



LCC-based approach for design and requirement specification for railway track system

Stephen Famurewa^{1,3} · Elias Kirilmaz² · Khosro Soleimani Chamkhorami¹ · Ahmad Kasraei¹ · A. H. S. Garmabaki¹

Received: 10 December 2023 / Revised: 5 May 2024 / Accepted: 14 June 2024
© The Author(s) 2024

Abstract Life cycle cost (LCC) analysis is an important tool for effective infrastructure management. It is an essential decision support methodology for selection, design, development, construction, maintenance and renewal of railway infrastructure system. Effective implementation of LCC analysis will assure cost-effective operation of railways from both investment and life-cycle perspectives. A major setback in the successful implementation of LCC analysis by infrastructure managers is the availability of relevant, reliable, and structured data. Different cost estimation methods and prediction models have been developed to deal with this challenge. However, there is a need to include condition degradation models as an integral part of LCC model to account for possible changes in the model variables. This article presents an approach for integrating degradation models with LCC model to study the impact of change in design speed on key decision criteria such as track possession time, service life of track system, and LCC. The methodology is

applied to an ongoing railway investment project in Sweden to investigate and quantify the impact of design speed change from 250 to 320 km/h. The results of the studied degradation models show that the intended change in speed corresponds to correction factor values between 0.79 and 0.96. Using this correction factor to compensate for changes in design speed, the service life of ballasted track system is estimated to decrease by an average of 15%. Further, the expected value of LCC for the route under consideration will increase by 30%. The outcome of this study will be used to support the design and requirement specification of railway track system for the project under consideration.

Keywords LCC · Track system · Requirement specification · Degradation models · Correction factor

1 Introduction

Life cycle cost analysis is a method for evaluating the total cost of ownership for a component, system, or complex system over its entire lifespan. The goal of LCC analysis is to identify the most cost-effective option by comparing the total costs of different alternatives over the life of the system. It is a decision-making tool commonly used in engineering, construction, and procurement to evaluate the cost-effectiveness of different design and technical solutions. It provides a comprehensive and objective way to evaluate and analyse the total cost of a system and support engineers or other asset managers in making effective decision from a cradle-to-grave viewpoint.

By considering the total cost which includes the costs of operating, maintaining, and disposing a system and not only the initial acquisition cost, LCC analysis allows engineers to make more informed decisions about the long-term

✉ Stephen Famurewa
stephen.famurewa@ltu.se

Elias Kirilmaz
eliaz.kirilmaz@sweco.se

Khosro Soleimani Chamkhorami
Khosro.soleimani.chamkhorami@associated.ltu.se

Ahmad Kasraei
ahmad.kasraei@associated.ltu.se

A. H. S. Garmabaki
amir.garmabaki@ltu.se

¹ Division of Operation and Maintenance Engineering, Luleå University of Technology, 971 87 Luleå, Sweden

² CERTIFER, Stockholm, Sweden

³ Swedish Transport Administration, Trafikverket, 972 42 Luleå, Sweden

economic feasibility of different design options. Additionally, this systematic approach to decision making can help to identify trade-offs between different designs such as between a more expensive, high-performance product and a less expensive, low-performance product.

The application areas of LCC analysis in railway infrastructure management include: ranking or selection of railway project, requirement specification, design and construction of railway system. It is also applied in selection of technical system, procurement of new system or component, selection of maintenance methods, maintenance intervention cycles, decision between maintenance and renewal, optimal timing of technological shift, decision between improvement and modification, as well as system upgrade or replacement.

Life cycle cost analysis has been used in the railway industry to evaluate the total cost of ownership for various rail infrastructure, rolling stock, and other railway-related systems. For example, LCC analysis has been used to evaluate the cost-effectiveness of different track maintenance and renewal options, for example slab or traditional ballasted tracks. Further, it has been used to evaluate the cost-effectiveness of different rolling stock options, such as diesel or electric trains, and to compare the costs of different signalling and train control systems. Additionally, LCC analysis can also be used to evaluate the sustainability of different railway-related systems and components. This is done by considering the environmental, social, and economic impacts of different alternatives over the entire service life. The method can help to identify options that are more sustainable in terms of their long-term impacts.

A vital advancement in the application of LCC in railway industry is the use of probabilistic and statistical methods such as Monte Carlo simulation which allows systematic incorporation of uncertainty and risk into the LCC analysis (1). This enables decision-makers to evaluate the potential impacts and cost implication of variations in design, operational parameters, or market conditions. The contribution of this paper is the application of deterioration models

to estimate correction factor that is included in the presented LCC model. This is aimed at studying the impact of increased design speed on track system. The result of this study is used to support the design specification at an early lifecycle phase of an ongoing railway project in Sweden.

The structure of the paper is as follows, Sect. 1 introduces the implementation of LCC in the railway industry and vital advancement in the field. Section 2 provides an overview of the three levels of LCC analyses i.e., network, asset, and component levels followed by description of the methodology used in Sect. 3. A case study is presented in Sect. 4 and the result is discussed in Sect. 5 with the concluding section presented afterwards.

2 State of the art

There are various LCC-based approaches for assessing economic performance of infrastructure asset considering factors such as complexity, cost bearing object, cost estimation approach, RAMS modelling, and decision-making level. Various mathematical formulations have been developed and utilized in both research and practice (see Table 1). The choice of the modelling level will also determine the amount of data and information required for the analysis, complexity of the computation and precision of the results.

2.1 LCC at network level

In railway structure, the network level comprises of the whole or a large part of a country's railway infrastructure assets. Some research works have developed LCC models to analyse and support engineering decisions at the network level. For instance, Patra et al. (2009) proposed a LCC formulation for assessment of improvement on the Swedish iron ore line. They proposed a methodology for estimation of uncertainty in LCC by introducing a hybrid model including a combination of design of experiment and Monte Carlo

Table 1 Modelling levels of LCC analyses

	Cost aggregate	Cost atom	Cost element
Complexity	Simple	Moderate	Detailed
Cost bearing object	Asset	Activity	Resource
Cost estimate	Relative	Moderate	Absolute
RAMS modelling	Rarely included	Often and partially included	Always included
Decision	Network/route design	Asset type design	Component design and maintenance
Formulation	$\sum_{t=1}^T \sum_{n=1}^N C_{t,n}$	$\sum_{t=1}^T \sum_{n=1}^N \sum_{a=1}^A C_{t,n,a}$ $\sum_{t=1}^T \sum_{n=1}^N \sum_{a=1}^A (C:f)_{t,n,a}$	$\sum_{t=1}^T \sum_{n=1}^N \sum_{a=1}^A \sum_{r=1}^R (C:f.p)_{t,n,a,r}$

where C is the cost incurred on a component, f is the frequency of an activity which takes p unit of time to complete. n is component 1 to N , t is period 1 to T , a is activity 1 to A , r is resource 1 to R

simulation. Stenström et al. (2016) presented preventive maintenance (PM) and corrective maintenance (CM) actions costs through the analysis of historical data, with the aim of finding the shares of PM and CM actions cost for a specific line of Sweden railway network. Furthermore, a novel framework that involves railway performance model was presented to estimate LCC for a part of railway line (Rama and Andrews 2016). Kasraei and Ali Zakeri (2022) in their research, assessed LCC associated with RAMS framework. They employed a stochastic linear degradation model, considering different thresholds to optimize the cost functions including inspection, PM and CM actions cost, and penalty for exceeding the specific threshold. In addition, according to EN 13848-5, they used the alert limit (AL) as an indicator to plan maintenance operations and differentiated between the PM and CM actions to enable better estimation of PM and CM actions and reducing the level of uncertainty.

2.2 LCC at asset level

The railway track is a heterogeneous system including interdependent assets, i.e., steel rail, sleepers, joints and fasteners, ballast, subgrade, overhead powerlines, and etc. At this level, economic dependency indicates the increase or decrease in maintenance cost when multiple components are maintained simultaneously (Kobbacy et al. 2008). For instance, Nissen (2009) proposed a LCC framework which comparing various types of S&Cs. The model can be utilized to identify the main cost drivers and perform sensitivity analysis to find effective parameters that have a significant influence on the result. Furthermore, a study has proposed a new multiple integer linear programming that uses predictive maintenance operation to optimize maintenance activities scheduling of ballast, rail and sleeper renewal (Caetano and Teixeira 2015). This model established a connection between the decision-making process for the renewal of these components and their respective conditions. By leveraging the integrated planning of renewal activities, the model aims to minimize the LCC of the railway track. In other research, the different factors, both on a global and local scale that play a role in the decision on the type of track system have been evaluated by Sárík (2018). Through LCC calculations, he provided recommendations regarding the preferred track system among three alternatives: ballasted track, ballast less track, and an alternating system option. Said Rajab (2019) conducted an integrated RAMS analysis combined with an LCC analysis to enhance the maintenance optimization of the signaling system. Formulas were developed to allocate costs associated with repairing or restoring asset failures, addressing service losses, and managing overall LCC during both the operation and maintenance phases.

2.3 LCC at component level

It is essential for infrastructure manager to have a deep insight regarding the performance of components to handle the demand for spare parts management and procurements, and maintenance planning (Galar et al. 2017). Degradation of each component is influenced by traffic and operational factors, e.g., train speed, axle loads, accumulative tonnage and performed maintenance. The cost that is consequence of degradation of component level can help decision maker to planed budget and financial program for each component (Galar et al. 2017).

Calle-Cordón et al. (2018) presented a methodology for combining RAMS in the LCC analysis of linear transport infrastructures. The method has been demonstrated in a railway use case at the component level of S&C. They showed how to obtain cost estimates and cost driver's dependencies using historical maintenance records, together with individual cost figures, in LCC formulas. Shang et al. (2020) proposed a reliability-LCC model for the embedded rail system at the level crossing to optimize the replacement time and decrease associated uncertainties. Senaratne et al. (2020) investigated the imperative to evaluate the LCC associated with adopting alternative materials for railway asset. Their research introduces a cost-effective and sustainable material specific to the Australian railway industry, offering an alternative to the widely used traditional timber in railway bridges. Alabdullah et al. (2020) investigated the reduction in railway track cost due to the use of geogrid reinforcement. The results show that the cost of reinforced railway track is lower compared to the unreinforced track and the cost contribution is as follows: the sub-ballast reinforced model (4.1%), the ballast reinforced model was (6.5%), and the double reinforced model was (3.73%). Sasidharan et al. (2020) introduced a comprehensive LCC approach under different uncertainty to determine the economically optimal maintenance strategy for the substructure of traditional ballasted railway tracks. The results showed that to maximize economic benefits for each route, different maintenance strategies are required. Thompson et al. (2022) conducted life cycle analyses of emissions and costs associated with timber, concrete, short-fiber, and long-fiber composite railway sleepers. Their objective was to identify the sleepers that exhibit superior environmental friendliness and cost competitiveness. The findings unmistakably underscore the environmental benefits of short-fiber plastic composites. Camille et al. (2022) examined the economic viability of incorporating macro synthetic fiber reinforced concrete (MSFRC) as an alternative material for railway sleeper applications. Utilizing a LCC approach, the research assesses the influence of various asset phases-acquisition, operation and maintenance, and end-of-life on a comprehensive cost comparison between MSFRC and conventional sleeper materials.

Table 2 Degradation models [see references 2–20]

Model nr	Degradation models (references)	Formulation	Comments
1	Sato (1995); Esveld (2001); Lichtberger (2011)	$N_S = 2,04 * 10^{-3} * T^{0,31} * V^{0,98} * M^{1,1} * L^{0,21} * P^{0,26}$	V-velocity T-annual tonnage M-structural factor L-CWR factor P-subgrade factor α, β, γ are dimensionless speed coefficients that depend on track and vehicle parameters
2	ORE: Doyle (1980); Esveld and Esveld (2001); Larsson (2004); Lichtberger (2011)	$N_{ORE} = 1 + \alpha + \beta + \gamma$	
3	Bing and Gross (1983)	$N_{BG} = 1,25 * \left(\frac{TQI1}{TQI2} \right)^{-0,58} * \left(\frac{V1}{V2} \right)^{-0,18} * \left(\frac{RA1}{RA2} \right)^{-0,11} * \left(\frac{BI1}{BI2} \right)^{1,04} * (1 + FS)^{-0,44}$	TQI-Track quality indices at time 1&2 V-velocity at time 1&2 RA-track age at time 1 and 2 BI-ballast index at time 1 and 2 FS-substructure factor k-track stiffness
4	Indian formula: Doyle (1980)	$N_{IN} = 1 + 0,5 * \left(\frac{V}{58,14 * k} \right)$	D-wheel diameter
5	South African formula: Doyle (1980)	$N_{SA} = 1 + 4,92 * \left(\frac{V}{D} \right)$	k-track stiffness
6	Clarke: Doyle (1980)	$N_{CL} = 1 + 0,5 * \left(\frac{19,5 * V}{D * k} \right)$	V-velocity
7	WMATA formula: Doyle (1980)	$N_{WHATA} = (1 + 3,86 * 10^{-5} * V^2)^{0,67}$	g-gravity Dj-sleeper pressure Pu
8	British railway formula: Doyle (1980)	$N_{BR} = 1 + \left(\frac{8,784 * (a1 + a2) * V}{P_s} \right) * \left(\frac{Dj * Pu}{g} \right)^{0,5}$	Pu Ps-axle load (a1 + a2)-total rail joint dop angle
9	AREA formula: Doyle (1980)	$N_{AREA} = 1 + 5,21 \frac{V}{D}$	D-wheel diameter

3 Research methodology

This study entails the development of a data-based decision model to support the selection of track system during the design phase of a new railway line. The method used in the study includes literature survey, degradation modelling, Monte-Carlo simulation and LCC modelling.

The first step in the study is to collect available cost data for the track system under consideration. Construction and maintenance costs for ballast system with speed up to 250 km/hr were obtained from literature and relevant database of the Swedish Transport Administration. Similar costs for slab track with operating speed up to 320 km/hr were obtained from benchmarking carried out during the study. Thus, these operating conditions became the baseline for both systems.

Furthermore, literature study was conducted to study how change in operating speed can affect the degradation, maintenance need and cost of ballasted track system. Several models were studied to capture the behaviour of ballasted track system under varying operating conditions. Based on relevance, robustness, model formulations, result accuracy as presented in the literature studied, 10 models were selected for detailed study. At the final stage, one model was exempted due to very high discrepancy in comparison to other models and poor performance with variation in speed, which is the parameter of interest. A list of the degradation models with simplified model formulation, remarks and literature source is given in Table 2. More information about these models can be found in the references provided.

It should be noted that the main aim of using these models is not to predict the absolute change in the condition of the track system but relative change in comparison to a baseline scenario. The relative change is then used to estimate a correction factor that will be used to adjust the maintenance parameters and cost of the known baseline scenario.

For the data collection, different sources of data were used to obtain the input values for the LCC model. The constant values of the degradation model parameters presented in Table 2 are collected from literature and the technical specifications for the construction of the route. Maintenance and cost data are collected from benchmarking and best practices. Line specification and system description are collected from the ongoing investment project within the Swedish Transport Administration, Trafikverket.

A correction factor (CF) is a common method used in engineering design and construction to compensate for changes or uncertainties in design parameters and operating conditions. Correction factor makes it possible to use the results of the different degradation models even though there are uncertainties in predicting the exact degradation value. The correction factor is estimated using the ratio of the predicted deterioration of the track system under 2 different operating speeds i.e., 250 and 320 km/h, see Eq. 1.

It should be noted that other parameters remain unchanged in the study. The correction factor is then used to adjust the possible change in maintenance need, service life of track components and costs due to speed change.

$$CF_{mod} = \frac{\text{Degradation value } 250 \text{ km/h}}{\text{Degradation value } 320 \text{ km/h}} \quad (1)$$

CF_{mod} is the correction factor for a given degradation model m.

A range of correction factors was obtained using the degradation models in Table 2. A normal distribution was assumed for the factors and the distribution parameters were estimated using a standard statistical method. The estimated distribution parameters of the CF were used for a probabilistic estimation of the values of the unknown LCC parameters under varying operational condition. These LCC parameters include service life and intervention interval of track systems.

In the design of track system and selection of optimal operating parameters, the amount of possession time that will be required for the purpose of maintenance and renewal is a vital criterion. This is a good indication of the availability performance that a track system can deliver over a given period. A benchmarking of existing maintenance plan of ballasted track with speed up to 250 km/h was carried out to create a realistic maintenance plan for the base scenario. The correction factors were used to adjust the intervention intervals for the different activities for ballasted track system with speed up to 320 km/h. A simplified formulation used to estimate the possession time requirement for the two systems is given in Eqs. 2 and 3. Note that this does not include the time required for the design, projection, and initial installation of the systems.

$$\text{Possession time} = \text{Maintenance Possession Time} + \text{Renewal Possession Time} \quad (2)$$

$$\text{Possession time} = \sum_{m=1}^M \frac{120}{\text{Interval}_m} * MPT_m + \sum_{r=1}^R \frac{120}{\text{Interval}_r} * RPT_r \quad (3)$$

where MPT_m and RPT_r are maintenance possession time for activity m and renewal possession time for activity r respectively.

For the life cycle cost of the two track designs, the costs of acquisition, operation and maintenance, renewal and disposal of replaced items are summed up over the required period of 120 years. Only significant, distinctive, and future cost elements are included in the model since the purpose of the study is to compare the proposed alternatives and to provide input for decision making. A simplified formulation of the LCC model is given in Eq. 4.

Table 3 Description of line sections

Line section	Alternative 1-design track system	Alternative 2-design track system	Speed (km/h)	Estimated trains per day	Estimated annual load (MGT)	Track length (km)
Line 1	Ballasted	Ballasted	250	179	16	177
Line 2	Slab	Ballasted	320	160	15	122
Line 3	Slab	Ballasted	320	100	9	83
Line 4	Ballasted	Ballasted	250	210	15	82,5
Line 5	Slab	Ballasted	320	100	9	207
Line 6	Slab	Ballasted	320	130	11	57

For analysis and comparison, a third option named alternative 3 with ballasted track and speed of 250 km/h on all the lines was projected

$$LCC = \text{Acquisition cost} + \text{Operation \& maintenance cost} + \text{Renewal and disposal cost} \quad (4)$$

For calculation without discount rate, LCCs for the alternative designs under consideration are estimated using the formulation below.

$$LCC = CA + \sum_{m=1}^M \frac{120}{Interval_m} * CM_m + \sum_{r=1}^R \frac{120}{Interval_r} * CR_r \quad (5)$$

LCC estimation with discount can be estimated using the formulation in Eq. 6.

$$LCC = CA + \sum_{m=1}^M \sum_{n=1}^{\frac{120}{Interval_m}} \frac{CM_m}{(1+i)^{(n*Interval_m)}} + \sum_{r=1}^R \sum_{n=1}^{\frac{120}{Interval_r}} \frac{CR_r}{(1+i)^{(n*Interval_r)}} \quad (6)$$

For ballast system with traffic speed equal to 320 km/h, the interval used in the LCC formulation is adjusted for speed change using the formular below:

$$Interval_{m,320} = \frac{Interval_m}{CF_{mod}} \quad (7)$$

where CA is the cost of acquisition of the different systems. CM_m and CR_r are the cost of maintenance for intervention m and cost of renewal for activity r respectively. $Interval_m$ and $Interval_r$ are the intervention intervals for maintenance and renewal activities m and r respectively. $Interval_{m,320}$ is the maintenance interval for activity m under an operating speed condition of 320 km/h.

The change in the track intervention intervals due to the impact of operational parameters was modelled using Monte Carlo Simulation assuming a normal distribution of the correction factor. 10 000 simulations were carried out to have a reliable estimate of the decision criteria.

Note that a discount rate of zero is used in the LCC calculation due to the long calculation period of 120 years required for technical specifications within the project.

4 Case study

The main aim of the study was to support the specification of track design requirement for an ongoing investment project in Sweden. An overall description of the route is given in Table 3 below. Only the features that are needed for modelling the impact of speed change are given in the table. The description of the route presented below was as it were in June 2022 when this study was carried out.

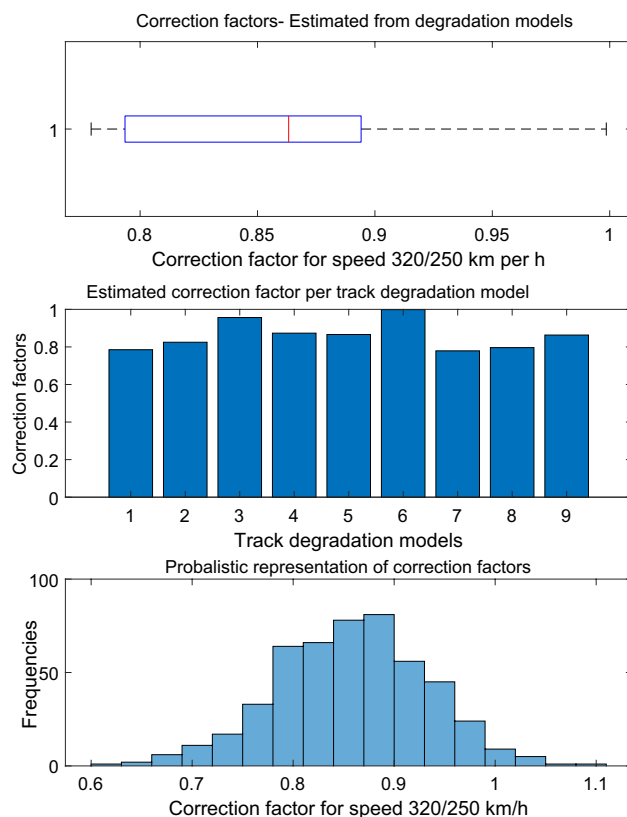
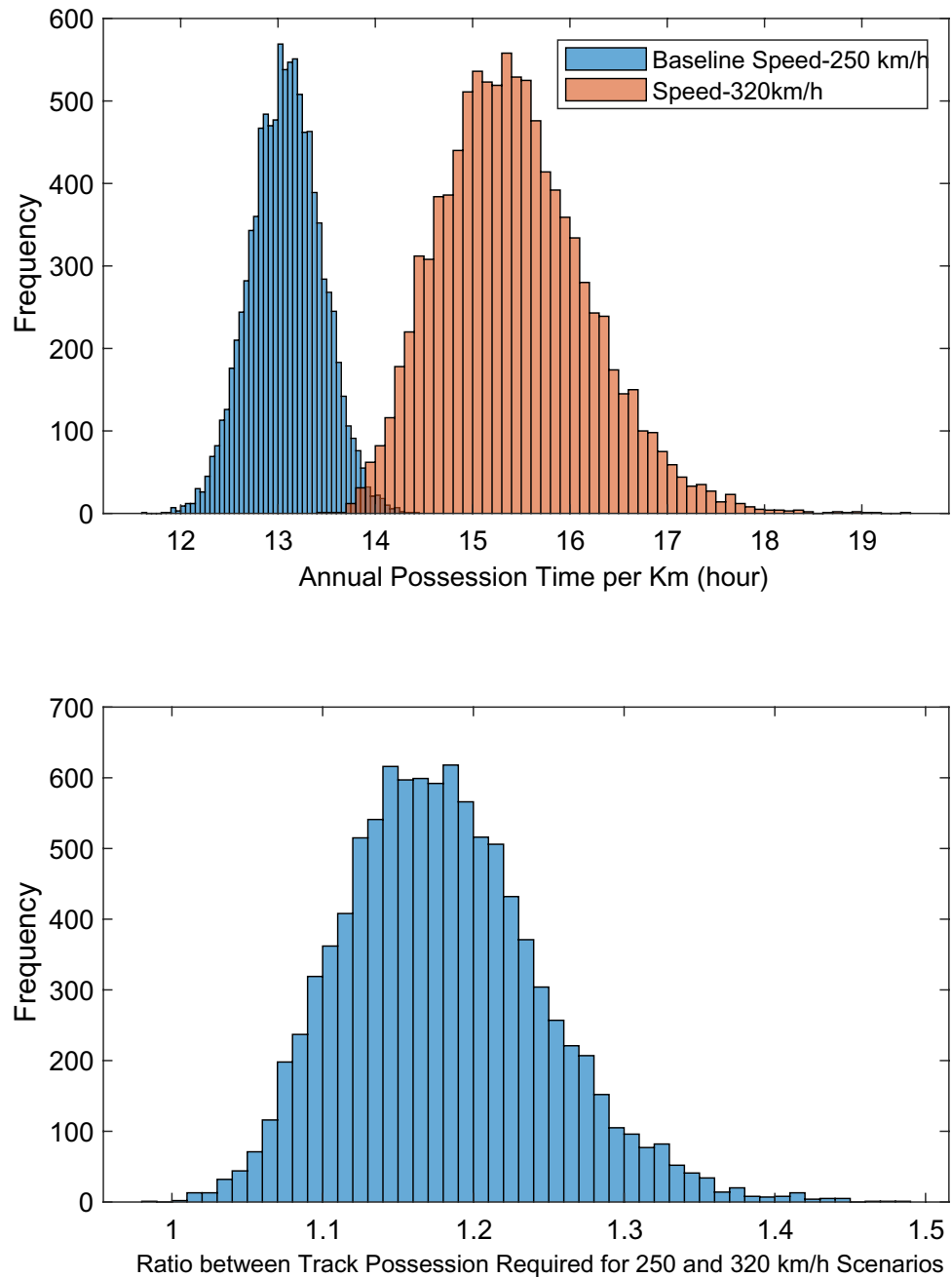
**Fig. 1** Correction factors for the adjustment of LCC parameters

Fig. 2 Change in track possession time for ballasted track with operational speed of 250 km/h and 320 km/h

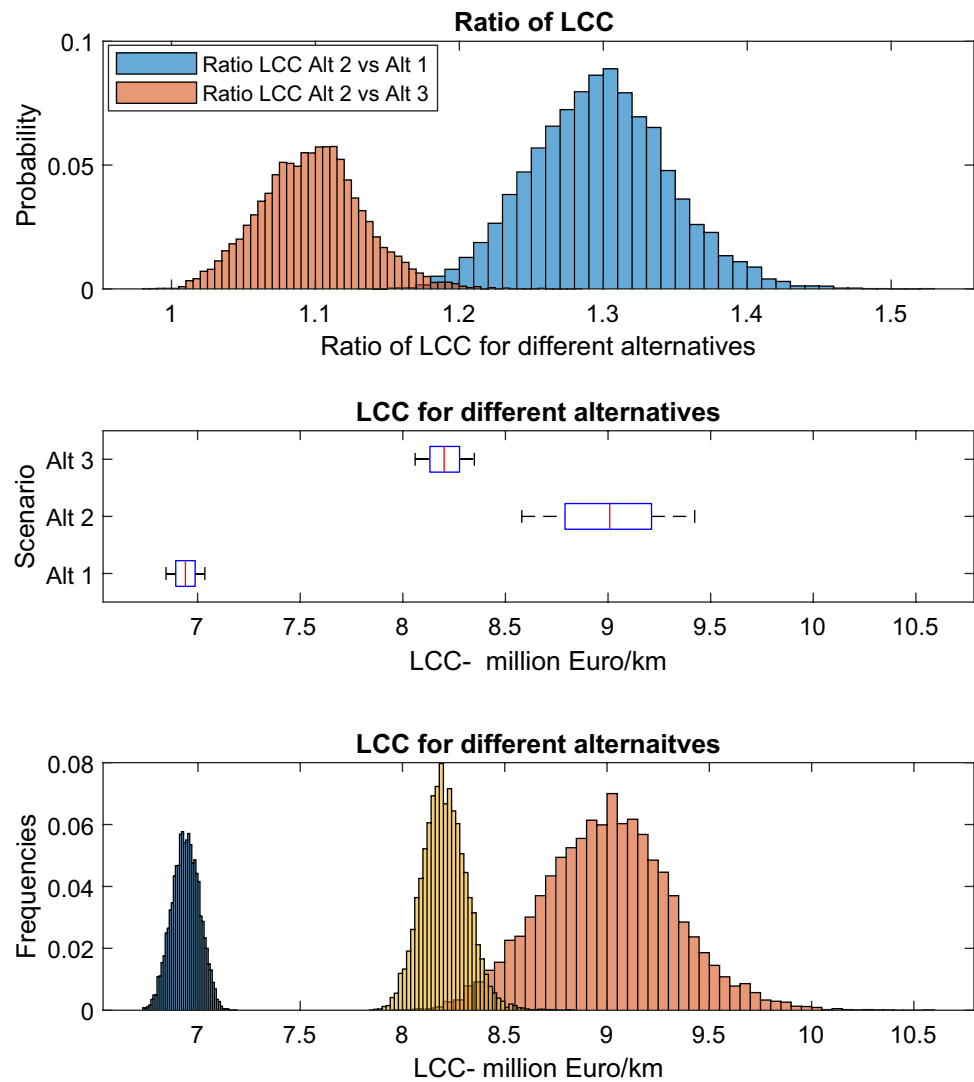


5 Results and discussions

Using all the degradation models presented in Table 2, a range of values was obtained for the correction factors. These values were used to adjust parameters in the LCC models that were expected to vary with change in speed. Figure 1 presents the values obtained for the different models. The variation in the correction factor is assumed to be due to aspects including assumptions of the deterioration models, parameter values used in the model, number of parameters in the model, application area of the model (for example heavy haul, mixed traffic), approximation and simplification in the

model. However, using several models gives a robust and practical range of the possible variation in the LCC parameters. In a nutshell, the values presented in the figures is a quantification of the impact of track force on maintenance and renewal actions as caused by speed increase in an uneven track. Technically, an increase in track force leads to the following: rail head wear, fatigue of the rail, increased bending stress of the rail foot, increased pressure at sleeper-ballast interface & rail-sleeper interface, higher bearing stress in ballast & subgrade, increased force on fasteners and higher track deformation.

Fig. 3 LCC for the three alternatives over 120 years



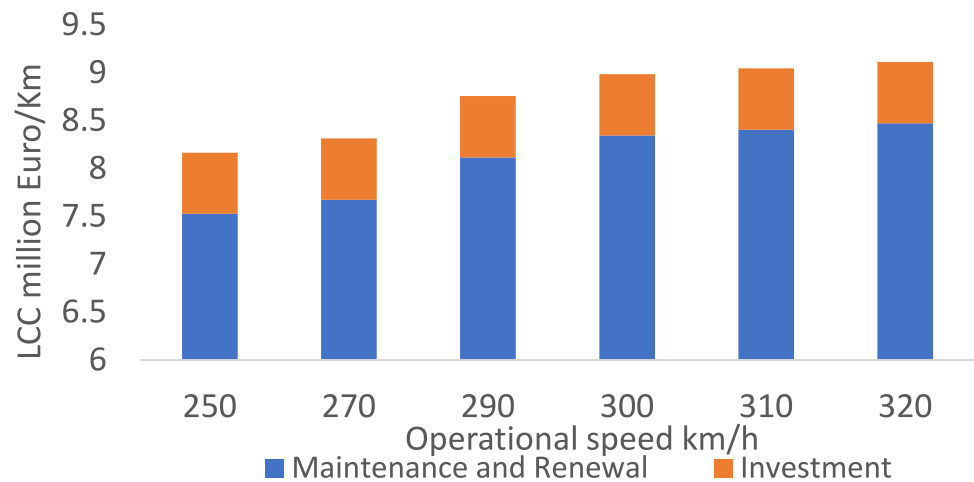
Using the distribution of the correction factor values to compensate for increase in design speed from 250 to 320 km/h, the service life of ballasted track system is expected to decrease by an average of 15%. This means a reduction from 30 years to a range between 23 and 28 years is expected. Similar level of decrease is expected in the service life of some other track components and their maintenance intervals. Note that there is no change in the design speed of line sections with slab track, thus a design life of 90 years is used in the analysis. In other words, correction factors were not applied to slab track scenarios.

Using the procedure described in Sect. 2 and in Eq. 3, the amount of possession time that will be required for the purpose of maintenance and renewal is estimated and presented in Fig. 2. This is an indication of the change in availability performance of ballasted track system when the speed is increased from 250 to 320 km/h. An increase of about 18% is expected in track possession time required to maintain the system in a dependable state. In reality, the outcome can

be far above the estimated value in this study if an effective maintenance programme is not adopted.

Similarly, the procedure described in Sect. 2 was used to estimate the LCC for the different design alternatives. It should be noted that intervention intervals in the models were treated as probabilistic variables due to uncertainties in the degradation models used to predict the impacts of speed. As a result, a probabilistic approach was used in the LCC estimations, and the results are presented in Fig. 3. The results show that there is a clear difference between the estimated LCC for alternatives 1 and 2. Alternative 1 which has about 67% of the entire route as slab track has a lower LCC than alternative 2 (100% ballast) even though the initial investment is higher. Alternative 1 is estimated to be 30% less expensive than alternative 2 from a lifecycle viewpoint. Also, the variation in the estimated LCC for alternative 1 is lower than the second alternative based on the variations in the input parameters.

Fig. 4 LCC for the entire route with ballast track form and varying operational speed on lines 2, 3 and 5



The results also show that increasing the speed from 250 to 320 km/h on a ballasted section would lead to an average of 10% increase in the LCC. The magnitude of the difference in LCC for alternative 2 and alternative 3 should be interpreted carefully due to the overlap of the box plot. This is due to the uncertainty of the impact of speed on LCC parameters such as intervention intervals and service life of track components. More data collection or expert opinion would be needed to confirm if the difference in LCC of these two alternatives is significant. However, there is an indication that increase in speed would lead to higher maintenance needs and if not well handled with appropriate preventive maintenance, cost of ownership could grow exponentially at an undesirable rate.

To further investigate the impact of speed on LCC, the speed of lines 2, 3 and 5 were varied for the second design alternative with ballast track form. Note that the speed of lines 1 and 4 were unchanged since 250 km/h is the design requirement for these lines and it's not expected to change. The result is presented in Fig. 4. The result shows a near-linear logarithmic relationship between speed and LCC. It implies that for every 10 km/h rise in speed, an increase of about 0.15 M Euro in LCC per km is expected over the design life length of the infrastructure (120 years). This translates to about 1 250 Euro per km and year. For the entire route in the case study under analysis, 10% increase in LCC is expected for a change in speed from 250 to 320 km/h.

It is worth mentioning that this study assumed relatively good ground formation along the route thus no need for extensive ground preparation and reinforcement for slab track in some areas. In future study, location-specific geotechnical works that is required for construction of both slab and ballast track system along the route will be considered in detail. Other important design and maintenance aspects that can reduce the impact of speed increase on LCC are ballast quality and profile, ground treatment, (differential)

settlement enhancement measures, use of under-sleeper pad (USP) and improved maintenance strategy.

6 Conclusions

This study has contributed to the advancement of LCC application in the design phase of railway infrastructure where there is inadequacy of data. It addresses the integration of deterioration model and LCC model to study the impact of increasing design speed on track system. A probabilistic approach has been used to capture the uncertainty in predicting the effect of speed change on LCC parameters such as maintenance intervals and service life of track system. In summary, an increase in the operational speed of a ballasted section from 250 to 320 km/h will lead to an average of 15% decrease in service life and 18% increase in possession time. From a route perspective, about 30% increase in LCC is expected with a change of the design from alternative 1 (67% of the entire route as slab track) to alternative 2 (100% ballasted track). On the other hand, an average of 10% increase in LCC is expected with a change in speed from 250 to 320 km/h on a ballasted track. In conclusion, this study is used by track engineers to motivate the selection of track system and to specify optimal design requirements for an ongoing investment project in Sweden.

Funding Open access funding provided by Lulea University of Technology. This investigation is funded by the Swedish Transport Administration, Trafikverket.

Declarations

Conflict of interest There are no conflicts of interest declared by any of the authors.

Human participants and/or animals Human Participants and/or Animals are not involved in this research.

Informed consent Informed consent was obtained from all individual participants included in the study.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Alabdullah SFI, Kadhim AJ, Khalaf HB (2020) Life cycle cost analysis for reinforced geogrid railway track. *GEOMATE J* 19(75):191–196
- Bing AJ, Gross A (1983) Development of railroad track degradation models. *Transp Res Rec* 939:27–31
- Caetano LF, Teixeira PF (2015) Optimisation model to schedule railway track renewal operations: a life-cycle cost approach. *Struct Infrastruct Eng* 11(11):1524–1536
- Calle-Cordón A, Jiménez-Redondo N, Morales-Gámiz J, García-Vilena F, Peralta-Escalante J, Garmabaki A, Famurewa SM, Duarte E, Morgado J (2018) Combined RAMS and LCC analysis in railway and road transport infrastructures. In: *Proceedings of the 7th transport research arena TRA*
- Camille C, Mirza O, Senaratne S, Kirkland B, Clarke T (2022) Life cycle cost analysis of macro synthetic fibre reinforced concrete for railway sleeper applications. *Struct Infrastruct Eng* 20(3):1–15
- Doyle NF (1980) Railway track design: a review of current practice
- Esveld C (2001) *Modern railway track: MRT-productions Zaltbommel*
- Galar D, Sandborn P, Kumar U (2017) *Maintenance costs and life cycle cost analysis*. CRC Press, Boca Raton
- Kasraei A, Ali Zakeri J (2022) Maintenance decision support model for railway track geometry maintenance planning using cost, reliability, and availability factors: a case study. *Transp Res Rec* 2676(7):161–172
- Kobbacy KA, Murthy DP, Nicolai RP, Dekker R (2008) *Optimal maintenance of multi-component systems: a review*. Springer
- Larsson D (2004) A study of the track degradation process related to changes in railway traffic
- Lichtberger B (2011) *Track compendium*. PMC Media House, Hamburg
- Nissen A (2009) Development of life cycle cost model and analyses for railway switches and crossings. *Int J COMADEM* 12(2):10–19
- Patra AP, Söderholm P, Kumar U (2009) Uncertainty estimation in railway track life-cycle cost: a case study from Swedish National Rail Administration. *Proceedings of the Institution of Mechanical Engineers. Part F, J Rail Rapid Transit* 223(3):285–293. <https://doi.org/10.1243/09544097JRRT235>
- Rama D, Andrews JD (2016) Railway infrastructure asset management: the whole-system life cost analysis. *IET Intel Transport Syst* 10(1):58–64
- Said Rajab N (2019) *Application of RAMS and Life cycle cost analysis on maintenance: a case of railway signaling systems*. Thesis in MSc. Railway Engineering, Addis Ababa University
- Sárik V (2018) *Decision-making model for track system of high-speed rail lines: Ballasted track, ballastless track or both?* Thesis, School of Architecture and the Built Environment (ABE), Civil and Architectural Engineering, KTH
- Sasidharan M, Burrow MPN, Ghataora GS (2020) A whole life cycle approach under uncertainty for economically justifiable ballasted railway track maintenance. *Res Transp Econ* 80:100815
- Sato Y (1995) Japanese studies on deterioration of ballasted track. *Veh Syst Dyn* 24:197–208
- Senaratne S, Mirza O, Dekruif T, Camille C (2020) Life cycle cost analysis of alternative railway track support material: a case study of the Sydney harbour bridge. *J Clean Prod* 276:124258
- Shang Y, van Martine dB, Amy dM, Wolfert ARM((2020) Reliability-based life cycle costing analysis for embedded rails in level crossings. *Proc Inst Mech Eng Part F J Rail Rapid Transit* 234(8):821–833
- Stenström C, Norrbin P, Parida A, Kumar U (2016) Preventive and corrective maintenance: cost comparison and cost–benefit analysis. *Struct Infrastruct Eng* 12(5):603–617. <https://doi.org/10.1080/15732479.2015.1032983>
- Thompson S, King C, Rodwell J, Rayburg S, Neave M (2022) Life cycle cost and assessment of alternative railway sleeper materials. *Sustainability* 14(14):8814

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.