the change of load factor is the main driver to calculate average unit price. Before 2004, the load factor was higher than the reference load factor, which had driven the slight increase of average unit price. After 2004, the decrease of load factor due to ASM expansion has induced a discount of the average unit price. The change of operating cost has almost no influence on the pricing strategy. This fact suggest that the "Cost Variation" loop explained in Section 6.2.3.1.4 is not active.

Table 6.4 Estimated Parameters in Train Operation of the Tokaido Shinkansen

Subpart	Unknown Parameters		Estimate	95% Confidence Interval	
				LB	UB
Demand	Elasticities of Ridership w.r.t.	GDP	1.04	0.89	1.16
		Price	-0.72	-0.91	-0.42
		Supply	0.13	0.07	0.23
		Travel Time	0.00	-0.03	0.00
		Reliability	0.00	0.00	0.00
		Airline	0.00	-0.02	0.00
	Adjustment Time w.r.t. [year]	Supply	0.12	0.02	0.71
		Reliability	1.20	0.10	3.00
Supply	Target Load Factor before 2003		0.66	0.65	0.66
	Target Load Factor after 2003		0.61	0.57	0.62
	Time Lag in Changing ASM [year]		2.14	1.01	3.70
	Fixed Cost [Billion 2010$]		0.96	0.62	0.16
	Unit Variable Cost [$/train-mile]		101.47	79.66	111.37
Pricing	Elasticities of Target Unit Price w.r.t.	Load Factor	0.12	0.09	0.21
		Cost	0.00	-0.01	0.04
	Time Lag in Changing Price [year]		0.85	0.59	1.58





	R^2	RSME/Mean
Ridership [passenger/year]	0.89	1.9%
Operating Cost [$/year]	0.79	3.2%
Average Unit Price [$/mile]	0.67	0.9%

Figure 6.22 Comparison of Simulation and Historical Data in the Tokaido Shinkansen

6.3.2.1.2 Amtrak Service in the NEC

Table 6.5 shows the estimated parameters with 95% confidence intervals in the train operation of Amtrak service in the NEC. Figure 6.23 shows the comparison between simulation and historical data in ridership, operating cost and average unit price, along with goodness-of-fit measures. Ridership and price are well predicted, but operating cost is not.

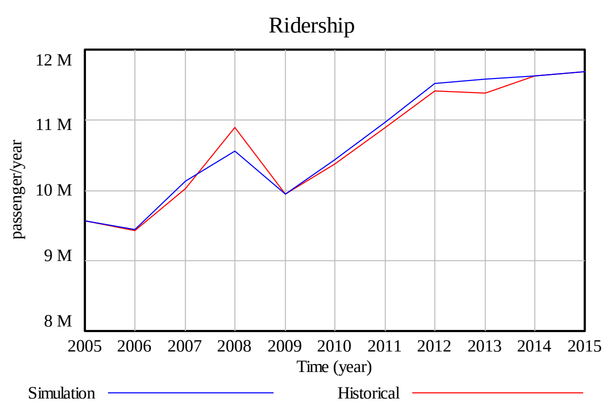
In the derivation of demand, GDP shows a positive correlation with ridership, same as the Tokaido. Average unit price influences ridership negatively, but its impact is smaller than that in the Tokaido. The change of supply contributes positively with small time delay. Reliability (average delay minutes) shows a small impact: the increase of reliability (decrease of average train delays) positively affects ridership. Effect of reliability on the ridership comes from the relative difference of average delay minutes between the current and reference value. In the NEC, the absolute value of delay minutes is much larger than that of the Tokaido, so the relative difference of reliability represents a more significant change of delay minutes. This is why the elasticity of ridership with respect to reliability is larger in the NEC than in the Tokaido. Safety shows almost no correlation. Airline response shows a slight negative influence on HSR demand, which means that HSR and air transportation behave as substitute modes. Travel time is not considered in the NEC, since it has not changed since 2001 when Acela was introduced.

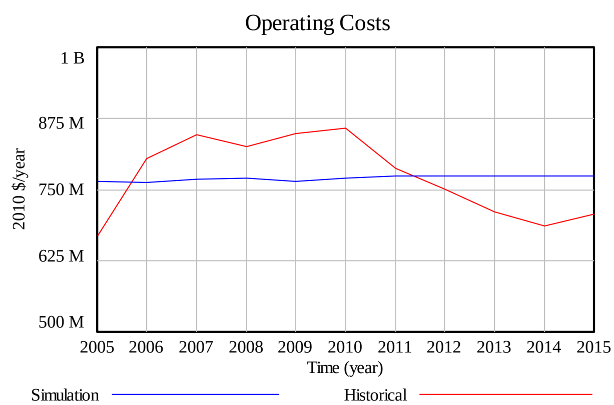
In the supply and cost part, there is almost no correlation in operating cost between simulation and historical data. This is because the trend of ASM and that of operating cost do not synchronize. After 2010, operating cost has steadily decreased, while ASM has gradually increased. The reason for this discrepancy is not clear, but the cost allocation framework (Amtrak Performance Tracking System) which Amtrak has used since FY2009 could be one of main factors. This system automatically allocates internal operating cost into routes and train services, so the change of other factors than cost may have influenced the allocation of common cost such as administrative cost. In addition to the cost allocation within Amtrak, the cost allocation policy among multiple train operators can influence the operating cost of the infrastructure manager, Amtrak. After PRIIA was activated in 2008, stakeholders in the NEC have designed new cost-sharing methods [72], so the process of this new policy implementation may have affected the calculation of operating cost.

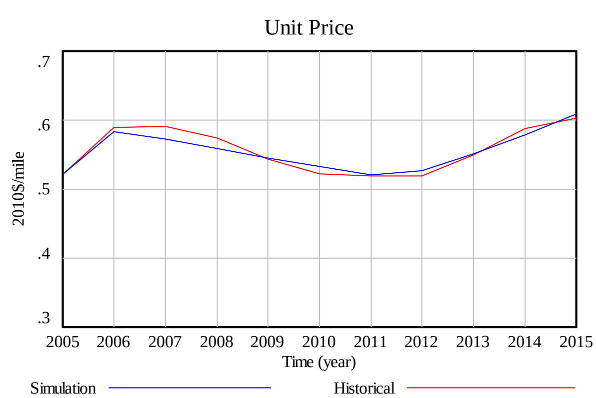
In pricing, both load factor and operating cost influences the average unit price. After the economic recession in 2009, the ridership growth has pushed load factor up, and increased the target unit price for HSR. The time delay to implement price changes is short, which suggests flexibility of the pricing strategy.

Table 6.5 Estimated Parameters in Train Operation of the Amtrak Service in the NEC

Subpart	Unknown Parameters		Estimate	95% Confidence Interval	
				LB	UB
Demand	Elasticities of Ridership w.r.t.	GDP	1.75	1.24	1.84
		Price	-0.46	-0.53	-0.18
		Supply	0.27	0.21	0.64
		Reliability	0.09	0.02	0.13
		Safety	0.00	-0.02	0.00
		Airline	-0.03	-0.06	0.00
	Adjustment Time w.r.t. [year]	Supply	0.02	0.02	0.04
		Reliability	0.94	0.69	1.00
Supply	Target Load Factor		0.49	0.47	0.49
	Time Lag in Changing ASM [year]		0.01	0.01	0.14
	Fixed Cost [Billion 2010$]		0.68	0.46	0.74
	Unit Variable Cost [$/train-mile]		10.36	1.79	37.37
Pricing	Elasticities of Target Unit Price w.r.t.	Load Factor	0.05	0.02	0.12
		Cost	-0.04	-0.09	-0.01
	Time Lag in Changing Price [year]		0.04	0.02	0.11







	R^2	RSME/Mean
Ridership [passenger/year]	0.97	1.2%
Operating Cost [$/year]	0.06	8.9%
Average Unit Price [$/mile]	0.96	1.7%

Figure 6.23 Comparison of Simulation and Historical Data in the NEC

6.3.2.1.3 Comparison between the Tokaido and the NEC

Table 6.6 shows the comparison of estimated parameters in the Tokaido Shinkansen and Amtrak service in the NEC. Interpretations of several parameter values are mentioned in this section.

In the demand part, GDP shows positive correlations with ridership in both cases, while the impact in the NEC is much larger. It suggests that the emerging HSR service (Acela, NER) has well captured the growing intercity travel demand which has been induced by economic growth. The Tokaido Corridor is a mature HSR market, and the change of GDP and ridership is synchronized. The elasticity of ridership with respect to price is negative, whose absolute values are less than 1. This suggests that passengers' response is not so sensitive to the price change. That is, the Tokaido Corridor and the NEC are business-oriented corridors, and the travel demand is relatively inelastic compared to other leisure-oriented O-D markets. The effect of reliability is observable only in the NEC. In the Tokaido, the average delay minutes have been constantly less than 1 [min/train], so the fluctuation within this range does not seem to change passengers' mode choice. The influence of airlines' response is negligible in the Tokaido, but has a small impact in the NEC. This is because HSR has taken away some market share from air transportation in the NEC, while the market share has been stable in the Tokaido.

In the supply part, the difference of target load factors is mainly due to the actual load factor in both cases. The Tokaido and Acela in the NEC have achieved a load factor more than 60%, while NER in the NEC had been less than 50%. Differences in time to change ASM, fixed cost and unit variable cost are likely to be because of the poor goodness-to-fit in the NEC case.

In pricing, the load factor is considered as an input of the pricing strategy in both cases, while operating cost is taken into account only in the NEC. The time delay to change average unit price to comply with target price is longer in the Tokaido than in the NEC. This is because Amtrak introduces revenue management strategies in their marketing, and can alter ticket prices quickly in response to the change of inputs.

Table 6.6 Comparison of Parameters between the Tokaido Shinkansen and the NEC

Subpart	Unknown Parameters		Tokaido	NEC
Demand	Elasticities of Ridership w.r.t.	GDP	1.04	1.75
		Price	-0.72	-0.46
		Supply	0.13	0.27
		Travel Time	0.00	-
		Reliability	0.00	0.09
		Safety	-	0.00
		Airline	0.00	-0.03
	Adjustment Time w.r.t. [year]	Supply	0.12	0.02
		Reliability	1.20	0.94
Supply	Target Load Factor	-2003	0.66	0.49
		2003-	0.61	
	Time Lag in Changing ASM [year]		2.14	0.01
	Fixed Cost [Billion 2010$]		0.96	0.68
	Unit Variable Cost [2010$/train-mile]		101.47	10.36
Pricing	Elasticities of Target Unit Price w.r.t.	Load Factor	0.12	0.05
		Cost	0.00	-0.04
	Time Lag in Changing Price [year]		0.85	0.04

6.3.2.2 Infrastructure / Rolling Stock Management

In the train operation part, parameters are estimated by comparing past historical data and simulation output. In the infrastructure / rolling stock management part, on the other hand, parameters are estimated to show possible past and future scenarios which comply with available reference data.

6.3.2.2.1 Tokaido Shinkansen

- Infrastructure Management

CJR states that the infrastructure of the Tokaido Shinkansen has been continuously maintained, but admits that major structures such as bridges and tunnels have deteriorated because of their extensive usage for more than 50 years [73] . Since the service suspension by reconstruction severely affects transportation in the Tokaido Corridor, major rehabilitation projects have been deferred. To solve this situation, CJR has developed the technology to rehabilitate major structures without service suspension. This new technology prevents structures from being distorted by external forces, and parts of structures are replaced if necessary after regular monitoring. This strategy can avoid replacing all major structures, with keeping soundness of infrastructure. The $7.3B major rehabilitation project started in FY2013, and will continue for 10 years until FY2022. In this project, the $350M special budget is invested annually in addition to the usual capital budget for infrastructure. Based on this background, and the information shown in Section 5.1.4.2, unknown parameters are estimated as shown in Table 6.7.

Figure 6.24 shows the trend of maintenance backlog from FY1992 to FY2034, with / without the special budget for rehabilitation. The operating profit is estimated from the simulation of the train operation part, with parameters shown in Table 6.4. Below are assumptions in the simulation after FY2014 where, of course, historic data does not exist.

- GDP growth rate is 0.5%/year
- The ridership in air transportation grows 1%/year
- Travel time and reliability is same as that of FY2014

In the case with special budget, after the rehabilitation project finishes, the backlog elimination rate accelerates more than the no special budget case. There are two reasons for this. First, since there is a time delay between capital investment and actual backlog elimination, the effect of the special budget continues even after FY2023, as shown in Figure 6.25. Second, there is a penalty rate, which accounts for the additional backlog generation rate from existing maintenance backlog. Thus, early reduction of maintenance backlog prevents future backlog generation from deteriorated infrastructure. In the case with special budget, the maintenance backlog is almost removed in FY2034. In the no special budget case, however, there is about a $5.2B maintenance backlog at that time. The extra amount of capital investment needed for the special budget is $3.5B, which is smaller than the difference of maintenance backlog in FY2034. If we consider the discount rate, which is about 0.3% in these 10 years in Japan [74], the present benefit (future reduction of maintenance backlog) as of 2013 is $4.96B, while the present cost (special budgets for backlog elimination projects) is $3.45B. Thus, the net present value of this special budget is positive, which suggests that the early countermeasures to reduce the maintenance backlog eventually saves money.

Table 6.7 Estimated Parameters in Infrastructure Management in the Tokaido Shinkansen

Unknown Parameter		Estimate
Fraction of CAPEX	out of Operating Profit	0.3
	for Infrastructure	0.8
	for Normal Replacement	0.8
Unit Investment per ASM [2010$/seat-mile]		0.027
Penalty Rate [%]		3%
Average Duration of Backlog Elimination Projects [year]		3
Maintenance Backlog in 1992 [Billion 2010$]		6

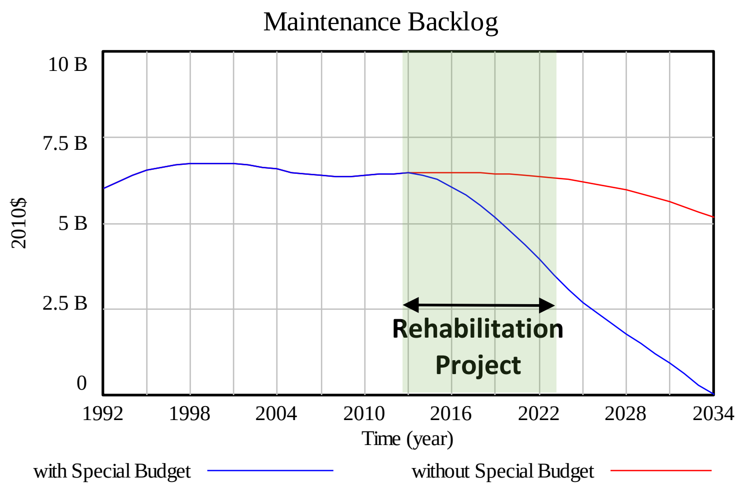


Figure 6.24 Trend of Maintenance Backlog in the Tokaido Shinkansen

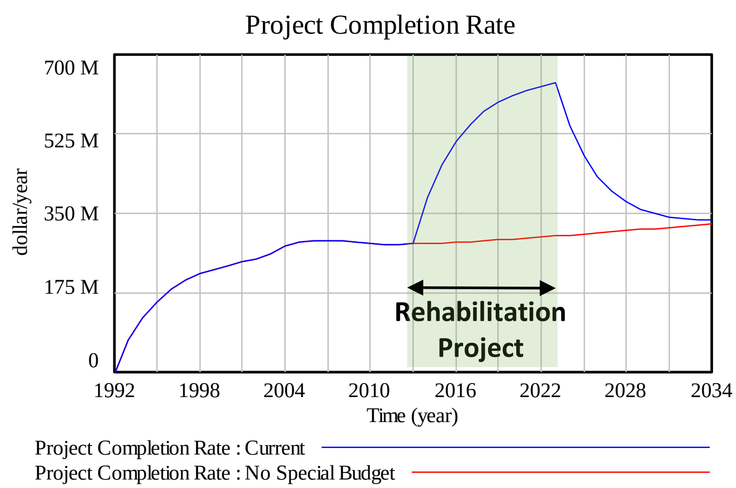


Figure 6.25 Completion Rate of Backlog Elimination Projects

- Rolling Stock Management

As shown in Section 6.2.3.46.2.3.4.1, fleet composition in the Tokaido Shinkansen has been continuously updated. From Figure 6.14, unknown parameters are estimated as shown in Table 6.8. Figure 6.26 shows the trend forecast of fleet composition until FY2040. Average fleet quality is calculated by a weighting of 1 for the new fleet, 0.5 for the intermediate one, and 0 for the old one. The initial condition complies with the actual fleet composition in FY1992. Continuous investment in rolling stock leads to the replacement of old rolling stock into new one. This improves the average fleet quality, and eventually results in the increase of HSR competitiveness such as service quality, travel time and reliability.

Table 6.8 Estimated Parameters in Rolling Stock Management in the Tokaido Shinkansen

Unknown Parameter	Estimate
Fraction of CAPEX out for Rolling Stock	0.2
Unit Price of Trainset [million 2010$/train]	40
Average Lifespan of Rolling Stock [year]	20
Maximum Fleet Size	135
Minimum Fleet Size	115

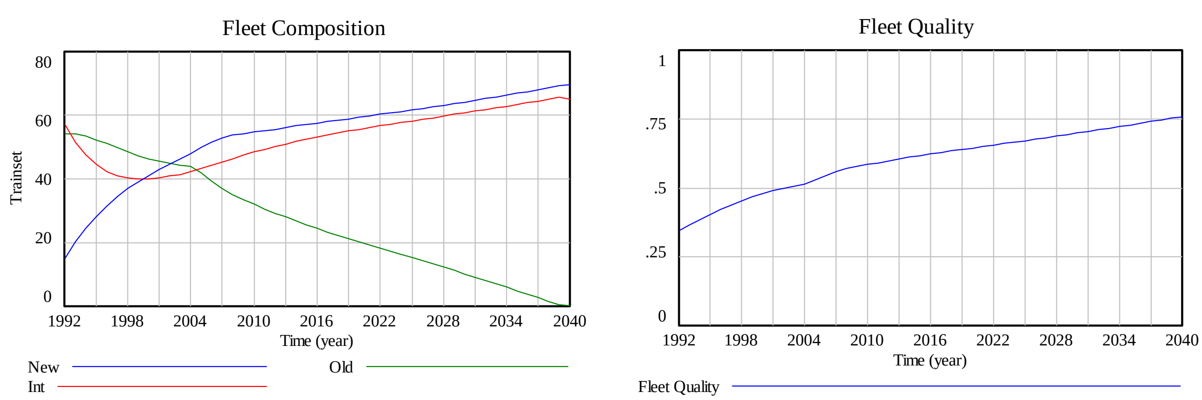


Figure 6.26 Trend of Fleet Composition in the Tokaido Shinkansen

6.3.2.2.2 Amtrak Service in the NEC

- Infrastructure Management

The NEC Commission published an estimate of funds to eliminate SOGR backlog in the NEC [62] [63]. According to these reports, as of 2014, the maintenance backlog in the entire NEC is $7.3B (Amtrak-owned main line only: $4.8B) in basic infrastructure and $13.8B (Amtrak-owned main line only: $11.1B) in major backlog projects such as replacement of bridges and tunnels. The NEC Commission estimates that the entire NEC requires about $1B/year to eliminate basic infrastructure backlog in 15 years, though part of it is used for the regular normal replacement. The required investment in the entire NEC to eliminate all backlog in 15 years can be estimated as $2B/year, from the statement that the investment for major backlog elimination costs as much as the investment only for basic infrastructure. From this information, unknown parameters are estimated as shown in Table 6.9.

Figure 6.27 shows the trend of maintenance backlog (basic infrastructure only and total backlog), with this hypothetical funding level, estimated from information shown in the paragraph above. At the funding level of 0.66 [billion 2010$/year], the backlog in basic infrastructure can be eliminated in 15 years. At the funding level of 1.32 [billion 2010$/year], most of total maintenance backlog can be eliminated. In reality, the funding level in the last 10 years was around $400M/year [62]. Figure 6.28 shows the trend of total maintenance backlog if the current funding level ($400M/year) is maintained. This funding level is more than the required investment for normal replacement, so it can prevent healthy infrastructure from deteriorating. However, due to the penalty rate, already deteriorated facilities generate further backlog, which eventually increases the total amount of maintenance backlog.

Table 6.9 Estimated Parameters in Infrastructure Management in the NEC

Unknown Parameter	Estimate
Fraction of CAPEX for Normal Replacement	0.8
Required Investment for Normal Replacement [Million 2010$/year]	327
Penalty Rate [%]	1%
Average Duration of Backlog Elimination Projects [year]	2
Backlog for Basic Infrastructure in FY2015 [Billion 2010$]	4.42
All Maintenance Backlog in FY2015 [Billion 2010$]	14.64

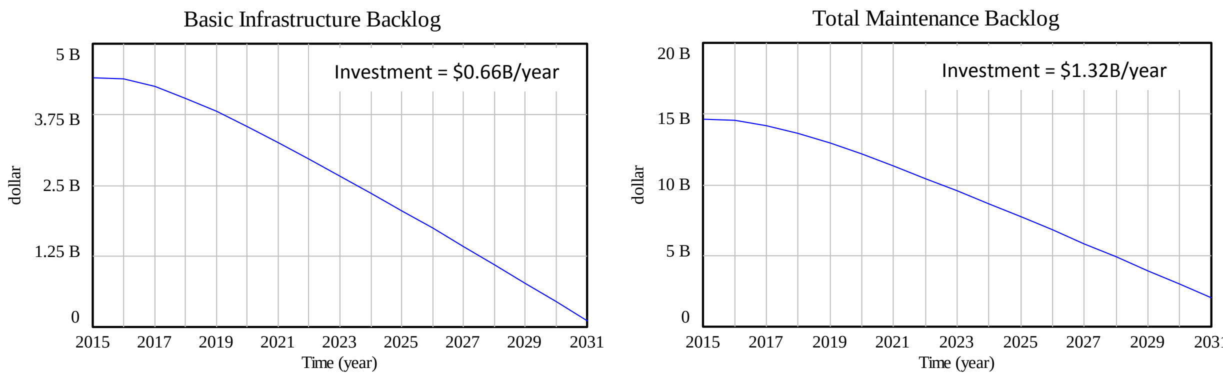


Figure 6.27 Trend of Maintenance Backlog in the NEC with Sufficient Funding Level

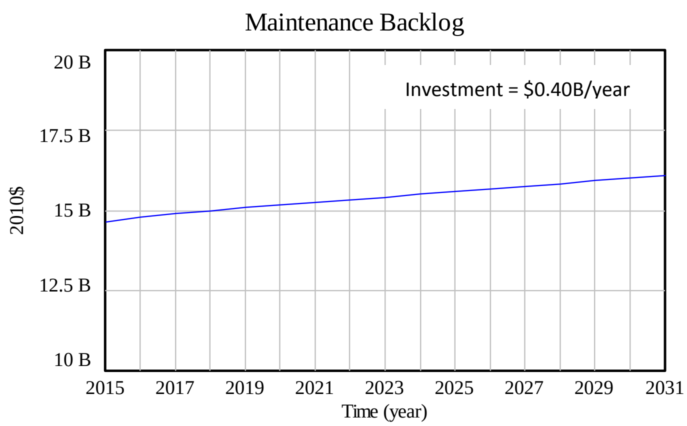


Figure 6.28 Trend of Maintenance Backlog in the NEC with Current Funding Level

- Rolling Stock Management

In the NEC, Acela uses 20 unique trainsets which are designed specifically for Acela to meet regulations in HSR operation. These trainsets are made up of 8 cars, which are not rearranged. NER, on the other hand, uses one or two locomotives (ACS-64, AEM-7) and coach cars (Amfleet I), and rearrange their composition according to the demand fluctuation. Locomotives are used in the NEC and the Keystone Corridor. Amfleet I is the commonly-used coach car in the northeastern US, such as NER and the Downeaster (Boston – Portland, ME).

Table 6.10 shows the fleet composition used in the NEC service as of the beginning of FY2016 [75]. 70 new locomotives (ACS-64) are being introduced in FY2014-2016 to replace old AEM-7 locomotives. Railroad Rehabilitation and Improvement Program (RRIF) loans are used as the capital funding source to procure ACS-64. Acela trainsets have been used for 17 years, and the current fleet cannot fully accommodate the surging demand in the NEC. Amtrak plans to introduce 28 sets new train to its Acela fleet, and an RRIF application process for its capital funding is ongoing as of 2016. Amfleet I has been used for 40 years. Amtrak intends to introduce new coach cars after FY2019, but it depends on the availability of capital resources if they can be procured as planned. Amtrak [75] states that most Amtrak-owned rolling stock has been maintained beyond its expected lifespan due to the lack of reliable, multi-year capital funding. Current capital funding for fleet replacements comes from an external grant, so Amtrak cannot fully control its own future fleet composition.

Based on current Amtrak fleet strategies [75] [76], unknown parameters are estimated as shown in Table 6.11. The initial state of simulation is derived from the actual fleet composition in FY2014. Figure 6.29 shows the trend of fleet composition until FY2030, assuming Amtrak's fleet acquisitions are conducted as planned. Average fleet quality is calculated by setting 1 for the new fleet, 0.5 for the intermediate one, and 0 for the old one. Just after the acquisition of the new fleet, it replaces old fleet and the average fleet quality increases. However, the capital funding on each fleet replacement is a "one-time shot", so a newly introduced fleet deteriorates again in the long term. That is, continuous capital investment is required to keep the average fleet quality at a high level.

Table 6.10 Fleet Composition in the NEC

Rolling Stock			Active Units	Year started in service	Average Age	Average Mileage
Acela			160	1999-2000	17	2,266,000
NER (*)	Locomotive	ACS-64	49	2014-2015	1	91,000
		AEM-7	17	1980-1988	34	4,662,000
	Coach Car	Amfleet I	456	1975-1977	40	4,703,000

* NER locomotives and coach cars are also used for other services such as Keystone or Downeaster.

(Source: Amtrak)

Table 6.11 Estimated Parameters in Rolling Stock Management in the NEC

Unknown Parameter		Estimate
Acela	Unit Price of Trainset [million 2010$/trainset]	90
	Average Lifespan of Rolling Stock [year]	20
	Maximum Fleet Size	50
	Minimum Fleet Size	20
Locomotive	Unit Price of Trainset [million 2010$/train]	8
	Average Lifespan of Rolling Stock [year]	25
	Maximum Fleet Size	70
	Minimum Fleet Size	60
Coach Car	Unit Price of Trainset [million 2010$/train]	3
	Average Lifespan of Rolling Stock [year]	30
	Maximum Fleet Size	600
	Minimum Fleet Size	450

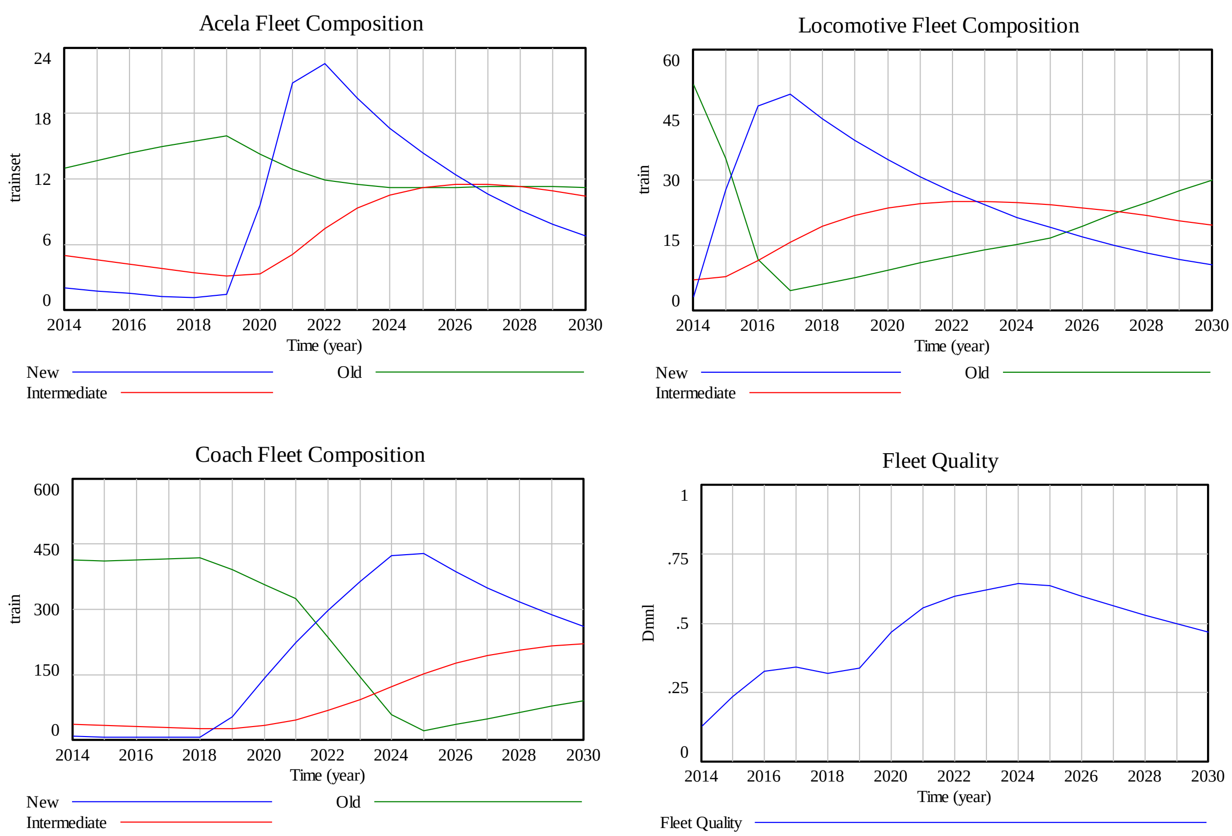


Figure 6.29 Trend of Fleet Composition in the NEC

6.3.3 Robustness of Parameter Estimation

In the parameter estimation in Section 6.3.2.1, the comparison between simulation and historical data is done for the entire time horizon. That is, the training period for the parameter estimation is equivalent to the entire time horizon. In this section, reference data is split into a training period and a validation period to examine whether the parameter estimation is robust or not. A visual image of the training period and the validation period is shown in Figure 6.30.

Since there are only 11 years of data available in the NEC, this examination is done only in the Tokaido case, which contains 23 years of available data. Two patterns of training period are examined as shown below.

Case 0: Training Period: 1992-2014, Validation Period: None (Base case, results are shown in Figure 6.22)
Case 1: Training Period: 1992-2003, Validation Period: 2004-2014
Case 2: Training Period: 1992-2005, Validation Period: 2006-2014

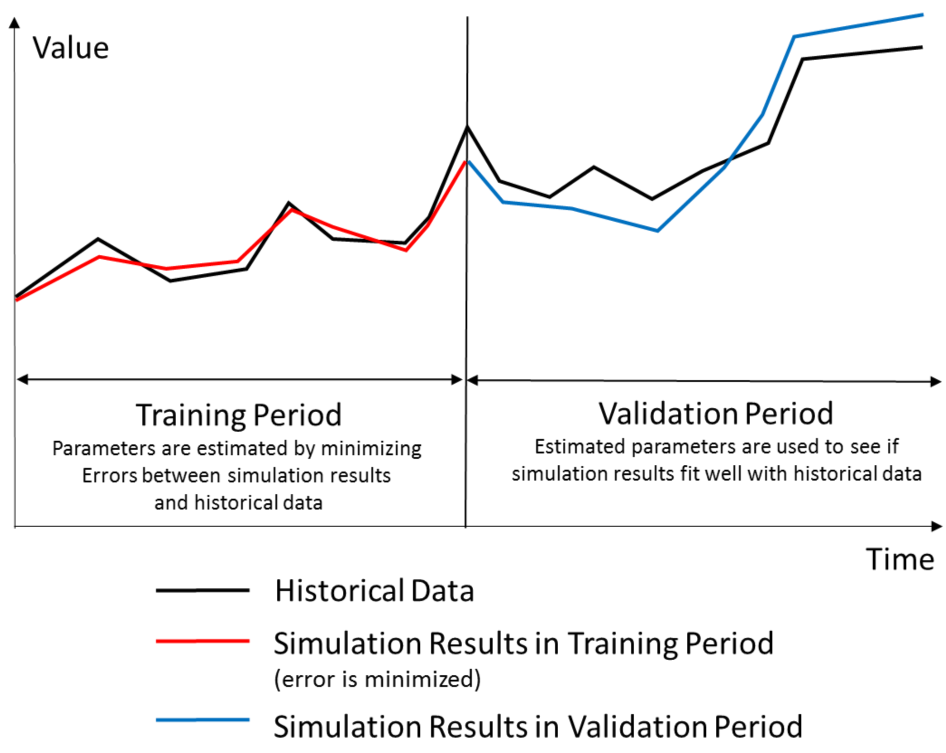
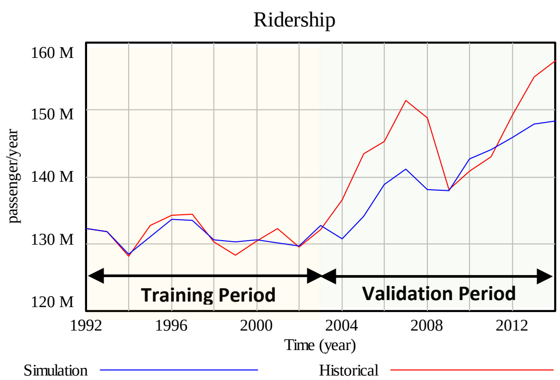
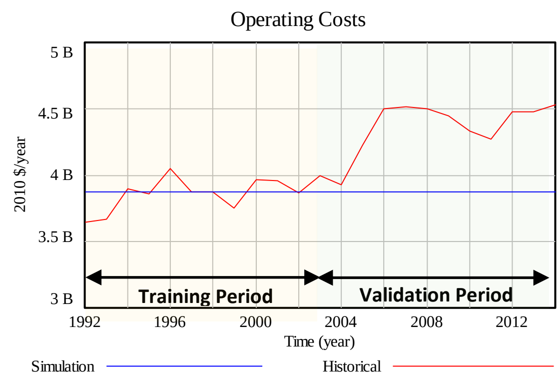


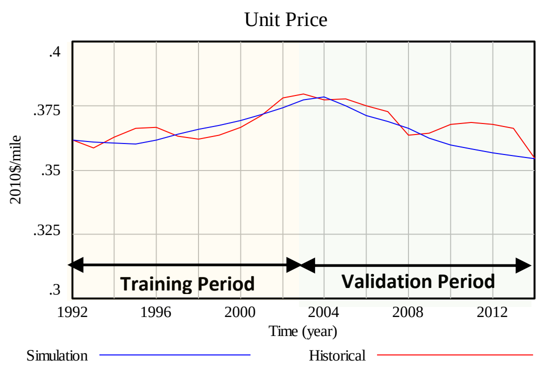
Figure 6.30 Image of Training Period and Validation Period

Figure 6.31 and Figure 6.32 shows the simulation results with given training / validation period. In Case 1, simulation of ridership in the validation period does not follow the historical data well. Further, the simulated operating cost is almost constant, and does not follow the increased cost in the validation period at all. This is because the training period does not contain the “information” after 2003, when the composition of fleet and train services dramatically changed to increase supply and demand. In Case 2, since the data in 2004 and 2005 is used as part of the training dataset, simulation follows the historical data well in the validation period. R-squared and RSME/Mean in Case 2 is not so different from the reference data in Case 0. This shows that important management actions such as fleet renewal can have a big impact on outcomes.

Figure 6.33 shows the comparison of simulation errors in Case 0, 1 and 2. Case 1 and Case 2 tries to minimize errors in their own training period, so RSME/Mean in their training period is less than that of Case 0. In turn, in the validation period, RSME/Mean becomes larger in Case 1 and Case 2 than Case 0. In particular, the error in Case 1 is much larger mainly due to the poor goodness-of-fit in operating cost. As a result, the overall error in Case 1 is also larger than Case 0. On the other hand, the overall error in Case 2 is at the same level of Case 0. These results suggest that the parameter estimation process is robust as long as the HSR operation environment does not change radically. One note here is that the comparison of three cases are conducted within the train operation part, so the input from infrastructure / rolling stock management part can influence the result.

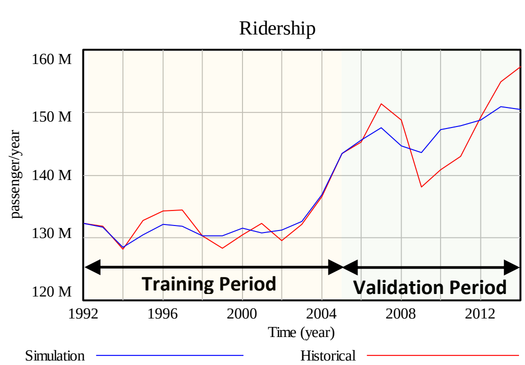


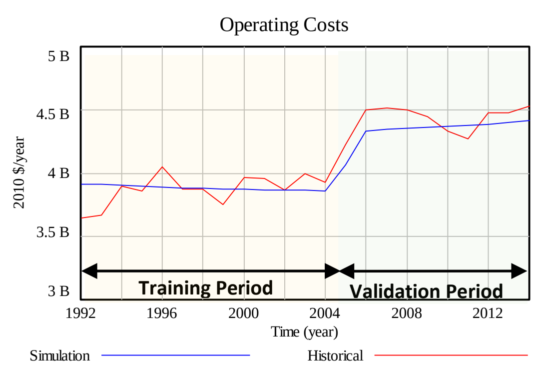


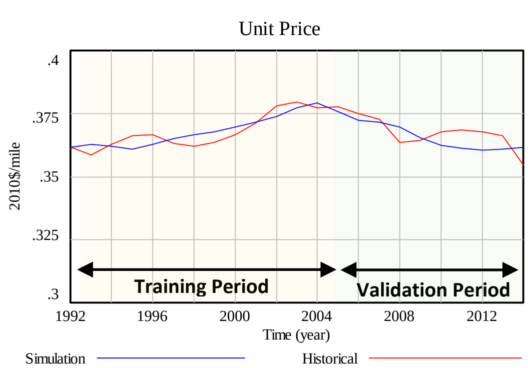


	R^2	RSME/Mean
Ridership [passenger/year]	0.79	3.3%
Operating Cost [$/year]	0	9.0%
Average Unit Price [$/mile]	0.55	1.4%

Figure 6.31 Simulation Results with Training Period of FY1992-2003







	R^2	RSME/Mean
Ridership [passenger/year]	0.88	2.0%
Operating Cost [$/year]	0.83	3.1%
Average Unit Price [$/mile]	0.61	1.1%

Figure 6.32 Simulation Results with Training Period of FY1992-2005

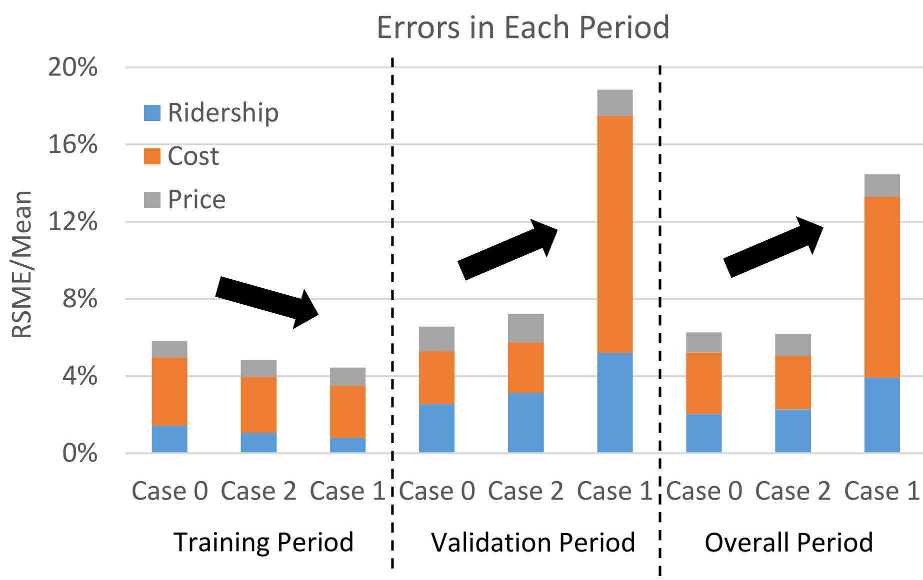


Figure 6.33 Errors in Training/Validation/Overall Period

To further study the robustness of parameter estimation, 10-year-long time horizons are chosen to see the change of estimated unknown parameters. That is, time horizons of reference data are set as FY1992-2001, FY1992-2002, and so on. Figure 6.34 shows one example of results, which shows how the estimated elasticity of ridership with respect to GDP has changed with different time horizons. The black broken line is the linear regression line, which shows that the elasticity has gradually increased. This is mainly because the change of HSR operation strategy after 2003 has boosted the growth rate of ridership. This result suggests that parameters in HSR operation model can change dynamically, as the HSR environment changes. HSR operators can foresee the future trend by using past data, but they should always take the latest operating conditions into account to update their forecast correctly.

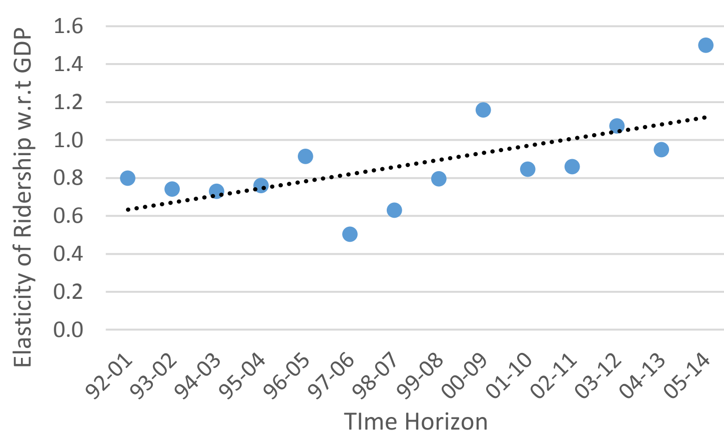


Figure 6.34 Elasticity of Ridership with respect to GDP in Different Time Horizon

6.4 Sensitivity Analysis

In this section, several cases with different values of parameters or causal relationships are considered to see how different policies affect "ilities" and other performance indicators in HSR operation. In the simulation in the Tokaido Shinkansen, parameters shown in Table 6.4 and Table 6.7 are used for future simulations (after FY2014), with additional assumptions shown below.

- GDP growth rate is 0.5%/year
- The ridership in air transportation grows 1%/year
- Travel time and average delay minutes is same as FY2014

In the simulation of the NEC, parameters shown in Table 6.5 and Table 6.9 are used for future simulation (after FY2015), with additional assumptions shown below.

- GDP growth rate is 1.5%/year
- The ridership in air transportation is constant and same as FY2015
- Average delay minutes and accident rates are the average of past 10 years
- Capacity constraints in the NEC is constant, except the sensitivity analysis in Section 6.4.1

6.4.1 Capacity Constraints

Various factors such as fleet size, rolling stock capacity, infrastructure condition and congestion in corridors determines the upper bound of available HSR capacity. When the actual supply approaches this capacity limit, it is difficult to expand supply even when increasing demand leads to congestion in existing HSR services. In the Tokaido, service expansion in 2003 once eased the congestion, but growing demand in these last 10 years has again pushed supply toward the capacity limit. JRC is constructing the 2nd HSR (Chuo Shinkansen) between Tokyo and Nagoya to ease the congestion in the Tokaido Shinkansen. In the NEC, current Acela service experiences difficulty in meeting the growing demand, particularly in the NY-DC market. Amtrak [75] states that most Acela services between New York and Washington D.C. during weekdays experience a load factor over 90%, and that the frequency of trains whose tickets are completely sold out has been increasing. Amtrak plans to procure new longer Acela trainsets to meet this surging demand in the NEC.

In this section, a sensitivity analysis in the NEC is conducted to see how the capacity expansion by the introduction of new Acela trainsets contributes to a potential increase ridership. It is still unclear when the actual fleet acquisition will begin due to uncertainty in political procedures, but it is assumed that Amtrak's acquisition plan goes as planned. That is, 18 new trainsets are acquired in 2020, and 10 more trainsets in 2021. Amtrak states this introduction can double the frequency of Acela services [75], so from historical ASM of Acela and NER, here the capacity limit is assumed to increase from 3.6 [billion seat-mile/year] to 4.65 [billion seat-mile/year].

Figure 6.35 shows the trend of ridership and load factor from FY2014 to FY2030 with/without capacity expansion. Before the introduction of new Acela trainsets, the ridership growth rate decelerates due to the increase of load factor and the accompanying increase of average ticket price. By adding capacity due to the new fleet, the growth trend of ridership returns. Also, the congestion is eased by adding new capacities. In the CLD shown in Figure 6.12, this policy corresponds to increasing the room for expansion and to weaken the "Capacity Limit" balancing loop. In corridors where the demand growth induces congestion, continuous capital investment in rolling stock and infrastructure can contribute to expand the upper bound of capacity and then attract potential new passengers.

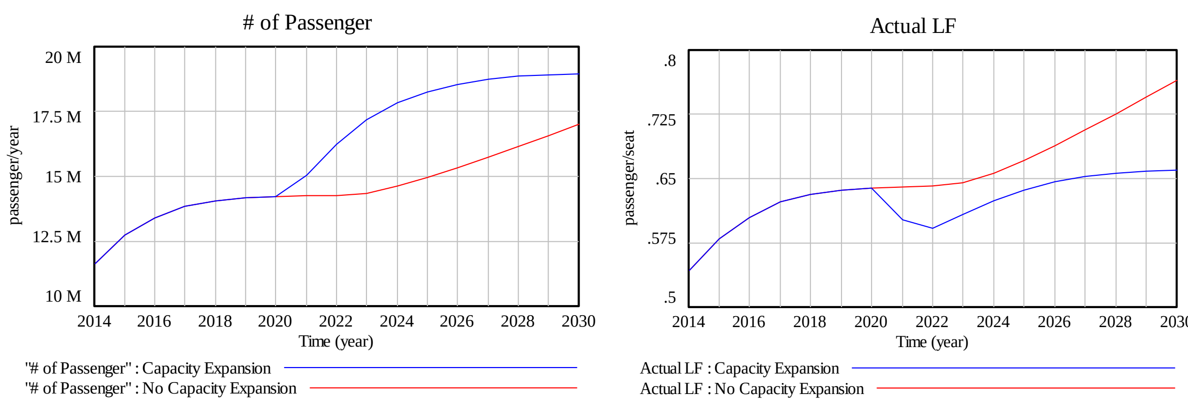


Figure 6.35 Trend of Ridership and Load Factor with/without Capacity Expansion

6.4.2 Eliminating Cross-subsidization

As described in Section 5.2.4, the operating profit generated in the NEC had been used to cross-subsidize other unprofitable train services throughout the US. After a new cost allocation policy was enacted in FY2015, this cross-subsidization was terminated and the NEC profit began to be used for the NEC capital investment. In this section, three cases in which different fractions (0%, 50% and 100%) of the NEC operating profit are used for infrastructure CAPEX are considered, given that the same amount of external funding (400million 2010$/year) is also supplied[14].

Figure 6.36 shows the trend of maintenance backlog in three cases, with/without external grant. The blue line shows the reference case, in which no operating profit in the NEC is used for the capital investment on the NEC. The red and green lines show cases in which a certain fraction (50% and 100%) of the operating profit is used for the infrastructure backlog elimination. Additional CAPEX from operating profit contributes to reduce the maintenance backlog in the long run. Connecting the "missing link" between operating profit and CAPEX can activate the "Infrastructure Quality" reinforcing loop which did not work with cross-subsidization as shown in Figure 6.16. However, as shown in the right figure in Figure 6.36, it is not sustainable to utilize operating profit in capital investment without receiving the external grant as a supplement, since the original maintenance backlog was already significant.

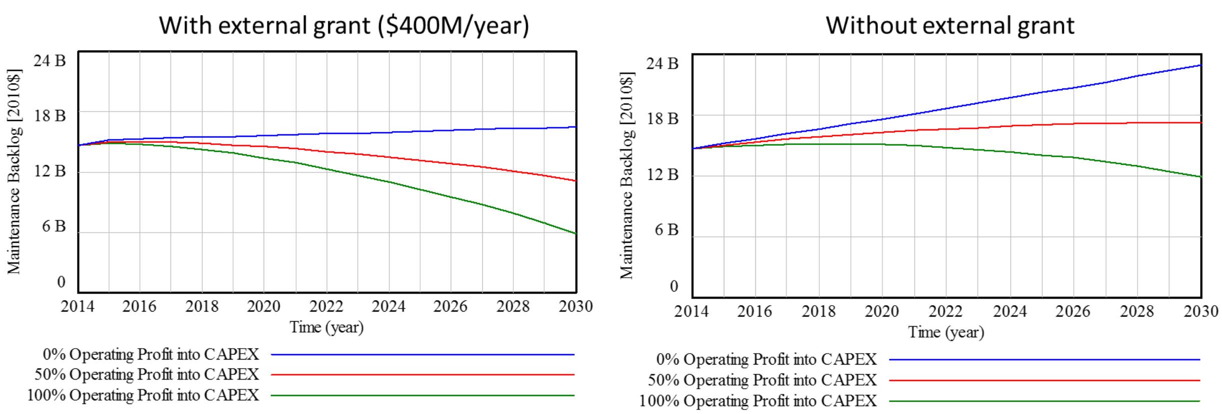


Figure 6.36 Trend of Maintenance Backlog in the NEC with Different Usage of Operating Profit

14 In practice, from FY2016, Amtrak's capital grant request for the NEC is "NEC total capital needs – NEC operating profit – Commuter Rails' payment – Federal Grant by FAST (Fixing America's Surface Transportation) Act" [75]. That is, Amtrak asks fewer capital grants for the NEC than in previous years due to the new cost allocation scheme and the elimination of cross-subsidization. Nevertheless, FAST Act will ensure additional capital grant for the NEC, so the assumption that Amtrak continues to receive a constant capital grant is not unrealistic.

6.4.3 Priority between Normal Replacement and Backlog Elimination

In infrastructure management, CAPEX for infrastructure is allocated between normal replacement and backlog elimination. In this section, three cases with different allocation policies of CAPEX are examined to see how these policies influence the maintenance backlog. A different fraction (0%, 50% and 100%) of CAPEX is allocated for normal replacement, and the rest is allocated for backlog elimination. One assumption here is that, if the allocated budget for normal replacement exceeds the required investment for replacement, the residual budget is automatically used for backlog elimination along with the initially allocated budget for it.

Sensitivity analyses are conducted both for the Tokaido Shinkansen and for the NEC. In the Tokaido case, the special budget in FY2013-2022 to remove maintenance backlog explained in Section 6.3.2.2.1 is taken into account. In the NEC case, it is assumed that the capacity expansion by the introduction of Acela new trainsets are conducted on time, and that 50% of the NEC operating profit is used for capital investment.

Figure 6.37 shows the trend of maintenance backlog in the Tokaido and in the NEC. In the NEC case, two cases (50% and 100% of CAPEX for Normal Replacement) show almost identical results. This is because 50% of CAPEX satisfies most of required investment for normal replacement. That is, marginal CAPEX for normal replacement from 50% to 100% is eventually used for backlog elimination, not for normal replacement.

In both cases, cases with larger CAPEX for normal replacement reduce more maintenance backlog. This is because backlog elimination projects contain time delays between their launch and completion (Tokaido: 3 years, NEC: 2 years). Thus, in cases where most CAPEX is allocated for backlog elimination, newly generated backlog from budget shortage for normal replacement impacts the maintenance backlog more than the backlog elimination does. When time delays become shorter, the effect of budget allocation becomes smaller. Figure 6.38 shows the trend of maintenance backlog with shorter time delays in backlog elimination projects, which suggests quicker completion of backlog elimination projects contributes to reduce the maintenance backlog itself and its deviations by different CAPEX allocation policies. Nevertheless, as long as there exist positive time delays in backlog elimination projects, allocating budget for normal replacement with priority works better to reduce maintenance backlog.

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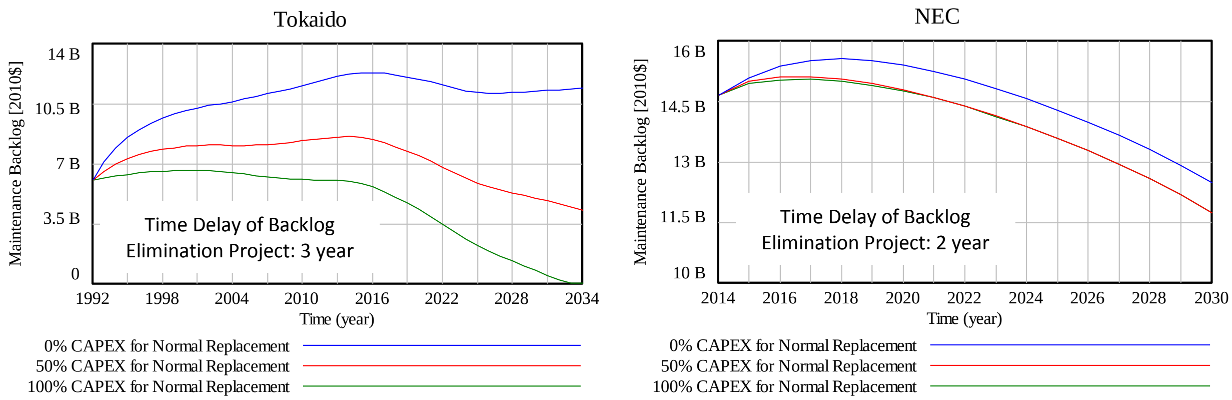

Figure 6.37 Trend of Maintenance Backlog with Different Allocation Way of CAPEX

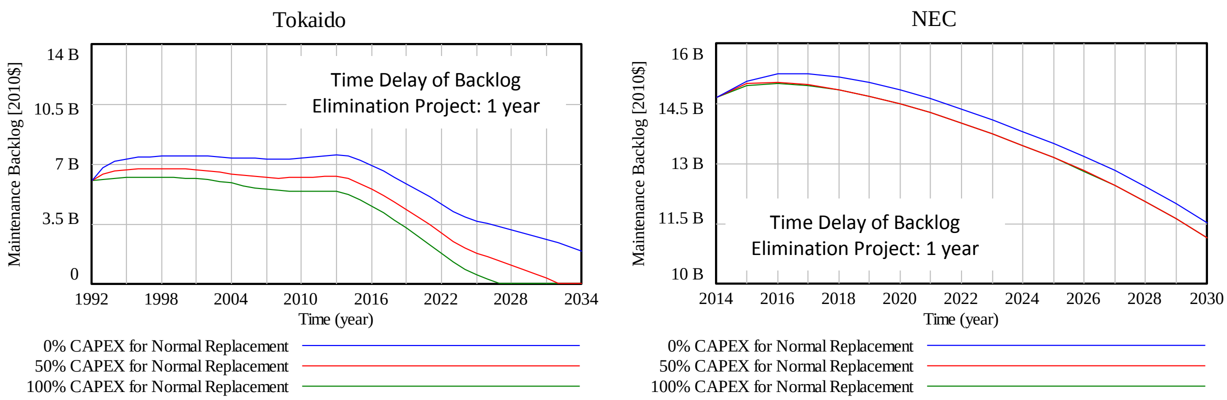

Figure 6.38 Trend of Maintenance Backlog with Quicker Backlog Elimination Projects

6.5 Conclusion

In this chapter, System Dynamics modeling is applied to consider the dynamic behavior of "ilities" and other variables in HSR operation. An overview of System Dynamics and its relevance with HSR study is discussed at first, and then qualitative and quantitative SD modeling is conducted on two case studies.

System Dynamics Overview

First of all, historical backgrounds and characteristics of System Dynamics are presented. One strength of SD is that causal loop diagrams (CLD) can systematically conceptualize causal relationships among variables of interest, and reveal subtle feedback loops which cannot easily be captured by other methodologies. Model formulation with stock-flow diagrams can be useful when the SD model is complex to predict dynamic model output. HSR is a complex, long-lasting system influenced by a variety of inputs. Application of SD is an effective approach to represent the comprehensive structure of HSR operation, and to understand its dynamic behaviors at the system level.

Qualitative SD Modeling (CLD) and its Analysis

In Section 6.2, CLD for vertically integrated HSR operation is constructed. HSR operation is divided into the train operation part and the infrastructure / rolling stock management part.

In the train operation part, demand/revenue, supply/cost and pricing subparts are at first considered separately and then they are integrated. Several feedback loops emerge through this integration. These feedback loops capture the balance between demand and supply, interaction between pricing strategy and ridership, and capacity constraints due to the operating environment. The output of the train operation part is the operating profit, which is used as a source of capital investment in the infrastructure / rolling stock management part.

In the infrastructure / rolling stock management part, infrastructure and rolling stock subparts are at first considered and then they are integrated. In the infrastructure management part, capital expenditures are split into normal replacement and backlog elimination. Not only does the lack of CAPEX for normal replacement generate new maintenance backlog, but also the further deterioration of existing backlog accelerates the backlog growth. In the rolling stock management part, CAPEX is used to replace older parts of the fleet, and the fleet composition determines the average fleet quality. Maintenance infrastructure backlog and fleet quality are drivers of safety, reliability, service quality and travel time, which are inputs to HSR competitiveness in the train operation part.

When the train operation part and the infrastructure management part are integrated, new reinforcing/balancing feedback loops emerge. When HSR is operated properly, reinforcing loops work as virtuous loops. That is, more capital expenditure on infrastructure and rolling stock bolsters HSR competitiveness, which increases the operating profit in train operation, and in turn it assures enough further capital investment. When there is not enough capital expenditure, these reinforcing loops act as vicious loops. Particularly, the combination of the "Infrastructure Quality" loop and the "Deferred Maintenance" loop result in an undesirable sequence. That is, lack of operating profit and CAPEX lead to the decision to defer necessary maintenance, which increases maintenance backlog. If backlog is not eliminated quickly, it generates further backlog, and HSR competitiveness deteriorates to further reduce HSR operating profit.

The designed CLD is applied to two cases to show their peculiar characteristics. In the Tokaido Shinkansen, rolling stock replacement in 2003 contributed to an increased capacity limit, resulting in a steep growth of demand and supply in following years. In the NEC, operating profit generated in the NEC was used to cross-subsidize unprofitable lines, so the causal relationship between operating profit and CAPEX did not exist.

Quantitative SD Modeling and its Analysis

In Section 6.3, the qualitative CLD is converted to a quantitative model by using stock-flow diagrams. In the model formulation, several unknown parameters are inserted in the models. In the train operation part, the MCMC (Markov-chain Monte Carlo) method is used to estimate values of unknown parameters by minimizing errors between simulation results and historical data. In the infrastructure / rolling stock management part, unknown parameters are estimated to comply with available reference data.

In the Tokaido Shinkansen train operation, changes of GDP, price and supply influence the ridership, while changes of reliability, travel time and airlines' response show little impact on it. Operating cost shows a step-shape growth when supply increased steeply after 2003. Load factor is the main driver to calculate the average unit price.

In the NEC, on the other hand, changes of reliability and airlines' response as well as GDP, price and supply show impacts on ridership. The larger effect of GDP and airlines' response suggests that the NEC HSR has grown rapidly in these 10 years, acquiring market share from air transportation. The simulation of operating costs does not follow the historical trend, because actual operating costs have decreased even when the supply has increased. This counterintuitive trend can result from the change of cost allocation frames within Amtrak's different train services or within different train operators in the NEC. In pricing, both load factor and operating cost show some influence on the average unit price.

In the infrastructure management of the Tokaido, sensitivity analyses with/without inclusion of a special budget for backlog elimination is conducted. Simulation results show that early capital investment on backlog elimination can save more money in the future. This is because agile backlog elimination can contribute to mitigate the vicious effects of the "Deferred Maintenance" loop shown in CLD. In rolling stock management, it is shown that continuous capital investment to replace rolling stock maintains the average fleet quality at a high level.

In the infrastructure management of the NEC, it is demonstrated that the current funding level is not enough to reduce the maintenance backlog level, even if the funding level exceeds the required budget for normal replacement. This is because a significant backlog already exists in the NEC, which generates further deterioration other than normally replaced facilities. A sensitivity analysis suggests that using the NEC operating profit in the NEC infrastructure management prevents the maintenance backlog from exploding further, but still a significant amount of external funding is required to reduce backlog rapidly. In the rolling stock management, replacement of the Acela fleet, locomotives and coach cars improves the fleet quality, but these replacements are projected to be a one-time shot, so the quality again starts deteriorating unless periodical replacements are done.

In addition to the numerical simulation of base cases, several other cases with different HSR operation policies are examined to see their impacts on "ilities" and performance indicators. In the capacity constraints analysis, it is shown that the capacity expansion by the introduction of Acela new trainsets can boost the growth trend of ridership, while easing current congestion. Capacity expansion can be done by improvement of both rolling stock and infrastructure, so continuous investment on them is one solution to sustain growth in HSR service. In the evaluation of cross-subsidization in the NEC, utilization of operating profit for capital investment is proven to be effective to reduce maintenance backlog. This flow of cash between operating profit and CAPEX can activate the "Infrastructure Quality" reinforcing loop, given that a certain amount of external grant is assured. In the analysis of budget allocation between normal replacement and backlog elimination, it is shown that investing in normal replacement with priority works better. HSR operators should at first replace facilities to prevent infrastructure from generating new backlog, then use residual budgets to eliminate existing backlog.

The next chapter summarizes the key findings and conclusions of this thesis. In addition, possible future work is shown to deepen studies of "ilities" in HSR operation.

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Chapter 7 Findings, Conclusions and Future Work

This chapter summarizes this thesis, to show key research findings and conclusions. In addition, potential future work is suggested to expand studies in HSR "ilities". HSR takes an important role in the intercity passenger travel, but it requires large capital, labor and sociotechnical knowledge to maintain HSR systems. In order to achieve successful HSR operation in the long run, HSR "ilities" need to be carefully designed and continuously monitored.

7.1 Findings

In this section, key research findings obtained in this thesis are shown as follows.

<u>HSR Overview and its Relevance with "Ilities" (Chapter 2, Chapter 3)</u>

- In HSR operation, important system properties such as safety and reliability emerge as a result of complex interactions of subsystems.

In HSR operation, multiple subsystems interact closely with various operands. Such complex interactions of subsystems are not simple or linear, so important system properties such as safety and reliability cannot be expressed as a pure aggregation of subsystems' properties. Rather, they can be treated as emergent properties from the interactions of subsystems.

- System properties in HSR operation are not static. They are continuously altered from their initial conditions.

There exist multiple feedback loops among various phases of HSR system lifecycle such as R&D, design, maintenance as well as operation. These feedback loops incrementally change HSR subsystems, and also change emergent behaviors of a total system. In addition, HSR is a CLIOS system, so external factors such as economy, actions in other transportation modes, regulations and so on heavily influence HSR properties as well.

- Various "ilities" have been studied in HSR domain, but studies about interactions of "ilities" in system-level HSR operation are sparse. The RAMS is one approach to consider such interactions of "ilities".

As shown in Figure 3.4, various "ilities" are studied in the context of HSR. However, macroscopic approaches to study interactions of "ilities" are not so common in academic research. In industry, RAMS (the international standard to design and control reliability, availability, maintainability and safety in rail industries) has become a common approach to consider interactions of "ilities" of interest. This thesis expanded the idea of RAMS by introducing economic perspectives in HSR operation – profitability – as one of the key "ilities".

“Ilities” in Two Case Studies (Chapter 4, Chapter 5)

- The Tokaido Corridor (Tokaido) in Japan and the Northeast Corridor in the US (NEC) show several commonalties and differences.

Two case studies – the Tokaido Corridor and the NEC - are chosen in this thesis to study “ilities”. There are commonalities and differences shown as follows, which lead to different trends of “ilities”.

➢ Commonalities
  - Both corridors are located at the most densely populated regions in their countries, where multiple major cities exist.
  - In HSR operation, vertically integrated operations are mostly conducted in both corridors, though some part in the NEC is vertically separated.

➢ Differences
  - HSR runs on the dedicated track in the Tokaido, but it runs on the shared track with commuter rails and freight rails in the NEC.
  - HSR is managed by a private entity (JR Central) in the Tokaido, while it is managed by a partially government-owned entity (Amtrak) in the NEC.
  - Culture for the intercity passenger travel is different. Japan is more rail-oriented, while the US is more auto-oriented.

- In terms of intermodal competition, the Tokaido and the NEC have shown quite contrasting trends.

The Tokaido Corridor and the NEC have shown contrasting trends regarding modal splits. In the Tokaido Corridor, HSR dominates intercity passenger transport, and its market share has been stable over the last 20 years. Air transport has also steadily grown in the Tokyo-Osaka market, with the opening of two new airports. In the NEC, auto travel dominates intercity passenger transports. In terms of rail-air share, the rail share has been dramatically improved in the Boston-NY and NY-DC markets, since the introduction of the Acela Express in 2000. Air transport has lost passengers since 2000, because of several reasons such as emergence of HSR, utility deterioration by enhanced security checks after 9.11, and the surge of oil prices[15].

[15] However recently fuel prices have decreased, leading to a substantial increase in airline profits.

- In the Tokaido Shinkansen, a positive feedback loop among safety, availability and profitability works to make HSR operation successful.

In the last 20 years, the Tokaido Shinkansen has shown steady and high profitability. The operating profit has been enough to ensure necessary capital investment for its infrastructure and rolling stock, which has supported high safety and availability. That is, the corridor characteristics (densely populated, medium distance etc.) and HSR competitiveness (safety, availability, travel time, accessibility etc.) enabled profitability, which in turn drives investments in safety and availability.

- The NEC shows high profitability these days, but it is not well reflected in safety and availability.

In FY2014, the NEC showed a 39% profit margin (operating profit/operating revenue). Acela's profit margin was 51%, which was close to the profit margin of the Tokaido Shinkansen (50-60%). This highly profitable operation in the NEC generates more than $400M operating profit. However, the operating profit in the NEC had been used to cross-subsidize unprofitable Amtrak lines throughout the US before FY2015. Capital investment on the NEC had depended totally on the federal/state support, which was not sufficient to eliminate the maintenance backlog accumulated by long-term deferred maintenance. In addition, shared use of infrastructure heavily affects HSR availability, as shown in the MNR speed restriction example in Section 5.2.3. That is, the contribution of high profitability to safety and availability is limited by several factors, and in turn such limitations become obstacles to further improve profitability.

- Primary causes of major accidents (with fatalities / injuries) and minor accidents (without fatalities / injuries) in the NEC are different.

In the NEC, 341 accidents were reported to FRA in FY2001-2015. More than 80% of accidents without casualties (fatalities and/or injuries) result from component failures, especially from defects in power supply systems. In contrast, in 14 accidents with casualties, primary causes are interferences of external objects and human factors. This fact suggests that systemic factors other than hardware failures heavily contribute to major accidents.

Application of System Dynamics (Chapter 6)

- System Dynamics (SD) is an effective methodology to capture interactions and dynamic behaviors of "ilities" and other key variables in HSR operation.

System Dynamics has been frequently applied to the transportation domain, due to its inherent strength to conceptualize complex structures and feedback loops among variables. HSR operation is an appropriate and new research field to which System Dynamics is applied, since multiple subdomains such as train operation, infrastructure management and rolling stock management are integrated to influence "ilities" and other variables of interest.

- Integration of multiple subparts in SD modeling reveals a holistic view of HSR operation. In particular, integration of train operation and infrastructure / rolling stock management leads to the emergence of major feedback loops.

In the conceptual SD modeling, multiple "subparts" in HSR operation such as demand, supply, pricing, infrastructure management and rolling stock management are considered at first to construct partial CLD structures. Then, these subparts are integrated to form a larger CLD. This approach enables CLD to provide a holistic view of HSR operation at the enterprise level, while detail relationships of variables in each subpart are not oversimplified.

In particular, by integrating train operations and infrastructure / rolling stock management, "Infrastructure / Rolling Stock Quality" reinforcing loops and "Infrastructure / Rolling Stock Utilization" balancing loops emerge. These feedback loops connect two parts with key attributes of "ilities" such as operating profit, CAPEX, travel time, safety and service reliability. It is important to control these feedback loops in order to make HSR operations successful. In particular, the combination of the "Infrastructure Quality" loop and "Deferred Maintenance" loop can become vicious reinforcing loops if HSR is underfunded.

- Although causal loop diagrams (CLD) are similar in the Tokaido and the NEC, some differences in CLD structure represent important contrasts in these two cases.

Figure 6.12 in Section 6.2.3.3 shows a general CLD for vertically integrated HSR operation, but its application to two cases in Section 6.2.3.4 suggests that the different environment in HSR operation leads to the differences in the CLD structure. For example, the causal relationship between the operating profit and CAPEX exists in the Tokaido, but not in the NEC, since all profit has been used for cross-subsidization in the NEC. Such differences in CLD structure influence effectiveness of feedback loops, and behaviors of "ilities" and other variables of interest.

- Estimated parameters in numerical SD modeling in the Tokaido case and in the NEC case suggest different strengths of causal relationships among “ilities” and other variables.

Unknown parameters in the train operation SD models are estimated using empirical data. These parameters in the Tokaido and in the NEC represent how variables of interest interact differently. For example, in the Tokaido, passengers are insensitive to change of reliability or airlines’ response, while such factors do influence passengers’ mode choice in the NEC. Other comparison of estimated parameters are described in Section 6.3.2. The parameter estimation process is robust as long as the HSR operation environment does not change radically. Therefore, estimated parameters can be used for sensitivity analysis to estimate policy implications in the future.

- Early countermeasures to mitigate the maintenance backlog will eventually save more money than initially invested, given current levels of discount rates.

In the Tokaido Shinkansen, a major rehabilitation project to eliminate maintenance backlog has been ongoing since FY2013. This project shows positive net present value, since the present benefit by removing backlog exceeds the present cost by investing a special budget for the project. The main reason for this result is that early removal of maintenance backlog can prevent deteriorated facilities from generating further backlog. That is, a mitigating the “Deferred Maintenance” feedback loop can contribute to maintaining infrastructure in a state of good repair.

- The current level of capital investment in the NEC infrastructure is not sustainable, even though it exceeds the required budget for normal investment.

The current level of capital investment in the NEC is about $400M. This is more than the required budget for normal replacement, which is needed to maintain healthy facilities in a state of good repair. However, at this funding level, the maintenance backlog is projected to increase. This is because there exist facilities with large historical maintenance backlog, and they deteriorate faster than others in good conditions. Additional generation rate of maintenance backlog from deteriorated facilities is more than the current funding level, and thus the reduced trend of maintenance backlog cannot be achieved.

- Replacement of rolling stock improves fleet quality, but continuous investment is required to maintain it in the long-term.

Rolling stock used in HSR operation has its own lifespan (20-30 years), and its quality eventually deteriorates even if it is regularly maintained. Capital investment on rolling stock to replace an old fleet with a new one improves the average fleet quality, but the simulation in the NEC case showed that a "one-time shot" investment results in the deterioration of fleet quality again in the long run, unless a better job of fleet maintenance is done.

- Mitigation of capacity constraints contributes to improve ridership growth in a saturated HSR market, while easing the load factor.

A sensitivity analysis in the NEC case shows that the introduction of a new Acela fleet can contribute to regaining the growth trend of ridership, which has fallen due to the supply shortage. Capital investment in rolling stock as well as infrastructure to expand the upper limit of capacity is required to continuously grow in markets where the demand is projected to increase in the future.

- Elimination of cross-subsidization to utilize HSR operating profit as HSR capital investment contributes to eliminate maintenance backlog, but external funding is still needed in some cases.

The simulation with different policies in terms of financial resources for capital investment shows that more utilization of HSR operating profit into HSR capital investment contributes to reduce maintenance backlog in the future. However, in the case where the existing backlog is too large, multi-year external grants are still necessary to reduce the backlog.

- Secured budget for normal replacement is more important than backlog elimination projects.

Another sensitivity analysis reveals that larger investment for normal replacement rather than backlog elimination reduces more backlog. Backlog elimination projects take time before their completion, so the budget shortage for normal replacement generates more new backlog than the backlog elimination projects remove.

7.2 Conclusions

In this section, conclusions of this thesis are summerized.

- "Ilities" in HSR operation are not isolated and static. They interact with each other, and they are dynamic.

Case studies of HSR "ilities" and the application of System Dynamics reveal that "ilities" in HSR operation closely interact and show dynamic behavior. Figure 7.1 shows the interaction of the three "ilities" (safety, availability and profitability) considered in this thesis. The relationship of each "ility" is bi-directional, so feedback loops among "ilities" need to be considered. The visualization of "ilities" by using key performance indicators, and the evaluation of interaction among them are indispensable steps for HSR operators to control "ilities" appropriately in the long-term operation.

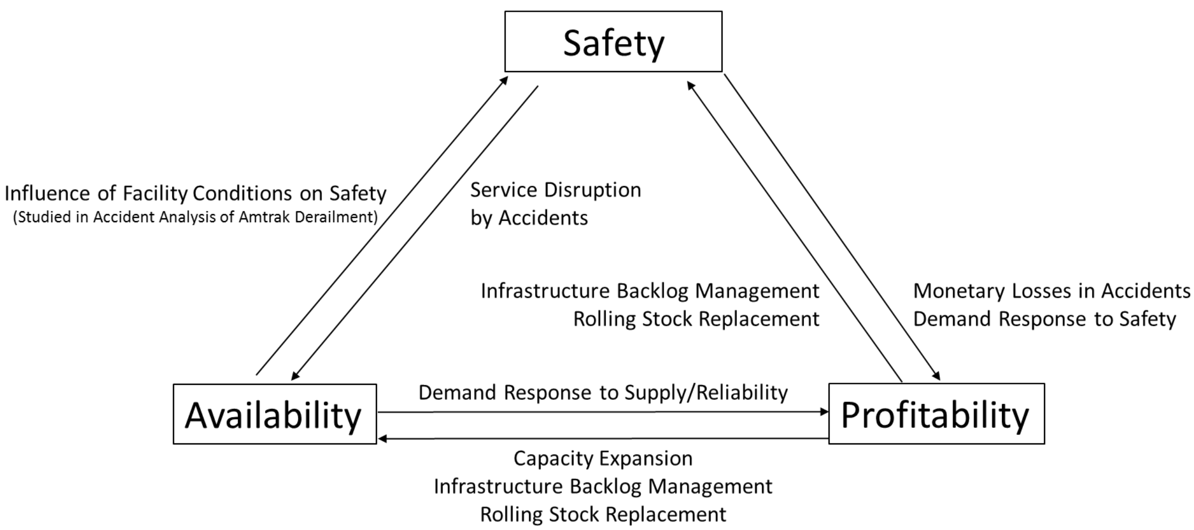


Figure 7.1 Interaction of HSR "ilities" Considered in this Thesis

- The overall picture including not only train operation but also infrastructure / rolling stock management should be taken into account to capture the comprehensive interaction of HSR "ilities".

There are various studies focusing on specific domains in HSR operation such as demand-supply balancing, pricing strategy, infrastructure maintenance, rolling stock design, and so on. However, in order to capture the holistic view of HSR operation and accompanying "ilities", integration of different domains into one overall picture is important. In the System Dynamics model in this thesis, several emergent feedback loops occupied an important role in the behavior of "ilities".

- HSR safety should be considered from multiple perspectives.

This thesis shows that the elimination of the maintenance backlog is a major factor to enhance safety. However, as stated in Section 5.2.2, systemic factors across multiple stakeholders as well as HSR operators need to be taken into account to prevent major accidents with casualties. The accident analysis of the Amtrak fatal derailment shown in Appendix A reveals that the decision-making processes by multiple stakeholders to implement PTC technology were not effective, and thus prompt actions were not taken. HSR operators and other stakeholders such as manufacturers, maintenance companies and regulatory agencies should collaborate to craft system safety programs focusing on institutional-level risk analysis.

- Utilizing HSR operating profit as HSR CAPEX is a necessary but not a sufficient condition to achieve self-sustaining HSR infrastructure management.

The utilization of HSR operating profit as part of financial sources for HSR capital investment is the initial step to make HSR operation self-reliant. In HSR where substantial capital investment is needed to achieve a state of good repair, however, external grants to eliminate backlog are still necessary to mitigate financial burden to tackle past deferred maintenance. Once the maintenance backlog is reduced to a "critical point", infrastructure management can be done only by HSR operating profit. This means that society may have to be willing to subsidize HSR at some level for its beneficial impacts on society (externalities).

- Maintaining healthy facilities in a state of good repair is no less important than replacing deteriorated ones.

Replacing deteriorated facilities into new ones is an essential action to enhance HSR quality, but it is more important to prevent new backlog generation. Stopping deferred maintenance, and conducting regular-basis inspection of facilities are of course necessary. In addition, R&D for new rail technologies to extend lifespan of facilities, or implementation of onboard monitoring systems to predict appropriate timing for maintenance are effective ways to keep HSR subsystems sound.

7.3 Future Work

This thesis shows a novel approach to deal with interaction of “ilities” in the context of long-term HSR operation, including train operation and infrastructure / rolling stock management. There are several areas of future work topics which can expand “ilities” studies in HSR operation.

- Application to vertically separated HSR operation model

This thesis mainly focuses on vertically integrated HSR operation model (the Tokaido Shinkansen in Japan and Amtrak service in the US NEC), in which train operation and infrastructure / rolling stock management are conducted within the same organization. In Europe, on the other hand, vertically separated HSR operation has dominant after the inauguration of the European Union in 1993. In vertically separated HSR, train operation and infrastructure / rolling stock management are conducted in different companies (e.g. Spain), or at least in different organizations under one holding company (e.g. Germany, France). Also, in some cases such as Italy, multiple HSR operators coexist within the same corridor. In such an operating condition, CLD constructed in Section 6.2 can take a different structure. Consideration of “ilities” in vertically separated European HSR cases and their comparison with vertically integrated HSR cases will be an interesting approach to evaluate effects of institutional structures in HSR operation. It can also assist in underplanning negotiations between the HSR players.

- Refinement of unknown parameter estimation in SD modeling

In this thesis, unknown parameters are assumed and estimated as constant values in their time horizons. However, as shown in Section 6.3.3, such parameters can change if the operating environment changes radically. Thus, a time-expanded parameter estimation processes in which unknown parameters are considered as time-dependent values can be one possible refinement from this thesis.
Also, studying revealed preference or stated preference in demand estimation for HSR can be an effective way to validate parameter estimation processes, particularly in the revenue/demand subpart.

HSR is a vital asset for nations to transport massive numbers of people efficiently. Like other infrastructure, a substantial amount of capital is required to maintain HSR for a long period. Therefore, it is important to consider the design of “ilities”, in order to make HSR operation sustainable and competitive. We thank all the readers, for your interest in this thesis, and we hope that it has offered you some useful perspectives to consider long-term HSR operation from systemic standpoints.

Appendix A: System-theoretic Analysis of the Amtrak Derailment in Philadelphia

This appendix focuses on the fatal derailment that occurred in the NEC on May 12, 2015. This accident was the deadliest accident in the NEC in the 21st Century. In this appendix, a system-theoretic approach is used to reveal systemic factors lying behind the direct cause. We hope this analysis provides supplemental ideas to consider HSR "ilities" (particularly safety) at the system level.

A.1 Accident Description

At 9:21pm on May 12, 2015, an Amtrak northbound Northeast Regional Train No. 188 (from Washington D.C to New York, and Boston) derailed and crashed at the Frankford Junction, north of Philadelphia, Pennsylvania. In this crash, out of 250 passengers and 8 Amtrak employees, 8 passengers were killed and over 200 people were injured. (Figure A.1, Figure A.2 [77])

According to the NTSB preliminary report [77], this train entered the Frankford Junction, where the main lines make a 4-degree steep curve to the north, at 106mph. The speed limit of this curve was 80mph in its approach and 50mph within it. The train engineer applied the emergency brake at the entrance of this curve, which decelerated the train from 106mph to 102mph, but it was too late to prevent the train derailment. He stated to NTSB that he could not recall anything after passing through North Philadelphia station, 3 miles to the south of the derailment sight.

The investigation of this accident is still ongoing by the NTSB as of May 2016, and an official investigation report has not yet been published. The direct cause was the overspeed, but there exist several systemic factors behind the accident [78]. This thesis intends to discuss possible scenarios, causal factors, and systemic backgrounds contributing to this derailment, using STAMP theory, which was proposed by Leveson [34].

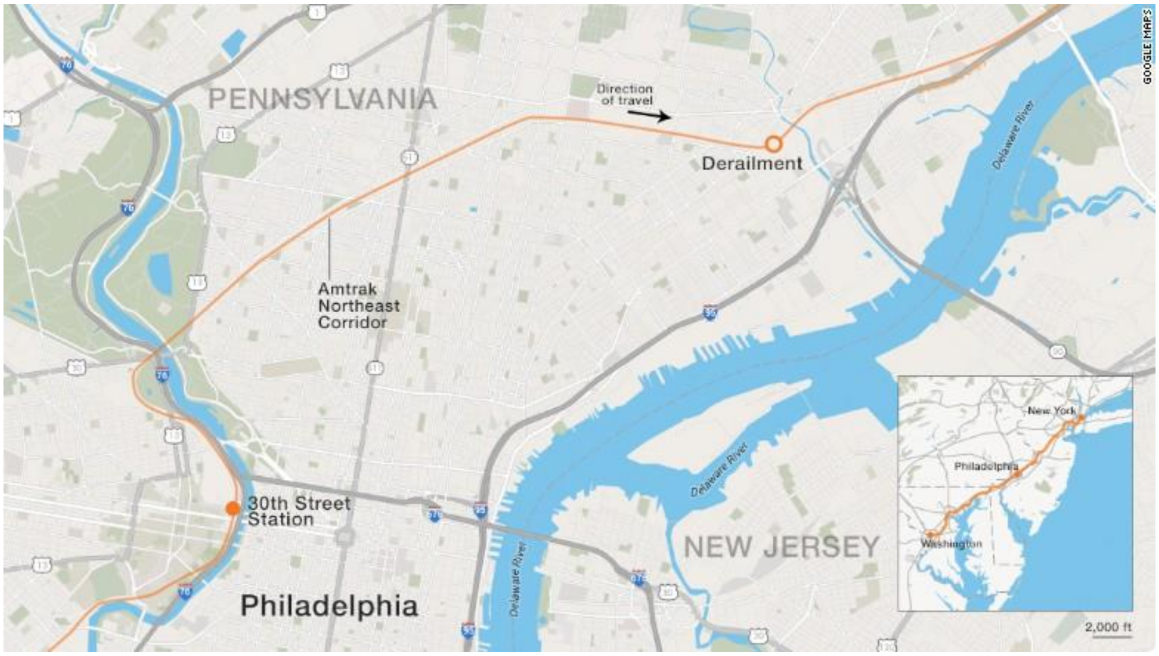


Figure A.1 Location of Train Derailment

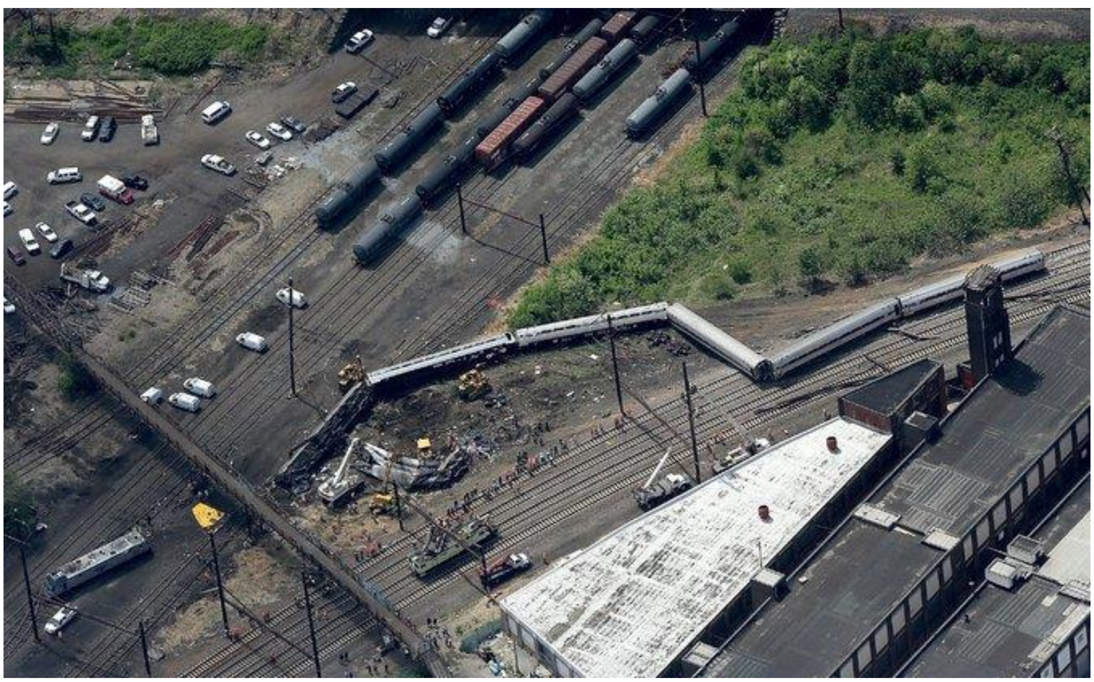


Figure A.2 Train Derailment

Source: NTSB, 2015)

A.2 STAMP Based Accident / Hazard Analysis

In STAMP theory, CAST (Causal Analysis based on STAMP) is used as a method for accident analysis. CAST is conducted in the following steps. [34]

Process of CAST analysis (Quoted from Leveson, 2011 [34] pp 350-351)

1. Identify high-level hazards involved in the accident.
2. Identify system requirements and safety constraints associated with these hazards.
3. Develop the safety control structure in place to control the hazard and enforce the safety constraints. Each system component's roles, responsibilities, controls provided or created pursuant to their responsibilities, and the relevant feedback are specified.
4. Determine the proximate events that led to the accident.
5. Analyze the accident at the physical system. Identify the contribution of the physical and operational controls, physical failures, dysfunctional interactions, communication and coordination flaws, and unhandled disturbances to the events. Analyze why the physical controls in place were not adequate in preventing the hazard.
6. Moving up the levels of the safety control structure, determine how and why each successive higher level contributed to the inadequate control at the lower level. For each safety constraint, either the responsibility for enforcing it was never assigned to a component in the safety control structure or a component or components did not exercise adequate control to ensure their responsibilities (safety constraints) were enforced in the components below them. Any human decisions or flawed control actions need to be understood in terms of (at least): the information available to the decision maker as well as any required information that was not available, the behavior-shaping mechanisms (the context and influences on the decision-making process), the value structures underlying the decision, and any flaws in the process models of those making the decisions and why those flaws existed.
7. Analyze overall coordination and communications contributors to the accident.
8. Determine the dynamics and changes in the system and the safety control structure relating to the loss and any weakening of the safety control structure over time.
9. Generate recommendations.

However, in this accident, the accident investigation is still ongoing, and an official accident report is yet to be published as of May 2016. That is, solid information needed to conduct step 4-9 in CAST analysis is not yet available.

Thus, in this thesis, STPA (System Theoretic Process Analysis) is used to think about the potential causes or scenarios of this accident. STPA is a hazard analysis method in STAMP theory, whose goal is to identify causal factors contributing potential hazards. STPA analysis is conducted as shown below.

Process of STPA analysis (Quoted from Leveson, 2011 [34] pp213)

Step 0: Fundamental processes for STAMP

- Identify accidents, hazards and system safety constraints (correspond to CAST Step 1, Step 2)
- Draw the control structure (correspond to CAST Step 3)

Step 1: Identify unsafe control actions

Identify unsafe control actions in the control structure developed in Step 0. Hazardous states result from these inadequate controls:

a. A control action required for safety is not provided or not followed
b. An unsafe control action is provided.
c. A potentially safe control action is provided too early or too late, that is at the wrong time or in the wrong sequence.
d. A control action required for safety is stopped too soon or applied too long.

Step 2: Identify causal factors and create scenarios

Determine causal factors and scenarios how each unsafe control action identified in step 1 could occur. Control flaws which could cause hazardous states are shown Figure A.3 [34].

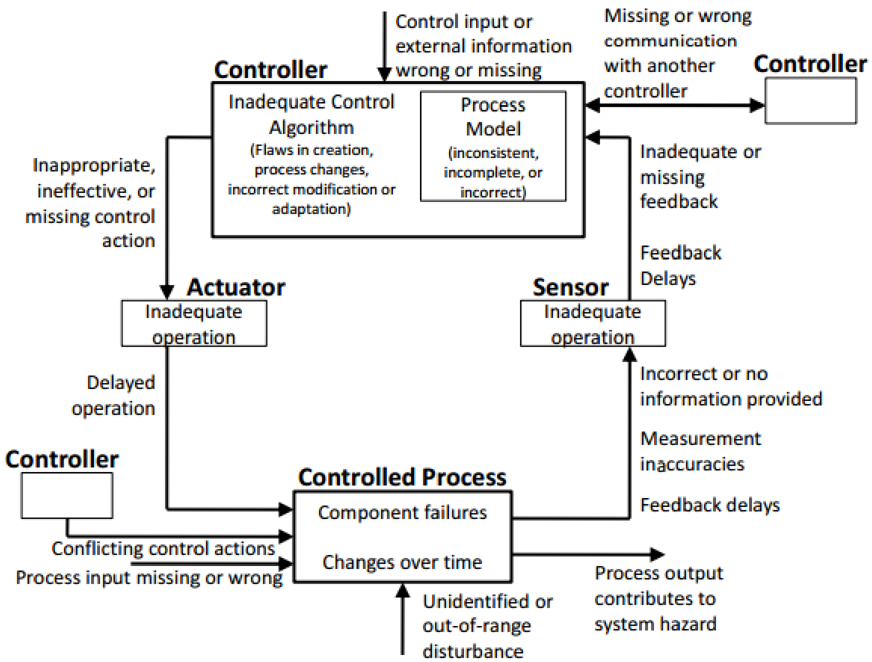


Figure A.3 Potential Control Flaws causing Unsafe Control Actions
(Source: Leveson, 2011)

A.3 STPA on Amtrak's Derailment

A.3.1 Step 0-a: Definition of System Accident, System Hazard and System Safety Constraints

Accidents (System-Level Losses)

An accident in STAMP theory are defined as "an undesired or unplanned event that results in a loss, including loss of human life/injury, property damage, environmental pollution, mission loss etc." [34]. In this thesis, the accident is

Accident: Passengers are killed or injured in the train derailment

In general, fatal accidents of railway result from either derailment/collision/fire of rolling stock. Here, since Amtrak derailment is the focus, only "train derailment" is considered as a cause of fatality, injury and property damage.

Hazards

Hazard is defined as "a system state or set of conditions that, together with a particular set of worst-case environmental conditions, will lead to an accident (loss)" [34]. In this case, hazards which would lead to the accident shown above is

Hazard: Rolling stock in operation derail from track

An accident occurs when a hazard exists with a particular environmental condition. In this case, the train derailment itself was hazard, and other environmental factors such as passengers' positions, train speed or surrounding structures were combined and eventually caused fatal accidents.

There are several possibilities which could cause the hazard above. Some examples are

- Rolling stock travels faster than the speed limit.
- Rolling stock has excessive payload.
- Physical infrastructures such as rails or bogies of rolling stock were not appropriately maintained and broken when rolling stock passed.

As for today, NTSB investigation shows that the train was running at 102mph at derailment, which was much more than the speed limit there. In addition, no anomalies are detected in train braking systems, signals and track geometry. Therefore, in this thesis, train overspeed is our main focus as a potential cause for this hazard.

System Safety Constraints

System safety constraints are defined to prevent hazards identified in the previous step from occurring. Safety constraints for hazards in this case are shown below:

A. Rolling stock must not exceed the speed limit of tracks.

B. Rolling stock must decelerate when they exceed the speed limit.

C. Facilities which control train speed must be installed and maintained appropriately.

When either of them or combinations of them are violated by unsafe control actions, the system (in this case, train operation) is in a hazardous state.

A.3.2 Step 0-b: Design of Safety Control Structure

The next step of STPA is to draw the hierarchical control structure of this system. Kawakami showed a generic control structure of the high speed rail industry [27]. Based on this structure, the specific control structure in this accident is crafted. Figure A.4 shows the control structure of this system. Table A.1 - Table A.4 shows the detail descriptions of control loops, responsibilities and process models of each controller. In these tables, gray cells represent physical components.

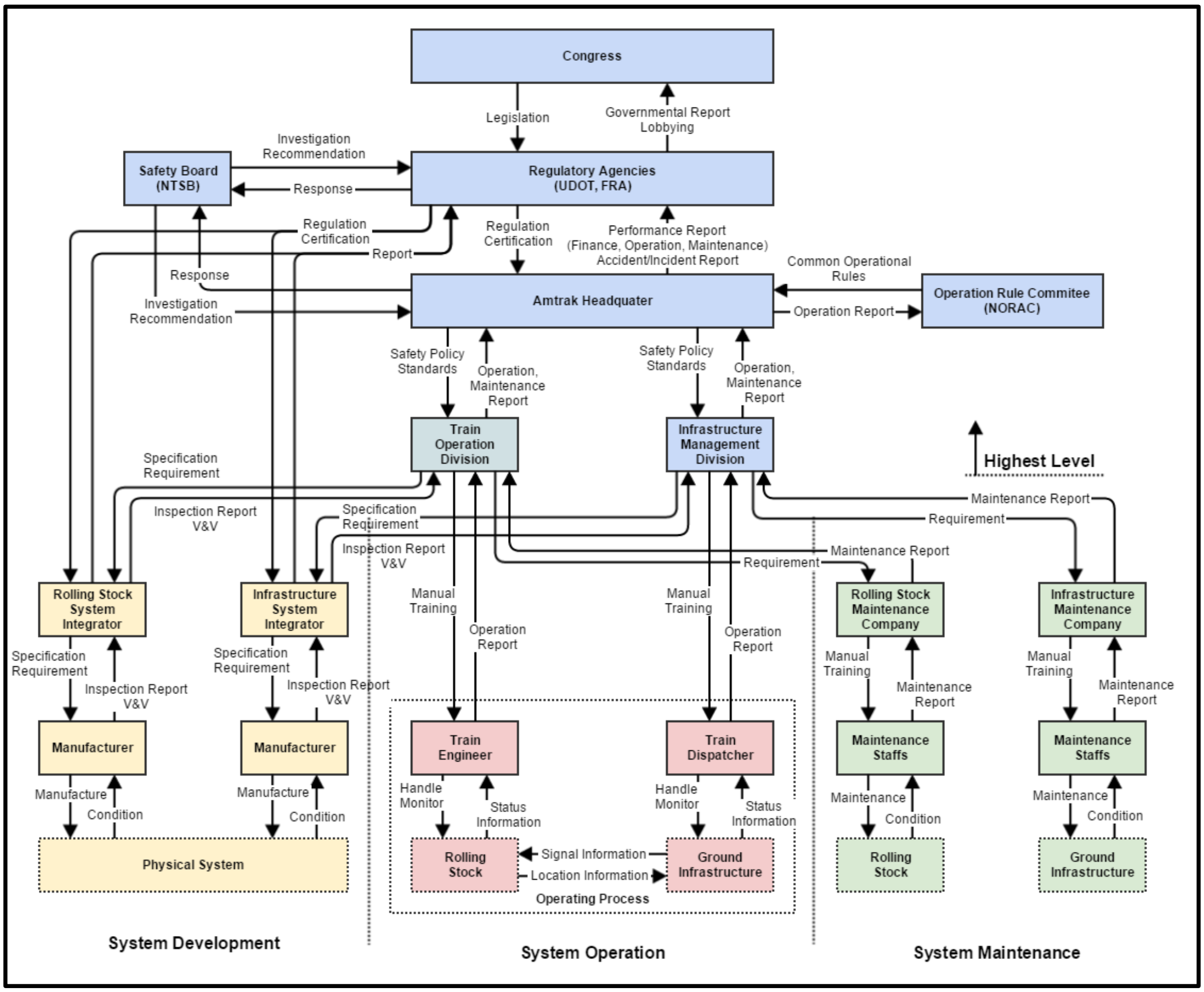


Figure A.4 Safety Control Structure

Table A.1 Detail Description of the Safety Control Structure – Highest Level

Controller	Responsibility	Controlled Process	Control Action	Feedback	Process Model
Highest Level					
Congress	- Legislate regulations about railway systems - Inspect and allocate federal budget for railway industry	Regulatory Agencies (UDOT, FRA)	Legislation	Government Report Lobbying	- Information about railway industry and entire transportation system from governmental report or lobbying - Policies of each party
Regulatory Agencies (UDOT, FRA)	- Develop regulatory frameworks (regulations, standards) in terms of railway safety - Issue certifications for operators and manufacturers who comply with regulations	Amtrak Headquarter	Regulation Certification	Performance Report (Finance, Operation, Maintenance) Accident / Incident Report	- Technical, financial circumstances of industry - Potential impact of regulatory design/changes
		Rolling Stock / Infrastructure System Integrator	Regulation Certification	Inspection Report	- Technical, financial circumstances of industry - Potential impact of regulatory design/changes
Safety Board (NTSB)	- Develop investigation reports of accidents - Craft recommendations based on insights obtained in investigations	Regulatory Agencies	Investigation Report Recommen-dation	Response to recommen-dation	- Technical knowledge and insight from past accidents
		Amtrak Headquarter	Investigation Report Recommen-dation	Response to recommen-dation	- Technical knowledge and insight from past accidents
Operation Rule Committee (NORAC)	- Develop and revise common operational rules for railroads mainly in Northeast US	Amtrak Headquarter	Common Operational Rules	Operation Report	- Experience and insight from railway operation of members in committee
Amtrak Headquarter	- Supervise current operation and maintenance - Develop long-term company strategies - Ask Regulatory agencies and Congress for subsidies - Develop long-term capital investment plan to ensure safe operation	Train Operation Division	Safety Policy Standards	Operation / Maintenance Report	- Regulation determined by agencies - Corporate strategy - Technical, financial circumstances of railway operation
		Infrastructure Management Division	Safety Policy Standards	Operation / Maintenance Report	- Regulation determined by agencies - Corporate strategy - Technical, financial circumstances of infrastructure management

Table A.1 Detail Description of the Safety Control Structure – Highest Level – cont.

Controller	Responsibility	Controlled Process	Control Action	Feedback	Process Model
Highest Level – cont.					
Train Operation Division	- Control train operation - Develop time table, manage fleet and train engineers - Craft and manage operation manuals - Conduct training on train engineers - Contract with maintenance companies and maintain rolling stock - Develop plans for new rolling stock installation in the future, craft specification and requirement for them, and make contracts with system integrators of rolling stock	Train Engineer	Supervise Manual Training	Operation Report	- Knowledge, experience of existing train operation system - Capability of train engineers
		Rolling Stock System Integrator	Specification Requirement	Inspection Report Verification & Validation	- Strategy of rolling stock improvement - Capability of system integrators
		Rolling Stock Maintenance Company	Requirement	Maintenance Report	- Knowledge, experience of existing rolling stock maintenance - Advice or report from rolling stock system integrator - Capability of maintenance company
Infrastructure Management Division	- Manage infrastructure operation - Craft and manage operation manuals - Conduct training on train dispatchers - Contract with maintenance companies and maintain infrastructures - Develop plans for new ground infrastructures installation in the future, craft specification and requirement for them, and make contracts with system integrators of infrastructures	Train Dispatcher	Supervise Manual Training	Operation Report	- Knowledge, experience of existing train dispatching system - Capability of train dispatchers
		Infra-structure System Integrator	Specification Requirement	Inspection Report Verification & Validation	- Strategy of infrastructure improvement - Capability of system integrators
		Infra-structure Maintenance Company	Requirement	Maintenance Report	- Knowledge, experience of existing infrastructure maintenance - Advice or report from infrastructure system integrator - Capability of maintenance company

Table A.2 Detail Description of the Safety Control Structure – System Operation

Controller	Responsibility	Controlled Process	Control Action	Feedback	Process Model
System Operation					
Train Engineer	- Operate trains - Communicate with train dispatchers for their train operation - Record and report the result of operations	Rolling Stock (Physical)	Handle Monitor	Status Information	(Engineer's mental model) - Operation manuals - Safety concerns - Operators' physiological / mental conditions
Train Dispatcher	- Dispatch trains - Communicate with train engineers for their train operation and control signals - Record and report the result of operations	Train Engineer	Instruction Permission	Report	(Dispatcher's mental model) - Operation manuals - Safety concerns - Dispatchers' physiological / mental conditions
		Ground Infra-structure (Physical)	Handle Monitor	Status Information	

Table A.3 Detail Description of the Safety Control Structure – System Development

Controller	Responsibility	Controlled Process	Control Action	Feedback	Process Model
System Development					
Rolling Stock System Integrator	- Develop overall design and integration of rolling stock from specification / requirement of Train Operation Division - Allocate requirement of sub-components and let manufacturers supply them with contracts	Manufac-turer	Specification Requirement	Inspection Report Verification & Validation	- Information of rolling stock operation and maintenance from Train Operation Division - Capability of manufacturer
Infra-structure System Integrator	- Develop overall design and integration of infrastructures from specification / requirement of Infrastructure Management Division - Allocate requirement of sub-components and let manufacturers supply them with contracts	Manufac-turer	Specification Requirement	Inspection Report Verification & Validation	- Information of infrastructure operation and maintenance from Infrastructure Management Division - Capability of manufacturer
Manufac-turer (Rolling Stock, Infra-structure)	- Manufacture sub-components of rolling stock / infrastructures, based on the specification and requirement from system integrators	Sub-components of Train System	Manufacturer	Condition Data	- Information of rolling stock/infrastructure from system integrator - Manufacturing manuals - Capacity of manufacturing facilities

Table A.4 Detail Description of the Safety Control Structure – System Maintenance

Controller	Responsibility	Controlled Process	Control Action	Feedback	Process Model
System Maintenance					
Rolling Stock Maintenance Company	- Maintain rolling stock based on contracts - Conduct training on maintenance staffs - Submit maintenance report to Train Operation Division and suggest feedback on design, operation and maintenance if necessary	Maintenance Staffs (Rolling Stock)	Maintenance Manual Training	Maintenance Report	- Knowledge, experience of rolling stock maintenance - Capability of maintenance staffs
Infrastructure Maintenance Company	- Maintain infrastructures based on contracts - Conduct training on maintenance staffs - Submit maintenance report to Infrastructure Management Division and suggest feedback on design, operation and maintenance if necessary	Maintenance Staffs (Infra-structure)	Maintenance Manual Training	Maintenance Report	- Knowledge, experience of infrastructure maintenance - Capability of maintenance staffs
Maintenance Staff (Rolling Stock, Infrastructure)	- Maintain rolling stock or infrastructures - Document maintenance records	Existing Rolling Stock / Infrastructure (Physical)	Maintenance	Condition Data	- Maintenance manuals - Staffs' physiological /mental conditions

A.3.3 Step 1: Identify Unsafe Control Actions

In this step, unsafe, inadequate control actions which could cause hazardous state shown in Section A.3.1 are identified. The accident, hazard and safety constraints identified in Step 0-a are shown below.

Accident

Passengers are killed or injured in the train derailment.

Hazards

Rolling stock in operation derails from track.

Safety Constraints

A. Rolling stock must not exceed the speed limit of tracks.

B. Rolling stock must decelerate when they exceed the speed limit.

C. Facilities which control train speed must be installed and maintained appropriately.

Hazardous states could occur because, in some control processes,

- Required control actions are not provided
- Unsafe control actions are provided
- Control actions are provided in an incorrect timing or order.
- Required control actions stopped too soon or applied too long.

In the following sections, unsafe control actions in different control processes are identified and discussed.

Table A.5 Identified Unsafe Control Actions – Physical Level

Controller	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
System Operation						
Train Engineer	Rolling Stock (Physical)	Handle Monitor	- Brake is not provided when train runs faster than its speed limit	- Train is kept on accelerating	- Brake is provided only after train speed becomes too fast	- Brake is terminated too soon - Acceleration is provided too long
Train Dispatcher	Infra-structure (Physical)	Handle Monitor	- Appropriate signals are not turned on	- Wrong signals are turned on	-	-
	Train Engineer	Instruction Permission	- Necessary instruction such as special operating procedure is not provided	- Wrong instruction is provided	-	-
System Maintenance						
Maintenance Staff	Rolling Stock/Infra structure (Physical)	Maintenance	- Appropriate maintenance is not conducted	- Maintenance is conducted in a wrong way	- Maintenance staff conduct maintenance less frequently than needed	-
System Development						
Manufac-turer	Rolling Stock/ Infra-structure (Physical)	Manufacture	- Components comply with safety requirement are not supplied	- Components which don’t comply with safety requirement are supplied	- Components are supplied beyond deadline	-

Table A.6 Identified Unsafe Control Actions – System Operation, Organizational Level

Controll-er	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
System Operation						
Train Operation Division	Train Engineer	Supervise Manual Training	- Engineers are not appropriately dispatched and substituted if necessary - Enough training is not provided - Comprehensive safety-critical contexts are not covered in manuals	- Wrong information exists in manuals	- Operation manuals or training curriculum are not appropriately updated as system changes	- Trainees are allowed to drive trains too soon
Infra-structure Manage-ment Division	Train Dispatcher	Supervise Manual Training	- Dispatchers are not appropriately allocated - Enough training is not provided - Comprehensive safety-critical contexts are not covered in manuals	- Wrong information exists in manuals	- Operation manuals or training curriculum are not appropriately updated as system changes	- Trainees are allowed to drive trains too soon

Table A.7 Identified Unsafe Control Actions – System Maintenance, Organizational Level

Controll-er	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
System Maintenance						
Rolling Stock Mainte-nance Company	Maintenance Staffs	Manual Training	- Appropriate maintenance manuals or training is not provided	- Manuals or training which contain wrong information is provided	- Manuals and training contents are not updated as system changes	- Trainees are allowed to conduct maintenance too soon
Infra-structure Mainte-nance Company	Maintenance Staffs	Manual Training	- Appropriate maintenance manuals or training is not provided	- Manuals or training which contain wrong information is provided	- Manuals and training contents are not updated as system changes	- Trainees are allowed to conduct maintenance too soon
Train Operation Division	Rolling Stock Maintenance Company	Require-ment	- Requirement is not comprehensive to achieve safety operation	- Ambiguous / wrong requirement to cause misunderstandi ng is provided	- Change of requirement is not provided as system changes	-
Infra-structure Manage-ment Division	Infra--structure Maintenance Company	Require-ment	- Requirement is not comprehensive to achieve safety operation	- Ambiguous / wrong requirement to cause misunderstandi ng is provided	- Change of requirement is not provided as system changes	-

Table A.8 Identified Unsafe Control Actions – System Development, Organizational Level

Controller	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
System Development						
Rolling Stock System Integrator	Manufac-turer	Specifi-cation Require-ment	- Necessary specification or requirement to achieve safety requirement of operation is not provided	- Inappropriate specification or requirement to achieve safety requirement of operation is provided	- Specification or requirement is not appropriately revised as other contexts (upward requirement, capability of manufacturer…) changes	-
Infra-structure System Integrator	Manufac-turer	Specifi-cation Require-ment	- Necessary specification or requirement to achieve safety requirement of operation is not provided	- Inappropriate specification or requirement to achieve safety requirement of operation is provided	- Specification or requirement is not appropriately revised as other contexts (upward requirement, capability of manufacturer…) changes	-
Train Operation Division	Rolling Stock System Integrator	Specifi-cation Require-ment	- Necessary specification or requirement for safety operation is not provided	- Inappropriate specification or requirement for safety operation is provided	- Specification or requirement is not appropriately revised as system changes	-
Infra-structure Manage-ment Division	Infra-structure System Integrator	Specifi-cation Require-ment	- Necessary specification or requirement for safety operation is not provided	- Inappropriate specification or requirement for safety operation is provided	- Specification or requirement is not appropriately revised as system changes	-

Table A.9 Identified Unsafe Control Actions – Highest Organizational Level

Controller	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
System Operation, Maintenance and Development						
Amtrak Head-quarter	Train Operation Division	Safety Policy Standards	- Comprehensive safety-critical contexts are not covered in safety policy or standards	- Mis-understanding is induced by safety policy or standards in crafting manuals or training	- Safety policy or standards are not appropriately updated as system changes	- Necessary policy or standards are terminated or changed
	Infra-structure Manage-ment Division	Safety Policy Standards	- Comprehensive safety-critical contexts are not covered in safety policy or standards	- Mis-understanding is induced by safety policy or standards in crafting manuals or training	- Safety policy or standards are not appropriately updated as system changes	- Necessary policy or standards are terminated or changed
Operation Rule Committee (NORAC)	Amtrak Head-quarter	Common Operatio-nal Rules	- Necessary operational rules for safety operation are not provided	- Operational rules cause hazardous operations	- Operational rules are not appropriately updated as system changes	- Out-of-date operational rules are still applied
Safety Board (NTSB)	Regulatory Agencies, Amtrak Head-quatrer	Investi-gation Report Recommen-dation	- Adequate recommen-dations regarding safety operation are not provided	- Recommen-dation based on inappropriate accident investigation is released	- Implementation of safety recommendatio n cannot match with current technical / financial circumstances	-
Regulatory Agencies (UDOT, FRA)	Amtrak Head-quarter	Regulation Certifi-cation	- Comprehensive safety-critical contexts are not covered in regulations	- Certification is given to operators not eligible for safe operation	- Regulation is not updated as system changes	-
	Rolling Stock / Infra-structure System Integrator	Regulation Certifi-cation	- Comprehensive safety-critical contexts are not covered in regulations	- Certification is given to integrators not eligible for safe system development	- Regulation is not updated as system changes	-
Congress	Regulatory Agencies	Legislation	- Regulatory Agencies are prevented from taking appropriate actions	- Inappropriate regulations are forced to be made by legislation	- Legislation is not updated as system changes	-

A.3.4 Step 2: Identify Causal Factors

In this step, possible scenarios and causal factors for each unsafe control action are considered. In this accident, system operation within Amtrak is primarily and directly involved in the derailment, but other systemic factors in system maintenance, system development and highest hierarchy are also considered as possible hazardous control actions which could indirectly contribute to the accident. Some analyses are based on interim report of NTSB or news articles, not on the official accident report (yet to be published), so these considerations might be changed after more solid information becomes public. Nevertheless, it is worth considering several systemic factors which could cause the actual accidents in the NEC to think about safety in high speed rail system.

A.3.4.1 Physical Level Analysis

0. Physical Components Level

Similar to the process of CAST, here the analysis of causal factors starts from the "lowest", physical level. Before going up to the level where human controllers or organizations are involved, failures or malfunctions of components in the train or ground infrastructure should be considered as a possible cause of the derailment. Uncontrollable overspeed of the train could happen if the throttle is stuck in full notches, or braking system is out of order, or other mechanical, or electrical failures. However, NTSB investigation has found no physical anomalies which could be connected to this unusual acceleration.

1. Train Engineer – Rolling Stock

Controller	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Train Engineer	Rolling Stock (Physical)	Handle Monitor	- Brake is not provided when train runs faster than its speed limit	- Train is kept on accelerating	- Brake is provided only after train speed becomes too fast	- Brake is terminated too soon - Acceleration is provided too long

The physical cause of this derailment was that the train was running at 102mph where the speed limit was only 50mph. The train engineer was responsible for controlling the train speed, but he couldn't do this because of some reasons. The train engineer stated that he could not recall anything after he passed through North Philadelphia station, several miles behind the accident site.

One possible causal factor of this inadequate control process was due to inadequate operation of controller, which could be caused by his incomplete process model. That is, even if the components of the train works correctly, the engineer might be unable to appropriately handle information from the train or infrastructure. As of today, there are several speculations (e.g. he was distracted by a flying projectile, he was using cellphone, he felt too tired etc.) about why the train engineer continued accelerating and couldn't appropriately apply brakes, and NTSB is still investigating.

In fact, there have been several fatal derailments caused by the overspeed, which was partly because of the process model flaws of drivers. For example, in the case of Santiago de Compostela rail disaster occurred in Spain in 2013 [79], the train engineer was on his phone and didn't notice that the train was running too fast. In Fukuchiyama Line Derailment [80], the driver feared punitive training and tried to recover from delays, which caused the overspeed. In both cases, the mental model flaws of the train engineer caused the inadequate control of train speed, which resulted in the overspeed at curves.

This causal factor is the most direct and easiest scenario to be understood as a cause of this accident, and this is why many people see the train engineer as the first man to be blamed. However, as shown in the following sections, there could be several systemic factors other than human factors (or human errors) which directly or indirectly contributed to this accident. For example, the fact that there was no safety backup systems which automatically slowed down the train was critical in that this is relevant with safety constraints B and C, and the discussion for this fact is conducted in Section A.3.4.5.

Another possible causal factor in this control loop is that the feedback from controlled process (=train) was inadequate. There was no malfunction of components reported so far, but one notable fact was that the train engineer experienced a "cab signal failure" in the previous train which he drove. [81] Cab signal system duplicates trackside signals into train cab, which can be easily seen by train engineers. (Detail description of cab signal is shown in Section A.3.4.5.) The train engineer's prior train, Acela 2121 (New York – Washington D.C.), experienced a failure on cab signal system. As a result, the engineer had to see trackside signals carefully, which might made him feel exhausted. This is not the direct cause of the accident, but the physiological/mental condition of the train engineer could be distracted by this event.

2. Train Dispatcher – Ground Infrastructure, Train Engineer

Controller	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Train Dispatcher	Infrastructure (Physical)	Handle Monitor	- Appropriate signals are not turned on	- Wrong signals are turned on	-	-
	Train Engineer	Instruction Permission	- Necessary instruction such as special operating procedure is not provided	- Wrong instruction is provided	-	-

Train dispatchers are responsible for monitoring ground infrastructure in operation and train engineers. Mishandling of infrastructure or inappropriate/ambiguous instructions to train engineers could cause a hazardous state. In this accident, the overspeed of rolling stock could not be controlled by dispatchers, and so far there seems no major unsafe control actions of train dispatchers which contributed to the derailment.

3. Maintenance Staff / Manufacturer – Rolling Stock, Ground Infrastructure

Controller	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Maintenance Staff	Rolling Stock/Infra structure (Physical)	Maintenance	- Appropriate maintenance is not conducted	- Maintenance is conducted in a wrong way	- Maintenance staff conduct maintenance less frequently than needed	-
Manufac-turer	Rolling Stock/Infra structure (Physical)	Manufacture	- Components comply with safety requirement are not supplied	- Components which don't comply with safety requirement are supplied	- Components are supplied beyond deadline	-

This control process is not the part of system operation which directly relates to the accident, but under the system maintenance or the system development. Inappropriate manufacturing or maintenance could happen if these staffs are not capable of doing these tasks, or if control input from upper stream such as maintenance manuals or requirement is inadequate. Hatfield Derailment in UK [27] is a good example where the inappropriate maintenance procedure induced derailment. In the Amtrak accident, there is no reported failure of components directly involved in the derailment, and so far there seems no major unsafe control actions of maintenance staffs or manufacturers which contributed to the derailment.

A.3.4.2 Organizational Level Analysis – System Operation

1. Train Operation Division – Train Engineer

Controller	Controll-ed Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Train Operation Division	Train Engineer	Super-vise Manual Training	- Engineers are not appropriately dispatched and substituted if necessary - Enough training is not provided - Comprehensive safety-critical contexts are not covered in manuals	- Wrong information exists in manuals	- Operation manuals or training curriculum are not appropriately updated as system changes	- Trainees are allowed to drive trains too soon

There are several potential unsafe control actions in this control process, as indicated in Table A.2. The first one is the allocation of engineers. Each train engineer is allocated and dispatched to each service train, based on the rosters designed by the crew management service office. If there are train delays or cancellations, this roster is changed accordingly. According to Daly [81] , there was an “unwritten” agreement between Amtrak and labor union that train engineers could take at least 90 minutes break before the next run. However, this article notes that this agreement was often ignored by Amtrak. In this accident, the train engineer experienced a cab signal failure in the previous run, as shown in 2-1-1, and his train arrived at Washington D.C. 26 minutes late. As a result, he could take only a 61-minute break before the next fatal run. (It is worth noting that, even in the scheduled roster, he had 87 minute break, which was less than 90 minutes.) This fact suggests that there could be “an inadequate control algorithm” in allocating engineers in that there was not a rigid, written agreement about dispatching engineers without taking their medical conditions into account.

The usage of operation manuals could be another unsafe control action. The detail of operation manuals for engineers is not open to the public, and it is not clear whether there were any actions in accordance with existing operation manuals which led to the accident. However, it is worth noting that NTSB recommended to FRA and Amtrak that audio/image recorders should be installed in operating cabs of all trains so that the behavior of train crews can be monitored. [77] This kind of information can be used not only for ensuring that train crews are acting in accordance with appropriate procedures, as NTSB suggests, but also for finding contents in manuals that need to be revised or updated. Also, the improvement of operation manuals is deeply related to training curriculums. Maintaining and monitoring capability and morale of train engineers is one of the biggest responsibility of train operation division to ensure operational safety.

2. Infrastructure Management Division – Train Dispatcher

Controll-er	Control led Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Infra-structure Manage-ment Division	Train Dis-patcher	Supervise Manual Training	- Dispatchers are not appropriately allocated - Enough training is not provided - Comprehensive safety-critical contexts are not covered in manuals	- Wrong information exists in manuals	- Operation manuals or training curriculum are not appropriately updated as system changes	- Trainees are allowed to drive trains too soon

Infrastructure management division is in charge of supervising and training dispatchers and crafting/revising operation manuals for them. The same things can be said in terms of allocation of dispatchers, usage of operational manuals and training curriculums.

A.3.4.3 Organizational Level Analysis – System Maintenance

1. Rolling Stock / Infrastructure Maintenance Company – Maintenance Staffs

Controll-er	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Rolling Stock / Infra-structure Mainte-nance Company	Mainte-nance Staffs	Manual Training	- Appropriate maintenance manuals or training is not provided	- Manuals or training which contain wrong information is provided	- Manuals and training contents are not updated as system changes	- Trainees are allowed to conduct maintenance too soon

Rolling stock / infrastructure maintenance companies make contracts with Amtrak and conduct necessary maintenance. They manage maintenance manuals and checklists in accordance with requirements or specifications shown in contracts, and regularly submit maintenance reports to Amtrak. Up-to-date manuals and training curriculums is necessary to ensure safe maintenance, and lack of them leads to unsafe control actions. Same as the lower level analysis, since there are no reported malfunctions due to inappropriate maintenance, no major unsafe control actions seem to be involved in this accident.

2. Train Operation / Infrastructure Management Division – Maintenance Company

Controller	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Train Operation / Infrastructure Management Division	Rolling Stock / Infra-structure Maintenance Company	Require-ment	- Requirement is not comprehensive to achieve safety operation	- Ambiguous / wrong requirement to cause misunderstanding is provided	- Change of requirement is not provided as system changes	-

These divisions in Amtrak are in charge of crafting specifications or requirements of maintenance, making contracts with maintenance companies, and monitoring maintenance data reported by them. If necessary, based on the result of maintenance, they also need to take further actions such as change of maintenance standards or renewal of facilities. To conduct these multidisciplinary tasks, these divisions need to know about not only maintenance procedure but also system operation and development, as clearly seen from the control structure shown in Figure A.4. The integration of these tasks is the core of the process model in these division, and incomplete process model is the prime factor of unsafe control.

A.3.4.4 Organizational Level Analysis – System Development

1. Rolling Stock / Infrastructure System Integrator – Manufacturer

Controll-er	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Rolling Stock / Infra-structure System Integrator	Manufac-turer	Specification Requirement	- Necessary specification or requirement to achieve safety requirement of operation is not provided	- Inappropriate specification or requirement to achieve safety requirement of operation is provided	- Specification or requirement is not appropriately revised as other contexts (upward requirement, capability of manufacturer…) changes	-

These system integrators receive specification of overall system of rolling stock or infrastructure from Amtrak, then craft requirements of subcomponents, outsource actual manufacturing into multiple manufacturers, and integrate supplied subcomponents into the total system. They need to understand upward requirements from Amtrak and appropriately allocate them into individual specifications of each component.

In terms of rolling stock, the locomotive used in Amtrak 188 was "Amtrak Cities Sprinter (ACS) - 64" No.601 made by Siemens in 2014. This train is based on the design of Eurosprinter and Vectron which are used in Europe and Asia, and reconfigured some features such as crashworthiness in order to comply with American standards. Also, because of Buy American laws, each subcomponents are manufactured and integrated in the US. Such background infers several possible scenarios which leads unsafe control actions. Below are some example of them:

- Amtrak's requirements which are different from European ones cause misunderstanding in crafting detail specification
- Ignoring different capabilities of US manufacturers from European manufacturers results in components' inadequate quality or reliability
- Incomplete understanding of design changes from original design leads to inadequate revision of specification shown to manufactures

Infrastructure varies from railroad trucks to signaling systems, and similar things can be said in terms of systems developed by foreign companies. In the systems developed by domestic integrators, several scenarios can be considered such as:

- Ambiguous requirements from Amtrak cause misunderstanding in crafting detail specification
- Overestimating capabilities of manufactures results in components' inadequate quality or reliability
- Incomplete understanding of incremental design changes from existing systems leads to inadequate revision of specification shown to manufactures

2. Train Operation Division – System Integrator

Controller	**Controlled Process**	**Control Action**	**Not providing Causes hazard**	**Providing causes hazard**	**Incorrect Timing / Order**	**Stopped too soon /Applied too long**
Train Operation / Infrastructure Management Division	Rolling Stock / Infra-structure System Integrator	Specifi-cation Require-ment	- Necessary specification or requirement for safety operation is not provided	- Inappropriate specification or requirement for safety operation is provided	- Specification or requirement is not appropriately revised as system changes	-

In addition to the responsibilities shown in Section A.3.4.3, these divisions are in charge of crafting specifications and requirements for newly-introduced systems. These requirements are outsourced to system integrators with contracts, and manufactured systems developed by them are put into revenue operations after verifying whether they comply with requirements, regulations and safety standards. In order to develop new systems without safety-critical design flaws, several conditions shown below are required:

<u>Control Input / External Information</u>

- Safety standards mandated by regulatory agencies are comprehensive
- Overall company's safety policy or long-term investment plan for safety is adequate

<u>Process Model within Divisions</u>

- Experience and insight from operation and maintenance is well reflected on requirements
- Necessary changes of requirements are timely reflected as surrounding system changes
- Checking verification & validation process of requirement at inspection phase is adequate

In other words, if these requirements are not fulfilled, comprehensive safety-critical factors may not be reflected in the specifications.

A.3.4.5 Organizational Level Analysis – Highest Level

1. Amtrak Headquarter – Train Operation / Infrastructure Management Division

Controller	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Amtrak Headquarter	Train Operation / Infrastructure Management Division	Safety Policy Standards	- Comprehensive safety-critical contexts are not covered in safety policy or standards	- Mis-understanding is induced by safety policy or standards in crafting manuals or training	- Safety policy or standards are not appropriately updated as system changes	- Necessary policy or standards are terminated or changed

Amtrak Headquarter develops its long-term strategy about company management, and allocate its budget into each operational expense and capital investment. Its safety policy and standards reflect regulations, financial circumstances, experiences in revenue operation, and so on. In this accident, signaling system was one critical subsystem which could have backed up train engineer's safety operation. In this section, the structure of signaling system in the NEC is at first introduced, and then unsafe control actions regarding the development of this system are discussed.

<u>Signaling System in NEC</u>

The signaling system in the NEC is originally developed in early 20th century. Originally, the signaling system was invented in order to prevent train engineers from driving trains into locations close to another train, and gradually more functions were added. Amtrak explains the modern signaling system of the NEC as a 4-layer pyramid [82]. Figure A.5 shows the overview of this pyramid-shape structure of signaling system in NEC.

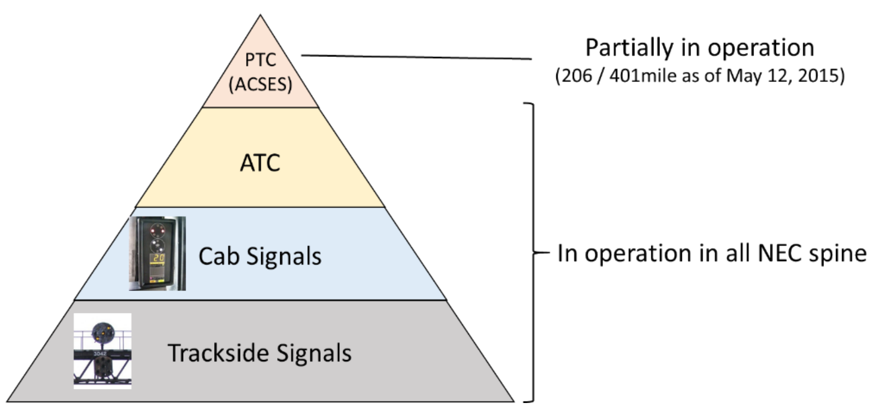


Figure A.5 Structure of Signaling System in NEC

(i) Trackside signals

Trackside signals are wayside components of Automatic Block Signal System, which prevents a train from entering the same "block" in which another train resides. These signals have colored lights whose combinations let train engineers take appropriate actions. However, signals do not have functions to override engineers' actions. In NEC, the rule of signal patterns are standardized at Northeast Operating Rules Advisory Committee (NORAC) [83], whose common rules are adopted by multiple train operators mainly in northeast US. Figure A.6 shows some examples of signal aspects and indications in NORAC [83].

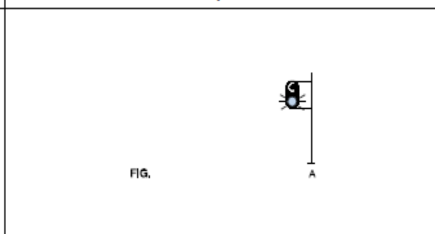
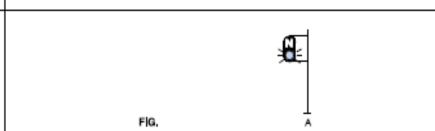
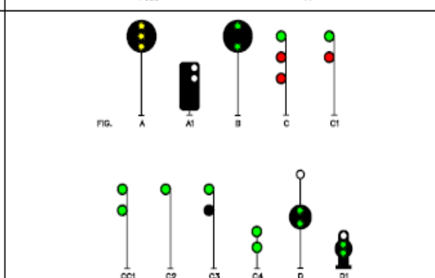
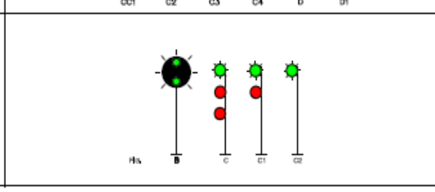
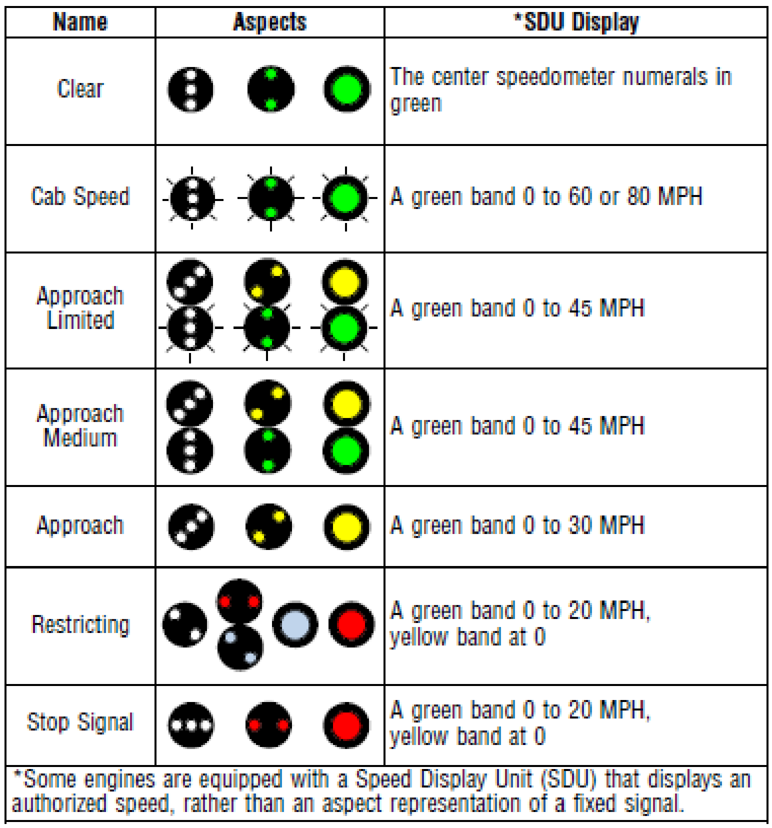
Rule	Aspects	Name	Indication
280a		CLEAR TO NEXT INTERLOCKING	Trains with inoperative cab signals, automatic train stop, or speed control must proceed on fixed signal indication (and cab signal indication, if operable) not exceeding 79 MPH. Trains with inoperative cab signals must approach the next home signal prepared to stop, unless Approach Normal (Rule 280b) is displayed on a distant signal prior to the home signal.
280b		APPROACH NORMAL	Trains without operative cab signals must proceed on fixed signal indication not exceeding 79 MPH.
281		CLEAR	Proceed not exceeding Normal Speed.
281a		CAB SPEED	Proceed in accordance with cab signal indication. Reduce speed to not exceeding 60 MPH if Cab Speed cab signal is displayed without a signal speed, or if cab signals are not operative.

Figure A.6 Examples of Trackside Signal Aspects and Indications

(Source: NORAC, 2011)

(ii) Cab Signals

Cab signals duplicate signs of trackside signals and show them on train cabs. They help train engineers to see signals easily in any conditions, but same as for trackside signals, they do not have power to override engineers' actions. Rules of cab signal aspects are also standardized at NORAC. Figure A.7 shows examples of cab signal aspects in NORAC.



Name	Aspects	*SDU Display
Clear		The center speedometer numerals in green
Cab Speed		A green band 0 to 60 or 80 MPH
Approach Limited		A green band 0 to 45 MPH
Approach Medium		A green band 0 to 45 MPH
Approach		A green band 0 to 30 MPH
Restricting		A green band 0 to 20 MPH, yellow band at 0
Stop Signal		A green band 0 to 20 MPH, yellow band at 0
*Some engines are equipped with a Speed Display Unit (SDU) that displays an authorized speed, rather than an aspect representation of a fixed signal.		

Figure A.7 Examples of Cab Signal Aspects

(Source: NORAC, 2011)

(iii) Automatic Train Control (ATC)

Trackside signals and cab signals are just supporting systems for train engineers, and safe train operations still fully depend on train engineers. As a third layer of signaling system, Automatic Train Control (ATC) can override train engineers' actions. ATC is integrated with the cab signal system. While cab signals just show information of trackside signals on displays in train cabs, ATC is equipped with onboard facilities which compare inputs from cab signals with actual speed and enforce brakes if train engineers fail to comply with speed restrictions.

In NEC, this system has been in operation since Amtrak took over infrastructure of the NEC in 1976. ATC automatically apply brakes and slow down trains to 20, 30 or 45 mph if engineers fail to comply with signal aspects. However, ATC do not have functions to automatically decelerate trains before curves or stop signals.

(iv) Positive Train Control (PTC)

The top layer of the signaling system is Positive Train Control (PTC). PTC is a set of functional requirements of railway operation which can prevent "Train-to-train collisions, overspeed derailments, incursion into an established work zone and movement through a main line switch in the improper position" [84][16]. After the deadly Chatsworth collision in California which killed 25 people and injured 102, Congress mandated the installation of PTC in the Rail Safety Improvement Act of 2008 (RSIA) [84]. PTC is mainly composed of three subsystems [85], which are:

- Onboard subsystem: Monitor trains' current location and speed, verify speed restrictions from input signal, and enforce automatic brakes if necessary
- Wayside (ground) subsystem: Communicate ground information (location, signals, switches…) and server information to trains
- Office server subsystem: Store information about railway operation (speed restriction, train information, track condition…) and communicate this information to trains

In NEC, since 1990s, Amtrak has been developing Advanced Civil Speed Enforcement System (ACSES) as the overlay of existing ATC system, whose functionalities now comply with the regulations for PTC published by FRA in 2010. Figure A.8 [86] shows the overview of ACSES. Server information and ground information are transmitted from wayside radios to onboard units, and if train engineers do not comply with speed restrictions shown by ACSES or cab signals, automatic brakes are applied.

RSIA mandated most of US rail network (incl. NEC) to install PTC systems by December 2015, though many train operators were not be able to meet this deadline. As a result, the mandated PTC deadline was extended by Congress to 2018 for installation and 2020 for implementation As of May 12, 2015, ACSES was in operation only on 206 miles out of 401 miles of track where Amtrak is responsible on the NEC spine (shown in Figure A.9 [87]); and on the accident site, ACSES was not in operation. By the end of 2015, Amtrak started PTC operation in all 401 miles in NEC.

[16] Regarding these functionalities, Association of American Railroads (AAR) states "PTC will ***not*** prevent accidents caused as a result of track or equipment failure; improper vehicular movement through a grade crossing; trespassing on railroad tracks; and some types of train operator error." That is, PTC is not an absolute solution to ensure the railroad safety.

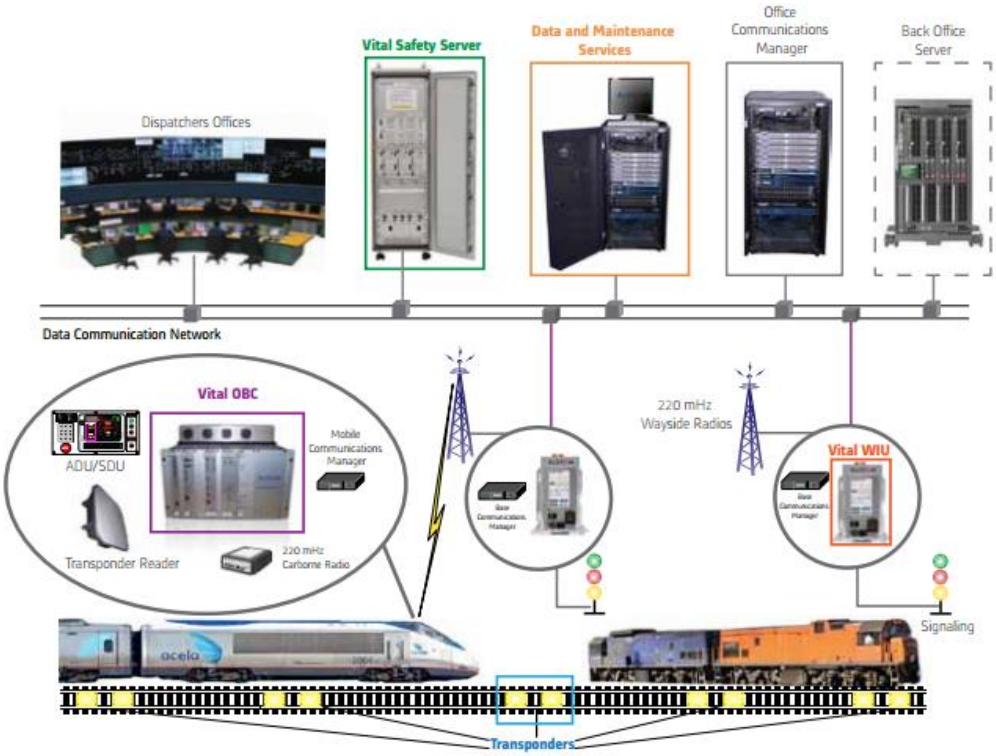


Figure A.8 Overview of ACSES

(Source: ALSTOM, 2013)

Figure A.9 Operational Areas of ACSES in the NEC as of May 12, 2015

(Source: NTSB, 2016)

Unsafe Control Actions

In this accident, no automatic speed control system backed up the overspeed of trains, which eventually led to the derailment. At the accident site, as shown in Figure A.9, ACSES (PTC) was not yet in operation and ATC did not have any functions to decelerate trains. In this point, unsafe control actions are derived from facts that:

- PTC system was not promptly installed in all of the NEC spine.
- ATC system was not appropriately upgraded to decelerate train before hazardous curves.

PTC system installation

ACSES began to be developed in 1990s, and went into operation in 2000. Amtrak said it had spent more than $110 million since 2008 to install PTC as of May 12, 2015. But Amtrak had not completed the installation at that time (206/401 miles in operation). Amtrak explains the difficulty of acquiring necessary spectrum from Federal Communication Commission (FCC). ACSES requires radio communication between the onboard subsystem and the wayside subsystem, where 220MHz radio is now designed to be used instead of 900MHz bandwidth, which has been originally used since 2000. Amtrak says it has tried to obtain this 220MHz bandwidth beginning in 2010, but this process didn’t go promptly due to litigation and regulation. In December 2014, Amtrak finally completed purchasing necessary bandwidth, and started testing at that time.

ATC system operation & development

ATC system on the NEC has been in operation at least since 1976, and this system does not have a function to slow down trains before curves or stop signals, where specific speed restriction signals are not applied. Instead, in order to control train speeds in such locations, “code change points” have been installed in certain locations and integrated into the ATC system. “Code change points” overwrite the information of cab signals, so at such points parmanent speed restrictions are applied regardless of relative locations of trains. In fact, at Frankford junction, a “code change point” was installed on the east side of the curve, since the maximum speed limit for westbound trains (to Philadelphia) was 110mph, much higher than the speed limit of curve 50mph. On the west side, however, since the speed limit for eastbound trains (to New York) was 80mph, the risk of derailment by excessive speed was overlooked and a “code change point” was not installed.

In these contexts shown above, at first it can be said that Amtrak Headquarter could not take appropriate actions to promptly develop PTC system due to missing control input from upper controllers. However, at the same time, it can also be said that there were process model flaws within Amtrak Headquarter. The example of “code change points” shows that “pitfalls” of ATC system could be compensated for by another add-on system. Appropriate risk assessment on potential hazardous operations could have allowed the infrastructure management group in Amtrak to take actions to install safety facilities at potentially incident-prone locations. In other words, there was a process model flaw at Amtrak Headquarter that overlooked the risk of operation which totally depended on the condition of train engineers.

2. Operation Rule Committee - Amtrak Headquarter

Controller	Controll-ed Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Operation Rule Committee (NORAC)	Amtrak Head-quarter	Common Operational Rules	- Necessary operational rules for safety operation are not provided	- Operational rules cause hazardous operations	- Operational rules are not appropriately updated as system changes	- Out-of-date operational rules are still applied

The train operation rules in the NEC are in compliance with common rules issued by Northeast Operating Rules Advisory Committee (NORAC). NORAC rules are composed of 25 categories, which cover common terminologies and their definitions, processes to deal with train movement, description of signaling system, responsibilities of employees, and so on. General operation rules of cab signals and speed control (=ATC)[17] are also documented. These rules are designed to enhance safe operation particularly from the standpoint of interoperability, because many railroads including the NEC are shared by multiple train operators.

It is unclear whether these common rules contributed to this accident, but a potential hazardous scenario regarding NORAC is that there exists a gap between NORAC rules and actual operational conditions in each train operator. For example, PTC system is being developed and installed by individual train operators, based on the regulation issued by FRA. This situation not only may produce gaps of operational rules between operators, but also may cause discrepancy between common rules and individual rules. The latest version of NORAC (10th Edition) was issued in 2011, and operation rules of PTC were not yet reflected. That is, process model flaws in NORAC which fail to integrate each member's operational condition can result in hazardous operational procedures.

[17] In NORAC, "Speed Control" is defined as "A device on an engine which will cause a penalty application of the brakes if the engineer fails to reduce the train's speed to the speed required by the cab signal indication". [83] Therefore, it can be said as a part of ATC system. In PTC system, or at least in ACSES, "civil speed restriction" calculated in its system is used to apply automatic brakes, after being compared with cab signal indication.

3. Safety Board - Amtrak Headquarter

Controller	Controll-ed Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Safety Board (NTSB)	Regulatory Agencies, Amtrak Head-quarter	Investigation Report Recommen-dation	- Adequate recommen-dations regarding safety operation are not provided	- Recommen-dation based on inappropriate accident investigation is released	- Implementation of safety recommendation cannot match with current technical / financial circumstances	-

NTSB investigates railroads accidents "in which there is a fatality or substantial property damage, or that involves a passenger train" [88], and suggest safety recommendations to regulatory agencies such as FRA or transportation operators, based on the investigation results. NTSB is an independent agency from other federal agencies, and doesn't have any legal authorities to enforce implementation of its recommendations.

The installation of a PTC-like system[18] has been recommended by NTSB since 1970. In 1990, it is placed on NTSB's "most wanted list", which meant PTC was one of the top 10 safety needs for the US in all transportation modes. But the actual implementation of PTC was slow, due to the lack of legal force and its large development cost. In 2008, RSIA finally mandated PTC installation, but its implementations is still ongoing more than 40 years after its initial recommendation. That is, in the control structure, NTSB has tried to take control actions to its controlled process (mainly to regulatory agencies, and indirectly to its higher controller, Congress), but there was the weakness of actions resulted from its position as an independent agency; this induced slow feedback from controlled process.

[18] The first recommendation in 1970 called for "automatic train control". In 1990s, NTSB called this technology as "positive train separation", and then renamed it as "positive train control" in 2001.

4. Congress - Regulatory Agencies - Amtrak Headquarter / System Integrator

Controller	Controlled Process	Control Action	Not providing Causes hazard	Providing causes hazard	Incorrect Timing / Order	Stopped too soon /Applied too long
Regulatory Agencies (UDOT, FRA)	Amtrak Head-quarter	Regula-tion Certifi-cation	- Comprehensive safety-critical contexts are not covered in regulations	- Certification is given to operators not eligible for safe operation	- Regulation is not updated as system changes	-
	Rolling Stock / Infra-structure System Integrator	Regula-tion Certifi-cation	-Comprehensive safety-critical contexts are not covered in regulations	- Certification is given to integrators not eligible for safe system development	- Regulation is not updated as system changes	-
Congress	Regulatory Agencies	Legis-lation	- Regulatory Agencies are prevented from taking appropriate actions	- Inappropriate regulations are forced to be made by legislation	- Legislation is not updated as system changes	-

To ensure railroad safety, regulatory agencies such as UDOT or FRA maintain and revise their regulations, which are usually in compliance with legislative acts of Congress. In terms of PTC, after RSIA was passed by Congress in 2008, FRA convened the Railroad Safety Advisory Committee (RSAC) whose members are composed of the rail industry and other stakeholders of regulations, in order to develop concrete regulations to implement RSIA. In 2010, FRA issued its final rules about PTC installation, followed by some amendments in 2010 and 2012. Since then railway companies have developed their PTC system under regulations, but technical challenges and bureaucratic processes such as spectrum acquisition have been preventing them from installing PTC on schedule. FRA should support these companies, and it actually does so, but FRA also suffers from the lack of PTC funding. Table A.10 shows the PTC funding from Congress (Requested vs Actual) [89].

Table A.10 PTC Funding from Congress to FRA

Fiscal Year	FY2011	FY2012	FY2013	FY2014	FY2015	FY2016
Requested	\$50M	\$50M	\$74M	\$4170M	\$825M	\$825M
Actual	\$0	\$0	\$0	\$42M	\$0	TBD

(Source FRA, 2015)

A.4 Conclusion

From discussions in the previous sections, conclusions and insights from this accidents are considered in this section.

1. This accident seemed to be induced not by component failures, but by human factors.

NTSB current investigation shows that there were no major malfunctions of components which contributed to the overspeed of the derailed train. At the same time, the behavior of the train engineer is being investigated carefully. From these points, the derailment could occur not because of train / infrastructure components' failure, but due to the violation of safety constraints by the train engineer. And various environmental factors such as fatigue affect train engineer's behavior.

Conventional hazard analysis methodologies such as FTA or FMEA are based on failure-oriented perspectives, in which reliability of each subcomponent composes overall reliability of total system. In these approaches, reliability and safety is considered to be closely related with each other. In STAMP theory, however, reliability and safety is clearly distinguished as different lifecycle properties. Leveson [34] insists that "High reliability is neither necessary nor sufficient for safety", which indicates that a reliable system could be both safe and unsafe. This case is an example where a reliable system (from failure-oriented standpoint) was revealed to be unsafe as an operating system.

In this derailment, the fact that the train engineer – the controller of physical system -could not appropriately control the train was the direct cause of overspeed and derailment. These days, since the reliability of each component in the physical system has been significantly improved, this kind of accidents where human factors are deeply involved are one of the major concerns to be taken into account carefully in safe railway operation. At the same time, unlike reliability approach to components failure, it is difficult to assess the reliability or probability of human factors, because they depend on several systemic factors such as operators' mental/physiological conditions, supervisions of operators, organizational atmospheres, and so on. Therefore, the negative impact of human factors should be mitigated or backed up by considering and appropriately designing these systemic factors in multiple control levels.

2. Supervision of human operators affects theie behavior, which can lead to unsafe operations.

James Reason [90], an English psycologist, proposed a famous "Swiss Cheese Model" (Figure A.10) as an accident causation model in 1990.[19] In this model, "active failures" and "latent failures" are considered as "holes of swiss cheese" in multiple levels, and accidents happen if all levels fail to prevent failures. Based on this model, Shappell and Wirgman developed HFACS (The Human Factors Analysis and Classification System) [91], which is now used in military and aviation sectors to investigate human-related causal factors of accidents. In Swiss Cheese Model, one of latent failures is unsafe supervision, and HFACS categorizes unsafe supervision into 4 subcategories, as shown in Figure A.11.

In this accident, as seen in Section A.3.4.2, several factors shown in Figure A.11 could be unsafe control actions in supervising train engineers. As an example of "Inadequate Supervision", performance of each train engineer could have been tracked more closely by introducing monitoring facilities such as audio/image recorders in train cabs, and operation manuals or training curriculums could have been improved based on actual performance records. In "Planned Inappropriate Operations" category, dispatching rule of engineers could have been more rigorous so that physiological/mental conditions of train crews can be more carefully monitored. These days, technical progress has propelled automation (e.g. ATC, monitoring systems at control room, track inspection facilities) in various aspects in railway operation, especially in high-speed rail. However, the same as other transportation modes such as aviation, human operators are still playing important roles in train operation, maintenance and development. Therefore, supervising these "forefront" human operators is crucial to ensure safe train operation.

[19] "Swiss Cheese Model" is one methodology of probabilistic risk assessment (PRA), since active failures and latent failures are dealt as exclusive event-chains, and the combination of these failures are supposed to cause accidents. In STAMP theory, various systemic factors are thought to be interwoven with nonlinear relationship behind hazards and accidents, and these systemic factors are often omitted when probability is calculated at PRA. Therefore, STAMP theory casts doubt on the effectiveness of PRA and Swiss Cheese Model.

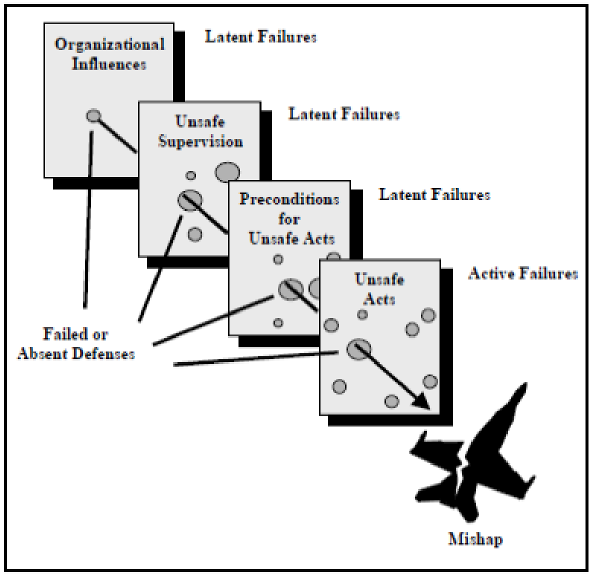


Figure A.10 Swiss Cheese Model

(Source: Reason, 1990)

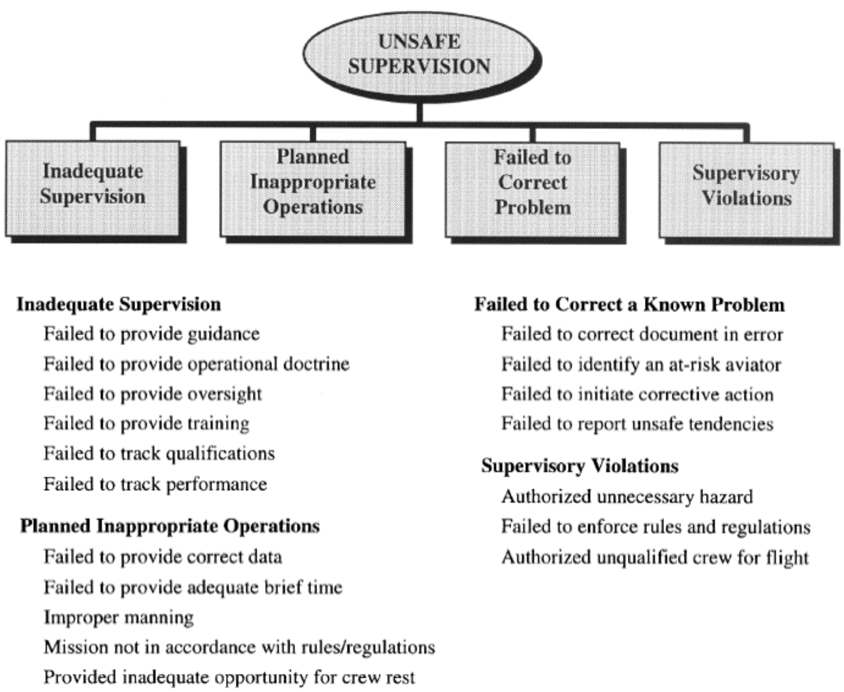


Figure A.11 Subcategories of Unsafe Supervision

(Source: Shappell et al., 2000)

3. Backup systems of human operators are indispensable in safe railway operations. Inappropriate risk assessment can overlook potential hazards where current backup systems don't appropriately work to support human operations.

While supervision of human operators is crucial as discussed above, hardware and software which supplements human operators' control is also necessary for safe rail operations. In order to effectively introduce such foolproof facilities, responsible departments or authorities need to appropriately assess the potential risk caused by unsafe control actions of human operators. In this derailment, ATC system could have prevented overspeed at the curve if an add-on speed-checking facilities were installed, even if PTC was yet to be installed. Such decisions depend on the predicted magnitude of risks and their cost, so recognizing and assessing these risks is the first and essential step to take appropriate safety actions.

The derailment accidents mentioned in Section A.3.4.1 have similarities in these points as well as train operators' direct unsafe controls. (Figure A.12) In Spanish Santiago de Compostela Derailment case [79], ASFA ("*Anuncio de Señales y Frenado Automático*", Automatic Braking and Announcement of Signals), a conventional automatic warning system which could not automatically apply brakes, was in operation at the accident site. ERTMS (European Rail Traffic Management System), an European standard automatic train control system, was in operation at new high-speed tracks, but not at some conventional tracks such as the accident site. In Japanese Fukuchiyama Line Derailment case [80], ATS-SW, an automatic train stop system without speed-checking function was in operation at the derailment curve. The responsible company, West Japan Railway Company, did not incorporate add-on speed-checking function into that curve, and also did not introduce ATS-P, an advanced automatic train stop system which originally possesses speed-checking function. In all these three accidents, responsible train operators could not appropriately assess potential cases in which train engineers did not comply with operating rules. This prevented them from installing adequate safety backup systems.

Accident	Amtrak Northeast Regional 188	Fukuchiyama Line 5418M	Santiago de Compostela Rail Disaster
Accident Site			
Date	05/12/2015	04/25/2005	07/24/2013
Place	Philadelphia, PA USA	Amagasaki, Hyogo, Japan	Santiago de Compostela, Galicia, Spain
Fatality	8 killed, +200 injured out of 238	107 killed, 562 injured out of 700	79 killed, 139 injured out of 218
Direct cause	Excessive Train Speed at Curve		
Human Factor	Driver did not appropriately apply brake? (Still being investigated)	Driver tried to recover train delay, in order to avoid punitive training	Driver was on his cellphone
Systemic Factor	- “Code Change Point” was not installed on ATC system at accident site - PTC installation was not finished	- Speed checking function was not added on ATS-SW system - New ATC-P system (with speed checking function) was not installed on this line, though other main lines already had	- ASFA (no speed checking function) was in operation - ERTMS (with speed checking function) was in operation on new high speed tracks, not at some conventional tracks such as the accident site

Figure A.12 Similarities in Three Derailment Accidents

4. <u>Complicated technical requirements, financial difficulties, bureaucratic decision making processes can prevent policy-executers from taking prompt actions toward enhancing safety.</u>

As the hierarchy of control diagram becomes higher, decision-making speed tends to become slower because of several reasons such as more complicated decision processes, increased number of stakeholders, significant financial impacts, and so on. The installation of PTC is one example of high-level decision making processes which has been taking very long time to implement initial recommendations and decisions.

Also, in policy implementation phase, particularly in the US rail sector, since many railroads are shared by multiple train operators, interoperability is one of biggest factors which regulatory agencies or train operators need to take into account when they intend to introduce new systems or operation procedures. This situation requires them to spend much time on coordinating various stakeholders, which can result in slow response to legislations or regulations.

This analysis shows that there exist various unsafe control actions in multiple control loops behind one accident. In the CLD shown in Figure 6.12, such factors corresond to the variables "Systemic Factors" or "Exogenous Factors (Regulation, Trespassers)", which cannot be explained as single quantities. We need to take such systemic perspectives into account in order to understand comprehensive pictures of safety in HSR operation, development and maintenance. To prevent future accidents, what we need to do is not to punish the train engineer, but to reflect lessons of this accidents in each stakeholder.

Appendix B: Prevalence Analysis of HSR "ilities"

The following table provides the raw data of the prevalence analysis of HSR "ilities" shown in Figure 3.4.

Date of Search	1/20/2016		
"High Speed Rail" + "ilities"	Hits		
	Google Scholar	Science Direct	Compendex, Inspec and NTIS Database
No "ilities" in search	33900	1716	2462
Quality	18000	980	199
Reliability	6570	392	131
Safety	14500	667	336
Flexibility	6260	332	20
Robustness	1490	128	31
Durability	1160	65	17
Scalability	235	7	1
Adaptability	758	33	2
Usability	464	21	1
Interoperability	1860	73	36
Sustainability	5870	287	24
Maintainability	344	10	9
Testability	35	0	0
Modularity	166	10	1
Extensibility	57	0	0
Agility	199	9	0
Manufacturability	46	3	0
Repairability	8	0	0
Evolvability	6	0	0
Availability	11900	465	35
Profitability	2680	171	26
Productivity	5970	280	13
Efficiency	13000	819	118
Effectiveness	6940	363	77
Affordability	1090	36	1

Appendix C: Rolling Stock in the Tokaido Shinkansen

The following table provides the technical characteristics [92] of rolling stock operated in the Tokaido Shinkansen, as described in Section 6.2.3.4.1.

Series	0	100	300	700	N700	N700A
Year Started in Service	1964	1985	1992	1999	2007	2013
Max Speed in the Tokaido [kph]	210-220	220	270	270	285	
Acceleration Rate [kph/s]	1.0-1.2	1.6	1.6	2.0	2.6	
Capacity (16 car) [seat]	1340	1277-1321	1323			
Weight (16 car) [t]	970	838.5	710	708	715	
Car Body Material	Steel		Aluminum			
Motor	DC Motor		Induction Motor			

(Source: JSME)

Appendix D: List of Variables in Numerical SD Model

The following table provides the list of variables used in the numerical SD modeling presented in Section 6.3. Some statistic variables used for the error minimization process (e.g. RMSE, standard deviation) are omitted from this list.

Subpart	Variable Name	Unit	Description
Demand/ Revenue	Current GDP	$	Current GDP
	Reference GDP	$	GDP at the initial point of simulation
	Elasticity wrt GDP	dimensionless	Elasticity of ridership with respect to GDP
	Effect of GDP	dimensionless	Effect of GDP on ridership
	Current Price	$/passenger-mile	Current average unit price
	Reference Price	$/passenger-mile	Average unit price at the initial point of simulation
	Elasticity wrt Price	dimensionless	Elasticity of ridership with respect to price
	Effect of Price	dimensionless	Effect of price on ridership
	Current ASM	seat-mile/year	Current ASM
	Reference ASM	seat-mile/year	ASM at the initial point of simulation
	Perceived ASM	seat-mile/year	ASM perceived by passengers
	Time Adjustment for ASM	year	Time delay until passengers notice the ASM change
	Elasticity wrt Supply	dimensionless	Elasticity of ridership with respect to ASM
	Effect of Supply	dimensionless	Effect of ASM on ridership
	Current Travel Time	minute	Current travel time
	Reference Travel Time	minute	Travel time at the initial point of simulation
	Elasticity wrt Travel Time	dimensionless	Elasticity of ridership with respect to travel time
	Effect of Travel Time	dimensionless	Effect of travel time on ridership
	Current Service Reliability	minute/train	Current average delay minutes
	Reference Service Reliability	minute/train	Average delay minutes at the initial point of simulation
	Perceived Reliability	minute/train	Average delay minutes perceived by passengers
	Time Adjustment for Reliability	year	Time delay until passengers notice the reliability change
	Elasticity wrt Reliability	dimensionless	Elasticity of ridership with respect to train delays
	Effect of Service Reliability	dimensionless	Effect of train delays on ridership
	Current Safety	accident/year	Current frequency of accidents
	Reference Safety	accident/year	Frequency of accidents at the initial point of simulation
	Elasticity wrt Safety	dimensionless	Elasticity of ridership with respect to safety
	Effect of Safety	dimensionless	Effect of safety on ridership
	Current Airline Ridership	passengers/year	Current airline ridership
	Reference Airline Ridership	passengers/year	Airline ridership at the initial point of simulation
	Elasticity wrt Airline Response	dimensionless	Elasticity of ridership with respect to airline ridership
	Effect of Airlines Response	dimensionless	Effect of airline ridership on HSR ridership
	# of Passenger	passengers/year	Current HSR ridership
	Reference # of Passenger	passengers/year	HSR ridership at the initial point of simulation
	Average Travel Distance	mile	Average travel distance per one HSR passenger
	RPM	passenger-mile/year	Revenue passenger mile
	Ticket Revenue	$/year	Annual HSR ticket revenue
	Ancillary Revenue	$/year	Annual HSR ancillary revenue (e.g. food service)
	Operating Revenue	$/year	Annual HSR total revenue

Subpart	Variable Name	Unit	Description
Supply/ Cost	Target Load Factor	passenger/seat	Target load factor aimed by HSR operator
	Target ASM	seat-mile/year	Target ASM based on target LF and current RPM
	ASM Change Rate	seat-mile/year/year	Annual change rate of ASM
	ASM Limit	seat-mile/year	ASM limit coming from capacity constraint
	Time to change ASM	year	Time delay to change ASM
	ASM Change by External Policy	seat-mile/year/year	ASM change by policies other than normal adjustment
	ASM	seat-mile/year	Current available seat mile
	Seats per one train	seat/train	Average capacity per one trainset
	Current Trainset Mile	train-mile/year	Estimated current train-mile
	Time Delay between Supply and OPEX	year	Time delay until train-mile is reflected on OPEX
	Trainset Mile Reflected on OPEX	train-mile/year	Train-mile used for OPEX calculation
	Unit Variable Cost	$/train-mile	Unit cost required to HSR train operation
	Variable Cost	$/year	Variable cost in HSR train operation
	Fixed Cost	$/year	Fixed cost in HSR train operation
	Operating Cost	$/year	Annual operating cost in HSR train operation
	Operating Profit	$/year	Annual operating profit
Pricing	Current Load Factor	passenger/seat	Current load factor, obtained from RPM and ASM
	Reference Load Factor	passenger/seat	Load factor at the initial point of simulation
	Elasticity wrt LF	dimensionless	Elasticity of price with respect to load factor
	Effect of Demand on Price	dimensionless	Effect of load factor on price
	Reference Operating Cost	$/year	Operating cost at the initial point of simulation
	Elasticity wrt Cost	dimensionless	Elasticity of price with respect to operating cost
	Effect of Cost on Price	dimensionless	Effect of operating cost on price
	Target Average Ticket Price	$/passenger-mile	Target ticket price aimed by HSR operator
	Ticket Price Change Rate	$/passenger-mile/year	Annual change rate of unit price
	Time to Change Price	year	Time delay to change unit price
	Average Ticket Price	$/passenger-mile	Current average unit price
	Initial Ticket Price	$/passenger-mile	Average unit price at the initial point of simulation

Subpart	Variable Name	Unit	Description
Infra Management	Total CAPEX	$/year	Total capital expenditure used for infrastructure and rolling stock
	Fraction of CAPEX wrt Operating Profit	dimensionless	Fraction of CAPEX out of operating profit
	External Funding	$/year	External funding source for CAPEX
	Fraction of CAPEX for Infrastructure	dimensionless	Fraction of infrastructure CAPEX out of total CAPEX
	CAPEX on Infrastructure	$/year	Total capital expenditure used for infrastructure
	Fraction of Budget for Normal Replacement	dimensionless	Fraction of budget for normal replacement out of infrastructure CAPEX
	Budget for Normal Replacement	$/year	Budget for infrastructure normal replacement
	Required Investment for Replacement	$/year	Required budget for infrastructure normal replacement
	Unit Investment per ASM	$/seat-mile	Unit cost per ASM required for infrastructure normal replacement
	Budget Shortage	$/year	Budget shortage for infrastructure normal replacement
	Budget for Backlog Elimination	$/year	Total Budget for infrastructure backlog elimination
	Special Budget for Elimination	$/year	Special budget for infrastructure backlog elimination
	New Investment	$/year	New investment for infrastructure backlog elimination
	Current Stock of Investment on Backlog Elimination	$	Ongoing backlog elimination projects
	Average Duration of Backlog Elimination Projects	year	Average duration to finish backlog elimination projects
	Project Completion Rate	$/year	Backlog elimination project completion rate
	Reflection on Backlog Elimination	$/year	Backlog elimination rate from project completion
	Cumulative Completed Investment	$/year	Completed backlog elimination projects
	Backlog Generation	$/year	New backlog generation rate
	Maintenance Backlog	$	Current infrastructure maintenance backlog
	Initial Backlog	$	Infrastructure maintenance backlog at the initial point of simulation
	Backlog Elimination	$/year	Backlog elimination rate
	Additional Deterioration from Backlog	$/year	Further backlog generation rate from existing maintenance backlog
	Penalty Rate	/year	Deterioration rate of maintenance backlog

Subpart	Variable Name	Unit	Description
Rolling Stock Management	Available CAPEX on Rolling Stock	$/year	Total capital expenditure used for rolling stock
	New Purchase	train/year	Annual acquisition rate of rolling stock
	Unit Price of Trainset	$/train	Unit price of rolling stock
	New Rolling Stock	train	Number of new rolling stock
	New RS 0	train	Number of new rolling stock at the initial point of simulation
	Obsolescence 1	train/year	Transition rate from new rolling stock to intermediate rolling stock
	Average Lifespan of Rolling Stock	year	Average lifespan of rolling stock
	Intermediate Rolling Stock	train	Number of intermediate rolling stock
	Int RS 0	train	Number of intermediate rolling stock at the initial point of simulation
	Early Retirement	train/year	Retirement rate of intermediate rolling stock
	Obsolescence 2	train/year	Transition rate from intermediate rolling stock to old rolling stock
	Old Rolling Stock	train	Number of old rolling stock
	Old RS 0	train	Number of old rolling stock at the initial point of simulation
	Retirement	train/year	Retirement rate of old rolling stock
	Total Rolling Stock	train	Total number of rolling stock
	Maximum Fleet Size	train	Upper bound of total rolling stock
	Minimum Fleet Size	train	Lower bound of total rolling stock
	New RS Quality	dimensionless	Quality of new rolling stock
	Int RS Quality	dimensionless	Quality of intermediate rolling stock
	Old RS Quality	dimensionless	Quality of old rolling stock
	Fleet Quality	dimensionless	Average quality of rolling stock

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