Life Cycle Cost Estimation for Building, Operating, and Maintaining High-Speed Rail

Etienne Le MAOUT and Hironori KATO

a, Direction Conseil France, SYSTRA, 72-76 Rue Henry Farman, 75015 Paris, France; E-mail: elemaout@systra.com
b Department of Civil Engineering, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan; E-mail: kato@civil.t.u-tokyo.ac.jp

Abstract: This paper develops a cost estimation model for building, operating, and maintaining a high-speed rail (HSR) system. The model introduces a macroscopic life cycle cost approach that encompasses HSR systems as a whole, the interactions between the subsystems, and the variability of the systems. For this reason, costs associated with HSR systems are categorized into operation, infrastructure, maintenance, and external costs, and their relationships and behaviors are modeled over their lifetime. A hypothetical line is assumed to illustrate how the model behaves with respect to demand, speed, length, and the infrastructure and rolling stock types. The results show that articulated train sets provide a lower life cycle cost than non-articulated sets, ceteris paribus. The results also indicate that the designs proposed by most of the manufacturers are less interesting from a life cycle cost perspective.

Keywords: high-speed rail, life cycle cost, rolling stock design, infrastructure, maintenance

1. INTRODUCTION

Many governments are currently investigating the possibility of introducing a high-speed rail (HSR) system, including India, California, and Australia (UIC, 2011). One of the most important issues in HSR construction is cost estimation. de Rus (2009) shows that the cost of building the HSR infrastructure, estimated from past projects, can vary from 5 to 66 million euros per kilometer. Such a large variation is the result of various factors, such as the locations, type of technology, and socio-demographic characteristics (Givoni, 2006).

A number of studies have proposed ways to estimate the costs of HSR systems. They are categorized into two approaches: the first uses case studies on specific lines with a bottom-up approach; the second assumes an average HSR system with a top-down approach. Those who have used the case study approach include Levinson et al. (1997), who conducted an economic analysis of the total direct and indirect costs of introducing HSR in California, and Kagiyama (2000), who conducted a study on implementing the Japanese Shinkansen in California. Other, more restrictive studies reviewed costs in the European market, such as de Rus (2009), Garcia (2010), and Sánchez-Borràs et al. (2010). Although the case study approach may be useful when evaluating a given or specific project, it does not lend itself to a general discussion on HSR system costs. The second approach to estimating HSR costs tries to develop a general model. This approach is categorized further into three methods. The first method is the life cycle cost (LCC) approach, which is typically applied to specific parts of the overall system. This approach estimates the costs throughout the life cycle, from construction to disposal. For instance, He et al. (2010) evaluated the LCC of viaducts, while Andrade (2008) and Zhao et al. (2006) estimated the LCC of rail and ballast components. The
second method is the reliability, availability, maintainability, and safety (RAMS) analysis, which focuses on maintenance strategies and their costs. Proponents of this approach include Innotrack (2010) and Patra (2007). The third method applies a life cycle assessment framework that evaluates the environmental impact of a project over its life cycle. Those who have adopted this method include RFF et al. (2009), Baron et al. (2011), Chang and Kendall (2011), Chester (2008, 2010), and Kato et al. (2005).

This paper adds an LCC model to the research area of HSR cost estimation that explicitly includes the engineering mechanisms. The LCC framework is used to evaluate the direct cost and environmental impact of different HSR systems over their lifetime. This paper first formulates a life cycle cost model for the HSR system and then examines its performance in a case analysis. Finally, the results will be summarized along with a discussion of further issues.

2. LIFE CYCLE COST (LCC) MODEL

2.1 Definition of LCC

LCC is defined as “the cost induced by a product (good or service) in its life cycle as borne directly and indirectly by public and private actors involved, and possibly including the cost of external effects.” (Huppes et al., 2004) Life cycle costing is popular in the building construction industry (State of Illinois, 1991; State of Alaska, 1999). However, there is no international standard or common methodology for LCC (Zoeteman, 2004).

The LCC model in this paper considers the following categories: operation, infrastructure, maintenance, disposal, and external impacts, which cover the lifetime of an HSR system. The output of the model is computed as the net present value (NPV):

\[
NPV = \sum_{n} \frac{C_n}{(1+i)^n}
\]

where \( n \) is the year, \( i \) is the discount rate, and \( C_n \) is the annual cost.

2.2 Model Framework

2.2.1 Basic Assumptions

Suppose a single HSR line runs between two terminal stations with a number of intermediary stations. Neither mixed traffic nor service through the conventional network is considered. First, the total demand \( D \) is given and assumed to be symmetric and constant throughout the year. \( D \) is expressed in million passengers per year (Mpax). Second, speed \( S \) is given as the maximum design speed. Third, the infrastructure length, \( L \), and number of intermediary stations are also given. To calculate the investment cost, the overall length of the infrastructure must be broken into types of structures (earthworks, viaducts, tunnels, and bridges) and into three population density categories (rural, urban, and city center). Each category is assigned a land cost. The number of stations and the average number of platforms per station must be specified for each density category as well.

2.2.2 Operating Constraints

Operating constraints determine the capacity of the line and the maximum number of roundtrips per train. These constraints are calculated from the following operating parameters:
- Train occupancy rate, \( \tau \);
- Headway: we consider that the headway is the sum of a constant time \( t_{\text{headway}} \) that depends on the signaling and communication technologies, and of the maximum dwell time, \( t_{\text{station}} \). The dwell time includes how long it takes for passengers to embark and disembark, and what time buffer the operator wants. This depends on the train design, for instance a higher capacity or a single door per car means that more time is needed; and
- The number of first class seats, \( \phi \), given as a percentage.

Given these parameters, the capacity of the line, \( \sigma_{\text{max}} \), is derived as:

\[
\sigma_{\text{max}} = \frac{60 \cdot OH}{t_{\text{headway}} + t_{\text{station}}}
\]  

(2)

Note that \( \sigma_{\text{max}} \) depends on the operating parameters, but also on the design of the train.

The daily traffic flow for both directions is derived as:

\[
\theta = \frac{OH}{2\left(\frac{L}{S} + N_{\text{stops}} \frac{t_{\text{station}}}{60} + \frac{t_{\text{turnover}}}{60}\right)}
\]  

(3)

where \( S \) is the average speed, \( N_{\text{stops}} \) is the number of stops, and \( t_{\text{turnover}} \) is the turnover time. Here, \( \theta \) depends on the infrastructure, the operating parameters, and the train design.

2.2.3 Rolling Stock Design

The rolling stock design is determined by body type, motorization, structure, and the time it takes to embark and disembark.

First, narrow trains have a body approximately 2.9 m wide, with two seats on each side of a corridor in the second-class layout. A wide train has one additional seat with a \( 2 + 3 \) layout and an additional width of 0.5 m. With a second deck, the capacity increases by 40% only since some space is required for the stairs, luggage storage, and so on. An increase in capacity increases the size of the train, and therefore the energy consumption and the size of the tunnels. These impacts will be described further in later sections.

Second, it is assumed that there are two types of motorization, namely electric multiple units (EMU) and locomotive. Yanase (2010) compared these two types and concluded that EMU is more efficient because it provides a larger power output, more seats, a flexible train length, and greater acceleration performance with less slipping risk. Better acceleration helps to reduce the headway and thus increases the capacity of the line (Emery, 2011). However, locomotive-pulled, high-speed rolling stock is still used and developed in several countries. There are also two different types of car structures, namely articulated and non-articulated cars. Non-articulated cars have one bogie at each end of the car, with the bogies located between two adjacent articulated cars. This structure provides a stronger link between cars, allowing the train to maintain its integrity in case of derailment (Brabie, 2007). The reduced number of bogies induces a higher weight per axle, which increases track deterioration. However, rolling stock maintenance might be cheaper with fewer bogies. Figure 1 illustrates the difference between train structures.
Train capacity is calculated by considering the capacity of each car: the middle cars and the first/last car, which have fewer or no seats because of the driving cab or the locomotive, respectively. The length of a car, and thus the number of seats per car, varies with the train design: articulated cars are shorter to avoid a larger weight per axle. Train capacity also depends on the train layout, and more precisely, on the division into one or more classes. The model presented here considers two classes. The capacity in the first class is assumed to be 60% of the second class, which is the average value for existing high-speed trains. Hence, the train length, $L_{train}$, and the capacity, $q$, of a train set with $N_{cars}$ cars, $R$ restaurant cars, and a proportion of first class, $\phi$, is given by:

$$L_{train} = 2L_F + (N_{cars} - 2 - R)L_M$$

$$q = \left((N_{cars} - R)q_{2M} + 2q_{2F}(1-0.4\phi)\right)\rho$$

where $q_{2M}$ and $q_{2F}$ are the capacities in the second-class layout of the middle cars and the first/last cars, respectively; $L_M$ and $L_F$ are the lengths of middle and first car, respectively; $\rho$ is the relative capacity of the body type in the second class. The relative capacity is the average capacity in a second-class car of the chosen body type divided by the average capacity in a second-class car of a narrow, single-deck car.

Finally, our model assumes that the time passengers need to embark and disembark increases as the number of passengers increases. The dwell time, $t_{station}$, is the sum of an operational margin, $t_{margin}$, and the time for embarking and disembarking per passenger, $t_{board}$, as suggested by Heinz (2003):

$$t_{station} = t_{margin} + t_{board} \cdot \frac{\beta \cdot \tau \cdot q}{N_{doors}}$$

where $\beta$ is the proportion of passengers embarking or disembarking, and $N_{doors}$ is the number of doors per car.

### 2.3 Operating Costs

Operating costs consist of rolling stock ownership costs, running costs, and fixed operating costs. First, the annual rolling stock ownership cost is defined as the sum of maintenance, rolling stock acquisition, refurbishment, and disposal costs:

$$C_{OP,RS}(n) = RS(n) \cdot c_{RS,maintenance} + \sum_{i=A,D,R} RS_i(n) \cdot c_{RS,i}$$
Where \( RS(n) \) represents the number of trains in year \( n \); \( RS_A(n) \) represents the number of trains acquired (we add a margin for the maintenance of the rolling stock); \( RS_D(n) \) represents the number of trains disposed of when reaching the end of their lifetime, \( \lambda_{RS} \); \( RS_R(n) \) represents the number of trains to be refurbished at their half-life; \( c_{RS,maintenance} \) represents the unit maintenance cost; and \( c_{RS,i} \) represents the unit cost of rolling stock acquisition, refurbishment, and disposal. \( R(n) \) is a function of the annual demand, \( D(n) \), the train capacity, \( q \), the occupancy rate, \( \tau \), and \( \theta \), calculated using Equation (3), as:

\[
RS(n) = \frac{D(n)(2 + 365)}{\tau \cdot q \cdot \theta} = \frac{\sigma(n)}{\theta}
\]

where \( \sigma(n) \) is the number of services required. Note that the demand can be accommodated only if \( \sigma < \sigma_{\text{max}} \), where \( \sigma_{\text{max}} \) is the maximum number of services defined by Equation (2). \( RS_A(n) \), \( RS_D(n) \), and \( RS_R(n) \) are defined as:

\[
RS_A(n) = \lceil RS(n + 1) - RS(n) \rceil (1 + \kappa) - RS_R(n + 1)
\]
\[
RS_D(n) = RS_A(n - \lambda_{RS})
\]
\[
RS_R(n) = RS_A(n - \frac{\lambda_{RS}}{2})
\]

where \( \kappa \) is the margin for the maintenance of the rolling stock.

Next, the running cost is formulated as:

\[
C_{OP,\text{running}}(n) = 365 \cdot \sigma(n) \cdot \left( c_{\text{wages}} \cdot N_{\text{manning}} + c_{\text{energy}} \cdot E_{\text{conso}} \right)
\]

where \( N_{\text{manning}} \) is the number of personnel per service needed on board to operate the train and provide all the onboard services and \( E_{\text{conso}} \) is the energy consumption. Energy consumption depends on various factors, such as running resistance, acceleration, the braking performance of the train, the use of regenerative brakes, the energy efficiency of the motors, the alignment of the line and eco-driving, and losses in the network between the power station and the pantograph.

Finally, the fixed operating costs are independent of the number of services or train sets. These costs consist of commercial costs and station and management costs:

\[
C_{OP,\text{fixed}}(n) = c_{\text{commercial}} \cdot D(n) + c_{\text{station}}(n) \cdot N_{\text{platform}} \cdot OH
\]

Commercial costs comprise ticket sales and advertisements, and are proportional to the demand. Station and management costs occur when the line is operated, and are proportional to the number of stations and the operating time.

2.4 Investment

HSR infrastructure is similar to conventional rail in principle: the trains run on two parallel steel rails. However, the infrastructure needs to be adapted for the higher speeds and the lighter weight per axle of the rolling stock. It must also ensure the safety and security of the passengers with, for instance, reliable signalization and communication systems, no gate crossings, and separation from its surroundings.
2.4.1 Track Type
There are two families of tracks: ballasted and slab tracks. There are various types of ballasted tracks, which differ in the layers under the ballast (Teixeira, 2007). With slab tracks, rails are not laid on ballast, but fastened on a concrete slab. The lighter weight of these ballastless tracks is an advantage when the track is built on an elevated structure or on soil with poor conditions. Ballastless tracks are not as easy to replace as ballasted tracks, so require higher precision during construction. However, slab tracks are more stable and require less maintenance. Nonetheless, CO2 emissions are very important because of large amount of concrete used. Ballasted tracks are still faster to build and sleepers are easier to change, but they require a large amount of rock. This means that the further away the quarries are, the more expensive it is to transport the ballast. In conclusion, ballasted tracks are usually cheaper to build, but require more maintenance. Ballastless tracks have a longer lifetime, as long as the concrete is of sufficient quality.

2.4.2 Power Feeding, Signalization and Communication Technologies
Electric power is fed from the power stations to the train through overhead lines and the catenaries. Power delivery only relies on the contact between the pantograph and the catenary, thus the quality of those lines is as paramount as the tracks. Recent studies by Yamashita and Ikeda (2012) and Tessun (2008) focused on improving the design of the pantograph and the catenaries, respectively. Current signalization and communication technologies use continuous speed control, but will gradually upgrade to moving blocks to locate the trains on the infrastructure. Wang and Wang (2011) explain that these technologies provide an optimal control of the train speed and headway to increase the capacity of the lines with improved safety. Although the precise communication and signalization systems may vary around the world (Matsumoto, 2005), they provide the same level of service to the operator.

2.4.3 Structure
The main structure families (earthworks, bridges, viaducts, and tunnels) vary depending on the climate, geology, alignment, construction methods, rolling stock design, and other factors. Only a precise alignment and knowledge of those factors can determine which structure to build. Therefore, a cost estimation of the main structure is made simply by using average linear costs under basic assumptions, with the exception of the tunnel section.

When estimating the cost of a tunnel, aerodynamics phenomena must be explicitly considered. The tunnel section and the train design must be adapted to each other to limit the pressure increase on the train section. When a high-speed train enters a tunnel, the drag increases. A pressure wave is generated that may cause discomfort or even ear problems to passengers, and a sound wave is created at the exit of the tunnel. Shetz (2001) and Sakuma and Suzuki (2011) describe and analyze these phenomena and how to overcome them by improving the train aerodynamics. Howe (2003, 2007) and Xiang and Xue (2010) study the impact of the shape of the tunnel exits, and N’Kaoua et al. (2006) analyze the tunnel itself. The increase in pressure generated by the train entering a tunnel can be estimated using the work of Ricco et al. (2007) and Raghunathan et al. (2002) as a function of the section of the tunnel, $A_{\text{tunnel}}$, the section of the train, $A_{\text{train}}$, and its speed, $S$:

$$
\Delta p = \frac{1}{2} \rho_0 M_t^2 \left( \frac{1}{q^2 + (1 - q^2) M_t^2} \right)
$$

where $q = 1 - A_{\text{train}} / A_{\text{tunnel}}$, $M_t = S / c_{\text{sound}}$ is the Mach number of the train, $c_{\text{sound}}$ is the celerity of the sound, $\gamma$ is the ratio of specific heats of air, and $p_0$ is the initial pressure inside the tunnel.
tunnel.

Suppose that, in a tunnel, Train 1 generates a micro-pressure wave with a pressure increase of $\Delta p_{\text{train}} = p_1 - p_{\text{atm}}$. When Train 2, running in the opposite direction to Train 1, enters the tunnel, the second micro-pressure wave may add to the first one, increasing the pressure to $\Delta p_{\text{train}} = p_2 - p_1$. In the worst case, the trains pass each other at maximum speed, with a third pressure increase proportional to the square of the speed and the train section (Ly et al., 2006).

The total pressure increase, $\Delta p_{\text{total}}$, is derived from a simple formula as:

$$\Delta p_{\text{total}} = \alpha A_{\text{train}} \gamma^2 + \Delta p_{\text{train}} \left( \frac{2 + \frac{1}{2} \gamma M_t^2}{\varphi^2 + \left(1 - \varphi^2\right) M_t - M_t^2} \right)$$  \hspace{1cm} (15)

where $\alpha$ is a constant determined using existing or modeled data. When $\Delta p_{\text{total}}$ is given, Equation (15) can be rewritten as a quadratic function for $\varphi^2$ with one positive solution. Then the tunnel section, $A_{\text{tunnel}}$, is given by:

$$A_{\text{tunnel}} = \frac{A_{\text{train}}}{1 - \sqrt{\varphi^2}}$$  \hspace{1cm} (16)

Once the optimal tunnel section is obtained, the tunnel cost is calculated using simple assumptions about the geology and construction method.

2.4.4 Stations, Workshops, and Maintenance Bases

The station construction cost is assumed to be proportional to the number of platforms, $N_{\text{platform}}$, and to the train length, $L_{\text{train}}$, with a margin at each extremity of the train. The amount of workshops and depots depends on the amount of rolling stock, and a simple model considers a linear cost proportional to the train length and the quantity of rolling stock.

2.5 Maintenance Costs

The safety of the HSR operation relies on the quality and availability of the infrastructure over time, thus the network manager must define a maintenance strategy. There are two main maintenance strategies: curative maintenance and preventive maintenance. Ly et al. (2006) observe that curative maintenance has a high impact on both availability and cost since it may require long and complicated interventions to repair a failure. UIC (2010) shows that preventive maintenance consists of periodic maintenance and condition-based maintenance. Periodic maintenance introduces a fixed maintenance schedule to increase the availability of the infrastructure without sacrificing safety. Condition-based maintenance monitors the infrastructure to detect defects and schedule an intervention before a failure occurs. That maintenance strategy offers greater availability than does periodic maintenance. Note that, even with evolved condition-based maintenance, curative maintenance is still required because unexpected failures could always occur.

Practitioners and researchers have established various models to assess the degradation of parts of the infrastructure and to optimize the inspection and intervention schedules, including Antoni and Meier-Hirmer (2006, 2008, 2011). However, despite this research, there is little knowledge about the interaction between the train and the tracks at speeds above 350 km/h.
2.6 External and Disposal Costs

Transportation systems also impact the surroundings, the environment, people, and society as a whole. The IMPACT handbook (Maibach et al., 2008) is one of the most extensive references on this topic, presenting various external effects with methodologies and unit costs to internalize them. However, the main limitation to internalizing these external costs is data availability. In this macroscopic LCC model, external costs must be included with respect to its purpose and to the availability of data. Disposal costs should be included for both rolling stock and infrastructure. However, HSR infrastructure, like conventional rail, has a long lifetime and so will not be disposed of within a few decades. As a result, it may be omitted.

3. CASE ANALYSIS

3.1 Assumptions

To illustrate the proposed LCC framework, a hypothetical case is set up using the geographic data of California. The project period is 50 years with a social discount rate of 4%. Wages, electricity prices, and energy mix were collected from United Nations, OECD, and International Energy Agency databases. The 2007 Census of Agriculture (2007) provided rural land costs, and the data for urban areas and city centers were estimated from Davis and Palumbo (2007).

The rolling stock designs are adapted from existing rolling stock, in particular, French TGV and Japanese Shinkansen. Table 1 shows 16 train designs with their respective capacities and dimensions assumed in our case studies.

A simple model has been set up in which data about average energy consumption were collected from various sources to calculate an average consumption for both locomotive and EMU. Three assumptions were made: (1) the motors are designed to reach their maximum efficiency at the line design speed; (2) given continuous improvements in energy consumption, as illustrated by Hagiwara (2008), and the fact that new train sets are designed for speeds around 350 km/h, it is assumed that current energy consumption will be the same at a speed of 350 km/h for recent rolling stock; and (3) energy consumption is assumed to be proportional to the hydraulic diameter of the train and the square of the speed to introduce aerodynamic effects, as per Raghunathan et al. (2002). This means that the mechanical resistance is assumed to be negligible compared to the aerodynamic drag, although Shetz (2001) suggests that the proportion is 20% and 80%, respectively. The reference hydraulic diameter is \( \sqrt{10.9} \) for both EMU and locomotives, as the data was gathered for Shinkansen and TGV Duplex, which have the same train section of 10.9 m\(^2\). The reference speed is 350 km/h according to the second hypothesis. Thus, the energy consumption, \( E_{\text{conso}} \), is given by:

\[
E_{\text{conso}}(q, S_{\text{max}}, A_{\text{train}}) = e_{\text{conso}}(\delta_{\text{EMU}}) \cdot q \cdot (1 + e_{\text{losses}}) \cdot A_{\text{train}} \cdot \left( \frac{S_{\text{max}}}{350} \right)^3
\]  

where \( e_{\text{conso}}(\delta_{\text{EMU}}) \) is the consumption in kWh per passenger for EMU or locomotive in the pantograph, and \( e_{\text{losses}} \) is the losses. Table 2 presents the operating parameters and costs considered in this case.
<table>
<thead>
<tr>
<th>No</th>
<th>Similar rolling stock*</th>
<th>$q_{2f}$ (seats)</th>
<th>$q_{2m}$ (seats)</th>
<th>$\rho$</th>
<th>$L_f$ (m)</th>
<th>$L_r$ (m)</th>
<th>Section (m²)</th>
<th>Width (m)</th>
<th>Wheelbase (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>ICE1&amp;2</td>
<td>0</td>
<td>72</td>
<td>1.00</td>
<td>27</td>
<td>25.0</td>
<td>9.6</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>1</td>
<td>ICE3, Mini-shinkansen, future KTX</td>
<td>56</td>
<td>72</td>
<td>1.00</td>
<td>27</td>
<td>25.0</td>
<td>9.6</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>TGV / KTX</td>
<td>10</td>
<td>60</td>
<td>1.00</td>
<td>23</td>
<td>18.7</td>
<td>9.6</td>
<td>2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>AGV</td>
<td>39</td>
<td>56</td>
<td>1.00</td>
<td>19</td>
<td>18.0</td>
<td>9.6</td>
<td>2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>Double decker ICE1&amp;2</td>
<td>0</td>
<td>72</td>
<td>1.40</td>
<td>27</td>
<td>25.0</td>
<td>10.9</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>Double decker ICE3 or Mini-Shinkansen</td>
<td>56</td>
<td>72</td>
<td>1.40</td>
<td>27</td>
<td>25.0</td>
<td>10.9</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>TGV Duplex</td>
<td>10</td>
<td>60</td>
<td>1.40</td>
<td>23</td>
<td>18.7</td>
<td>10.9</td>
<td>2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>7</td>
<td>AGV 2</td>
<td>39</td>
<td>56</td>
<td>1.40</td>
<td>19</td>
<td>18.0</td>
<td>10.9</td>
<td>2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>8</td>
<td>Wide ICE1&amp;2</td>
<td>0</td>
<td>72</td>
<td>1.25</td>
<td>27</td>
<td>25.0</td>
<td>10.9</td>
<td>3.4</td>
<td>2.5</td>
</tr>
<tr>
<td>9</td>
<td>Shinkansen, Velaro, Zefiro, Chinese rolling stock</td>
<td>56</td>
<td>72</td>
<td>1.25</td>
<td>27</td>
<td>25.0</td>
<td>10.9</td>
<td>3.4</td>
<td>2.5</td>
</tr>
<tr>
<td>10</td>
<td>Wide TGV, KTX</td>
<td>10</td>
<td>60</td>
<td>1.25</td>
<td>23</td>
<td>18.7</td>
<td>10.9</td>
<td>3.4</td>
<td>3.0</td>
</tr>
<tr>
<td>11</td>
<td>Wide AGV</td>
<td>39</td>
<td>56</td>
<td>1.25</td>
<td>19</td>
<td>18.0</td>
<td>10.9</td>
<td>3.4</td>
<td>3.0</td>
</tr>
<tr>
<td>12</td>
<td>Double-decker wide ICE1&amp;2</td>
<td>0</td>
<td>72</td>
<td>1.70</td>
<td>27</td>
<td>25.0</td>
<td>12.4</td>
<td>3.4</td>
<td>2.5</td>
</tr>
<tr>
<td>13</td>
<td>Shinkansen E4</td>
<td>56</td>
<td>72</td>
<td>1.70</td>
<td>27</td>
<td>25.0</td>
<td>12.4</td>
<td>3.4</td>
<td>2.5</td>
</tr>
<tr>
<td>14</td>
<td>Wide TGV Duplex</td>
<td>10</td>
<td>60</td>
<td>1.70</td>
<td>23</td>
<td>18.7</td>
<td>12.4</td>
<td>3.4</td>
<td>3.0</td>
</tr>
<tr>
<td>15</td>
<td>Wide AGV2</td>
<td>39</td>
<td>56</td>
<td>1.70</td>
<td>19</td>
<td>18.0</td>
<td>12.4</td>
<td>3.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*Current, past, or hypothetical rolling stock with a similar design. Names in italics designate hypothetical rolling stock.

### 3.2 Construction cost

The example considers French ballasted track and Japanese regular and tunnel slab track; average earthworks from the latest and planned French LGV; a single type of viaduct (Japanese viaducts); two types of bridges (a regular bridge and a special bridge for highly seismic areas); and a single type of tunnel (a single tunnel with a double track). In tunnels, only Japanese tunnel slab track is used.

A linear cost model is used with respect to the length and the width of the structure, with the exception of tunnels. For the tunnels, our analysis of data from the British Tunnelling Society (2012) shows that the cost is proportional to the hydraulic diameter of the tunnel. Signalization and overhead lines are aggregated with the track cost. As for tunnels, the value of $\alpha$ in Equation (15) was determined from simulation results using RFF (2006). According to available data, it is found that $\alpha = 1.05 \times 10^{-6}$. Using this value, the calculated pressure level, $\Delta p_{total}$, generated by a 10.9m² Shinkansen at 300km/h in a regular 63.4m² tunnel are considered as the reference level to evaluate $\varphi$ in Equation (16), and then to calculate $A_{tunnel}$. That means that, in the model, the aerodynamics of the rolling stock is assumed to be as good as the latest Shinkansen. For instance, this gives a tunnel section of 91 m² with a 10.9 m² train...
section at 350 km/h.

The unit costs of the tracks and the linear and fixed structures were collected from interviews with RTRI, SNCF, and RFF regarding high-speed lines in France, Japan, and Taiwan, as well as from the UIC (2010).

Table 2. Summary of Parameters and Unit Costs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating hours</td>
<td>$OH$</td>
<td>18 Hours</td>
<td>Assumption</td>
</tr>
<tr>
<td>Average speed between stations</td>
<td>$\bar{S}$</td>
<td>80% of max speed</td>
<td>Average value for recent lines in 2007 world speed survey (Taylor, 2007)</td>
</tr>
<tr>
<td>Occupancy rate</td>
<td>$\tau$</td>
<td>75%</td>
<td>Assumption</td>
</tr>
<tr>
<td>First class seats</td>
<td>$\varphi$</td>
<td>30%</td>
<td>TGV Value</td>
</tr>
<tr>
<td>Dwell time</td>
<td>$t_{margin}$</td>
<td>30s</td>
<td>Heinz (Heinz, 2003)</td>
</tr>
<tr>
<td>Dwell time</td>
<td>$t_{board}$</td>
<td>3s / pax</td>
<td></td>
</tr>
<tr>
<td>Headway</td>
<td></td>
<td>4 min</td>
<td>TGV Value</td>
</tr>
<tr>
<td>Turnover</td>
<td>$t_{turnover}$</td>
<td>30 min</td>
<td>Assumption</td>
</tr>
<tr>
<td>Acquisition cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Locomotive-hauled train</td>
<td></td>
<td>n.a. 163 k$10$/m Interviews</td>
<td></td>
</tr>
<tr>
<td>EMU train</td>
<td></td>
<td>n.a. 131 k$10$/m Interviews</td>
<td></td>
</tr>
<tr>
<td>Wide body</td>
<td></td>
<td>n.a. +5% Fröidh (2012)</td>
<td></td>
</tr>
<tr>
<td>Double-deck</td>
<td></td>
<td>n.a. +10% Assumption</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td></td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>Articulated train</td>
<td></td>
<td>145 k$10$/bogie Alstom (2004, 2009)</td>
<td></td>
</tr>
<tr>
<td>Non-articulated train</td>
<td></td>
<td>160 k$10$/bogie Alstom (2004, 2009)</td>
<td></td>
</tr>
<tr>
<td>Refurbishment</td>
<td></td>
<td>0.8 k$10$/seat Alstom (2004, 2009)</td>
<td></td>
</tr>
<tr>
<td>Disposal</td>
<td></td>
<td>1.6 k$10$/seat Assumption</td>
<td></td>
</tr>
<tr>
<td>Energy consumption</td>
<td>$e_{conso}$</td>
<td>0.053 kWh/seats.km RFF</td>
<td></td>
</tr>
<tr>
<td>Locomotive-hauled train</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMU train</td>
<td></td>
<td>0.027 kWh/seats.km Estimation from Kobayashi (2010) and East Japan Railway Company (2010)</td>
<td></td>
</tr>
<tr>
<td>Energy consumption</td>
<td>$e_{losses}$</td>
<td>5% Assumption</td>
<td></td>
</tr>
<tr>
<td>Commercial cost</td>
<td>n.a.</td>
<td>35$10$/h.platform Estimated from SNCF (2012)</td>
<td></td>
</tr>
<tr>
<td>Employee per train</td>
<td>n.a.</td>
<td>5 Assumption</td>
<td></td>
</tr>
</tbody>
</table>

Note: “n.a.” denotes not available.

3.3 Maintenance Costs

The UIC (2010) shows the workforce required for inspection and maintenance, based on a review of several high-speed lines around the world, to be 0.47 employee/km for ballasted tracks and 1.01 employee/km for slab tracks.

Maintenance tasks have been modeled using a deterministic model: an element is changed when its lifetime is reached. Lifetimes were gathered from the UIC (2010) and interviews. For ballasted tracks, a track renewal implies both ballast and rail renewal, and rail renewal is coupled with a ballast renewal to reset both lifetimes and avoid faster degradation. For slab tracks, the lifetime is longer than the life cycle period, thus only regular maintenance
Regarding ballast degradation, Öberg (2006) reviews several models and concludes that Sugiyama’s model seems appropriate. This model gives the growth of vertical irregularities, $\mu$, for continuously welded rails with respect to speed and annual tonnage in particular:

$$\mu = k \cdot \sqrt{T} \cdot S_{\text{average}} \cdot M$$

(18)

where $T$ is the cumulative tonnage, $k$ is a constant of proportionality, and $M$ is a structure factor depending on the quality and composition of the track.

In addition, at high speed, a resonance phenomenon occurs between bogie and track, which increases the ballast scattering. The frequency of resonance is determined by the speed of the train and the wheelbase:

$$f = \frac{S}{\text{wheelbase}}$$

(19).

Ballasted tracks are assumed to have the same quality as French ballasted tracks, whose lifetime is 35 years at 300 km/h. Thus, from Equations (19) and (20) and data about the TGV, the lifetime of the ballast is modeled as:

$$\lambda_{\text{ballast}} = 35 \left\{ \frac{37.4 \times 10^3}{\text{trainweight} \cdot \sigma} \right\}^{\frac{1}{3}} \left\{ \frac{300}{S} \cdot \frac{\text{wheelbase}}{3} \right\}$$

(20).

Finally, Antoni (2011) mentions that, on average, there are 20 ballast-tamping interventions before the ballast is changed, and that grinding the rails once a year provides substantial cost savings. Both conditions are included in the case analysis.

### 3.4 External Costs

Only CO2 emissions are considered within a linear cost model in this case study. CO2 emissions from the construction of slab tracks and civil structures were estimated from Japanese documents detailing the last phase of the Tohoku Shinkansen (Japanese Railway Construction, Transport and Technology Agency, 2012). For stations, the emissions were estimated from the LCA of the California HSR based on Chester (2008). Other emissions were estimated from the carbon assessment of the French Rhin-Rhône line (ADEME et al., 2009). In this example, the unit cost for CO2 emissions is $30/t_{CO2}$.

### 3.5 Results

Figure 2 shows the average LCC compositions and the average NPVs per km of track estimated from the results of the 16 rolling stock designs shown in Table 1. The reference case uses slab track with 5% tunnels and 5% viaducts, with $D = 25$ Mpix and $S = 360$ km/h. Cases a, b, and c assume lines 100, 300, and 500 km long, respectively. Case d assumes ballasted track on a 300 km line, case e assumes 40% tunnels and 40% viaducts on a 300 km line, and case f assumes $S = 320$ km/h on a 300 km line.

First, in all cases, construction costs vary from a half to three-quarters of the total cost, while maintenance and external costs remain relatively constant between 1% and 3% of the total cost. These figures are reasonable and show that the model is coherent. Second, cases a
to c show that the NPV per km decreases as the line becomes longer. This is because operating costs benefit from economies of scale. Third, the introduction of ballasted track (case d) leads to a lower LCC, while an increase in tunnels and viaducts (case e) impacts significantly on the cost.

Figure 2. Average LCC composition estimated with the results of 16 rolling stock designs under six cases.

Figure 3 illustrates the impact of the train design on the LCC when demand is low (a) and when demand is high (b). First, when the demand is low, the increase in capacity caused by larger trains (No. 4 to 7), using double decks (No. 8 to 11), or both (No. 12 to 15) does not compensate for the increase in construction costs when there are many tunnels and viaducts. Second, locomotive-hauled trains (even number) induce a higher LCC, as expected. Third, articulated structures offer a lower LCC than non-articulated structures. The longer cars provided by non-articulated trains do not compensate for the difference in train maintenance costs. In this case, design No. 3 appears to be the best. However, the results are different when demand is high. In this case, most train designs are better than design No. 0, except No. 8 and 12, which are also non-articulated, locomotive-hauled trains. Because of the higher constraint provided by the demand, the trade-off between construction costs and operating costs is in favor of designs No. 6 and 7, both double-decker, articulated trains.
4. CONCLUSIONS

This paper presented a life cycle cost model that enables us to compare different systems and their life cycle costs. This approach was motivated by the diversity of HSR cost studies, with their variety of focuses and scopes, and the difficulty in estimating a local life cycle cost for different HSR systems based on these studies. A hypothetical line was considered to illustrate how the model behaves with respect to the demand, speed, and length, as well as the infrastructure and rolling stock types. In particular, it appears that articulated train sets provide a lower life cycle cost than non-articulated sets, ceteris paribus. However, most manufacturers propose a non-articulated design, which is less interesting from a life cycle cost perspective.

The model has been designed to be easily upgraded and updated, and offers a wide scope for future work. Inputting more accurate and up-to-date cost elements would ensure more precise cost estimations without significantly modifying the model. However, as a life cycle cost model, it is by its nature limited by data availability. Fortunately, the numerous HSR projects that are being implemented will provide both data for the model and new lessons to enable us to continue building more efficient and sustainable HSR systems. Finally, this model is a first step towards more inclusive life cycle cost and cost-benefit models that encompass both the choice of a system and the relationships between the subsystems and demand. These models will eventually provide an optimized model of the system, its alignment, and its operating parameters.

ACKNOWLEDGEMENT

This paper is a part of achievements from Master Research at the University of Tokyo. This study is supported by many experts from France, Japan, and Switzerland. We thank Mr Bouillaut, L. (IFSTTAR), Mr Antoni, M. (SNCF), Mr Cazier, O. (RFF), Mr Zwanenburg, W.-J., Mr Kikuchi, K. (JRTT), and Mr Kojima, M. (JRTT) for their valuable comments and advice.

REFERENCES


