RENEWAL MANAGEMENT FRAMEWORK FOR URBAN RAIL TRANSIT ASSETS

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Abstract. Decision-making surrounding asset renewal is essential for the efficient use of renewal resources and safe operation of urban rail transit. In this study, major problems in the current management of urban rail industries in countries with the same problems as those in China were analysed, and in response, a renewal management framework based on service life estimation was proposed to provide adequate decision-making support for urban rail transit assets. In this framework, the cumulative failure frequency of an asset is used to indicate its health condition, and considering the uncertainties and heterogeneities in the deterioration process of assets, a Poisson–Weibull process model-based methodology was developed to estimate the service and residual lives of each asset, which are then employed in analysing its renewal demand and renewal period. Finally, the model is validated through an empirical study of rail renewal in the Beijing Metro. Our evaluation demonstrates that the proposed framework can estimate each asset's service life accurately and can be used by asset management personnel to establish reasonable renewal plans and provide decision-making support for a scientifically informed resource allocation, thus mitigating major problems in current management practices.

Keywords: urban rail transit, China, asset renewal, Poisson–Weibull process, service life, residual life.

Introduction

Urban rail transit is one of the most effective ways of meeting the public's travel needs and alleviating urban traffic congestion, and governments in many countries and regions have made significant investments to develop it. In many cities, such as London, Paris, New York, and Tokyo, of developed countries, urban rail transit has been operating for many years. Further, in many cities of developing countries, it has been developing rapidly. For example, 30 cities in mainland China were successfully served by urban rail transit on main lines in 2016, with a total of 133 lines and 4152.8 km of operations mileage (CAM 2017). To modernise the inventory and sustain safety and operability, the assets of urban rail transit require continuous renewal (Rashedi, Hegazy 2015). However, progressively expanding assets and continuously increasing working hours not only quickly increase renewal costs, creating acute financial pressure for the local government (Zhang, Han 2011), but also pose a tough challenge for asset managers to optimally allot limited renewal resources (Chen, Ng 2007). Therefore, determining appropriate renewal actions is of great significance in ensuring safe operation while effectively controlling asset management expenses.

1. Background

1.1. Asset renewal management in urban rail industries

In many countries, such as China, design working life and health condition are the 2 major bases of managing asset renewal in urban rail industries (Scarf *et al.* 2007; Scarf, Hartman 2008; DB 11/T718:2016):

- *Asset renewal management based on design working life*. When an asset reaches the end of its design working life, it should be renewed; if instead it fails before reaching the end of its design working life, maintenance should be performed to sustain the asset's operability. The relevant design or management standards (IEC 62278:2002; GB 50490:2009;

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GB 50157:2013; DB 11/995:2013; ISO 2394:2015; DB 11/T718:2016) and asset suppliers are the main source of design working life. However, the service processes of assets are influenced by many heterogeneous factors, resulting in the uncertainty and heterogeneity of deterioration processes of different assets (Durango-Cohen, Madanat 2008); thus, the actual service lives of assets may differ from their design lives, and the actual service lives of assets of the same type in diverse operating environments can vary. Asset renewal management based on the design working life ignores uncertainty and heterogeneity in deterioration. As such, resource waste may easily be caused by unnecessarily replacing an asset that has reached the end of its design life but can remain in service; conversely, hidden safety risks may result from failure to replace an asset that has not reached the end of its design life but cannot remain in service (Zhang, Han 2011);

– *Asset renewal management based on health condition.* When failures occur frequently in an asset before the end of its design working life, a manager should organise experts to evaluate whether the asset's health condition meets safety requirements by using its inspection and maintenance records, then make a qualitative renewal decision (DB 11/T718:2016). However, because of the scale of assets, this method is inefficient in operations requiring significant time and funds, and may add to the workload of asset managers and reduce management efficiency (Li, Wang 2012).

The aforementioned problems in asset renewal management for urban rail transit hinder asset managers' ability to renew assets scientifically and rationally, and may lead to wasted resources or potential danger.

1.2. Literature review

Many models have been developed to support infrastructural asset renewal decisions. Some researchers have proposed that asset renewal should be decided based on a condition, which is usually represented by discrete ratings or states. For example, Mishalani and Madanat (2002) divided concrete bridge deck condition into ten ratings, characterised its deterioration, and predicted its future condition state by using a time-based stochastic duration model to support renewal decision making. Zambon *et al.* (2017) also examined bridge decks and used stochastic prediction, including Markov chain, Markov process, and Gamma process models, to predict a bridge deck condition (as discretised into six ratings); these ratings determined whether the bridge deck needed to be renewed. Baik *et al.* (2006) modelled the deterioration of sewer pipe by using a Markov chain model in which the pipe condition was represented by five discrete states and the transition probabilities between the states were estimated using an ordered *probit* model-based methodology for developing appropriate proactive maintenance and renewal strategies.

Han *et al.* (2014) classified the highway pavement condition into five states by using three performance indicators: cracking, rutting, and the international roughness index. Pavement deterioration was characterised using a Markov hazard model and Bayesian estimation. Andrade and Teixeira (2013) presented a hierarchical Bayesian model to predict rail track geometry degradation, which was quantified in terms of longitudinal-level defects, and thus guided planning maintenance and renewal actions.

Researchers have optimised renewal decisions by considering not only asset condition but also management costs. Durango-Cohen and Madanat (2002) presented two optimisation models for maintenance and renewal decisions regarding infrastructure assets over a finite planning horizon. One model integrated the Markov decision process formulation and a Bayesian approach under uncertain asset deterioration rates, while the other integrated latent Markov decision process formulation and a quasi-Bayesian approach under performance model uncertainty (Durango-Cohen, Madanat 2008). Caetano and Teixeira (2013, 2016) proposed two multi-objective optimisation models based on the Non-Sorting Genetic Algorithm 2 (NSGA2) for planning railway ballast, rail, and sleeper renewal operations by separately considering the track Life Cycle Cost (LCC)-unavailability trade-off and LCC-reliability trade-off. Rashedi, Hegazy (2015, 2016) and Hegazy, Rashedi (2013) used genetic algorithms, an advanced modelling tool (GAMS/CPLEX), and system dynamics to handle capital renewal optimisation problems for network-level infrastructure assets in terms of condition and LCC. Barone and Frangopol (2014) developed four bi-objective approaches to optimise the life-cycle maintenance and renewal plans of deteriorating structures by considering cost and four performance indicators: reliability, risk, availability, and hazard.

Other studies focused on estimating an asset's service life to determine its renewal period. Aoki *et al.* (2007) and Kobayashi *et al.* (2010) verified the efficacy of applying a Weibull distribution function to empirically estimate the service lives of tunnel reflectors, and using binary and multiple condition states to describe the deterioration process. In addition, Zakeri and Shahriari (2012) developed a time-based probabilistic discrete-state deterioration model by using a Weibull distribution to analyse the distribution of the duration over which a rail wear degrades to specified states. Kobayashi *et al.* (2012) proposed a deterioration forecasting model for highway pavement to estimate its service life and provide renewal decision-making support; this model expressed the deterioration speed in two or more condition states in conjunction with elapsed time and followed an exponential distribution function. Bai *et al.* (2015) presented an approach utilizing a Markov stochastic process to analyse the life expectancy of railway track irregularities, in which deterioration states were described through a track quality index and discretised into four ranks, and deterioration processes were characterised using an exponential hazard model.

1.3. Objectives of current paper

Although numerous studies have examined asset renewal, it is still not well managed in the urban rail industries of many countries, such as China (Liu *et al.* 2011). In response to the existing problems pointed out earlier, this paper proposes a renewal management framework based on service life estimation to provide decision-making support for the assets of urban rail transit. In the proposed framework, the cumulative failure frequency of an asset is selected as its health condition indicator. Furthermore, considering the uncertainties and heterogeneities in the deterioration process of assets, a Poisson–Weibull process model-based methodology was developed to estimate the service and residual lives of each asset for analysing its renewal demand and renewal period based on its inspection records.

2. Research methodology

2.1. Model framework

Figure 1 shows the proposed renewal management framework based on service life estimation. Compared with existing management methods analysed in Section 1.1, the proposed model provides several improvements:
- each single asset is regarded as a unit, the renewal demand and period of which are analysed individually, considering the uncertainty and heterogeneity in deterioration;
- asset health, as evaluated by cumulative failure frequency, is selected as the basis of asset renewal, considering the actual operating condition;
- a Poisson–Weibull process model-based methodology is developed to estimate the service life of each asset, which can then be used to analyse the renewal demand and renewal period quantitatively, and guide planning appropriate renewal action.
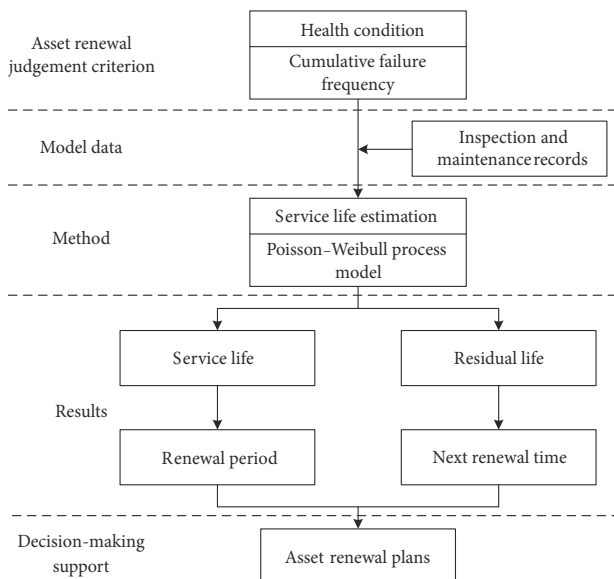

Figure 1. Proposed renewal management framework
for urban rail transit assets

2.2. Model for estimating service life

Given that infrastructure assets deteriorate naturally with time and the occurrence of various failures in their service lives (Mishalani, Gong 2009), in this study, the cumulative failure frequency of an asset was selected to reflect its health condition; an asset should be renewed when N failures have occurred. Among the diverse types of assets, the thresholds for N are inconsistent, and these values should be based on individual management requirements.

For asset k $\left(k=1, 2, ..., K\right)$, T_0^k represents the initial time at which it is put into use, and T_1^k, T_2^k, T_3^k, ..., T_N^k represents its N $\left(N \geq 1\right)$ failures. Hence, time interval X_i^k between two successive failures can be expressed as:

$$X_i^k = T_i^k - T_{i-1}^k, \, i = 1, 2, 3, ..., N, \tag{1}$$

where: $N^k\left(t\right)$ represents the cumulative failure frequency of interval $\left(0, t\right]$; thus, $N^k\left(0\right) = 0$. In general, cumulative failure frequencies of two disjoint intervals are independent (Cao, Cheng 2012). As a result of this stipulation, the authors assume that $N^k\left(t\right)$ has independent increments, that is, $N^k\left(b_i\right) - N^k\left(a_i\right)$ of disjoint intervals $\left(a_i, b_i\right]$, $\left(i = 1, 2, ..., n\right)$ with arbitrary n are independent. For any $0 \leq t < s$, the cumulative failure frequency i of interval $\left(t, s\right]$ corresponds to a Poisson distribution with parameter $\Lambda(t, s)$, and can be expressed as:

$$P\left(N^k\left(s\right) - N^k\left(t\right) = i\right) = \frac{\left(\Lambda^k\left(t, s\right)\right)^i}{i!} \cdot \exp\left(-\Lambda^k\left(t, s\right)\right), \tag{2}$$

where: $\Lambda^k\left(t, s\right)$ is given by the following equation:

$$\Lambda^k\left(t, s\right) = \int_t^s \left(\varphi^k\left(\mu\right)\right)d\mu, \tag{3}$$

in which $\varphi^k\left(t\right)$ is a non-negative function representing the hazard rate of asset k at time t. A Weibull hazard rate function is used to represent $\varphi^k\left(t\right)$ through the following equation:

$$\varphi^k\left(t\right) = \lambda^k \cdot \beta^k \cdot t^{\beta^k - 1}, \, t \geq 0, \, \lambda^k, \beta^k > 0. \tag{4}$$

2.2.1. Calculation of service life

The probability distribution density function for the service life of asset k can be expressed as:

$$f^k\left(x\right) = \frac{\left(\int_0^x \left(\lambda^k \cdot \beta^k \cdot u^{\beta^k - 1}\right)d\mu\right)^{N-1}}{\left(N-1\right)!} \lambda^k \cdot \beta^k \cdot x^{\beta^k - 1} \times$$

$$\exp\left(-\int_0^x \left(\lambda^k \cdot \beta^k \cdot u^{\beta^k - 1}\right)d\mu\right), \tag{5}$$

where: x is the service life of asset k. The service life $AL^k\left(x\right)$ is then expressed by:

$$AL^k\left(x\right) = \int_0^\infty \left(x \cdot f^k\left(x\right)\right)dx. \tag{6}$$

An asset's renewal period can be determined based on its service life.

2.2.2. Calculation of residual life

By assuming j ($0 \le j < N$) failures occurred prior to time t, i.e., $N^k(t) = j$, the probability distribution density function for the residual service life of asset k can be expressed as:

$$f^k(s) = \frac{\left(\int_t^{t+s}\left(\lambda^k \cdot \beta^k \cdot u^{\beta^k-1}\right)d\mu\right)^{N-j-1}}{(N-j-1)!} \times$$
$$\lambda^k \cdot \beta^k(t+s)^{\beta^k-1} \cdot \exp\left(-\int_t^{t+s}\left(\lambda^k \cdot \beta^k \cdot u^{\beta^k-1}\right)d\mu\right), \quad (7)$$

where: s is the residual service life of asset k. The expected residual life $RL^k(s)$ is then expressed by:

$$RL^k(s) = \int_0^\infty \left(s \cdot f^k(s)\right)ds. \quad (8)$$

Based on the residual life calculation, the next period at which the asset should be renewed can be determined.

2.2.3. Parameter estimation

Parameters λ^k and β^k in Equations (4)–(8) must be estimated and are variable between different assets owing to the uncertainties and heterogeneities in their deterioration process. These values can be determined using maximum likelihood estimation based on each asset's historical inspection data. If n failures occurred between the initial time and time t, $0 \le T_1^k \le \cdots \le T_n^k \le t$, then the joint probability density of $T_1^k, \ldots, T_n^k$ can be written as:

$$f\left(T_1^k, \ldots, T_n^k\right) = \exp\left(-\int_0^{T_n^k}\left(\lambda^k \cdot \beta^k\left(T_n^k\right)^{\beta^k-1}\right)d\mu\right) \times$$
$$\prod_{i=1}^n\left(\lambda^k \cdot \beta^k\left(T_i^k\right)^{\beta^k-1}\right). \quad (9)$$

The values of parameters λ^k and β^k can be obtained from $\dfrac{\partial f\left(T_1^k, \ldots, T_n^k\right)}{\partial \lambda^k} = 0$ and $\dfrac{\partial f\left(T_1^k, \ldots, T_n^k\right)}{\partial \beta^k} = 0$ expressed by Equations (10) and (11), respectively:

$$\hat{\beta}^k = \frac{n}{\sum_{i=1}^n \ln\dfrac{t}{T_i^k}}; \quad (10)$$

$$\hat{\lambda}^k = \frac{n}{t^{\hat{\beta}^k}}. \quad (11)$$

3. Empirical analysis

Rail is an important urban rail transit asset. Hence, an empirical analysis of rail renewal in the Beijing Metro was used to verify the proposed method's applicability.

3.1. Overview

In China, rail transit management departments generally refer to the replacement of rail segments longer and shorter than 1000 m as renewal and maintenance, respectively (DB 11/T718:2016). To reduce the impact of uncertainty and heterogeneity in rail deterioration, continuous rails on a line of track are divided into segments of 1000 m; each segment is regarded as an individual asset for analysis of renewal demand and renewal period. A schematic of the division of rail segments is shown in Figure 2.

The health condition of a rail is most often indicated by the state of rail defects (such as shelling, fatigue cracks, oval flaws, and wear). In China, rail defect evolution is divided into the following four ranks: small, aggravated, severe, and broken rail defects (The Railway Ministry… 2010) based on wear volumes or fatigue defects. The Beijing Metro track maintenance rules (QB(J)/BDY(A)XL 003:2009) stipulate that severely defective and broken rails must be replaced in a timely manner. The rules of railway track maintenance (The Railway Ministry… 2010) state that rail renewal should be scheduled when the concentration of average cumulative severe and broken rail defects is 2…4 defects per kilometre.

As a result of the above stipulation, severe and broken rail defects were regarded as failures in this study, and the health condition of a rail segment was quantified by the number of cumulative severe and broken rail defects. In the Beijing Metro, if the number of cumulative severe and broken rail defects in a rail segment is equal to or greater than three, the rail segment must be renewed, i.e., all rails along that segment must be replaced. The standards for severe rail defects in the Beijing Metro are shown in Tables 1 and 2, and the standards for broken rail defects are shown in Table 3 (QB(J)/BDY(A)XL 003:2009).
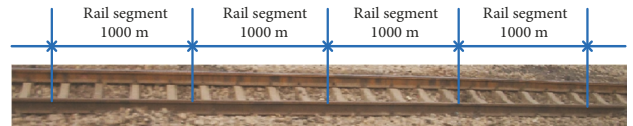
Figure 2. Schematic of the division of rail segments

Table 1. Standards for severe rail defects in the Beijing Metro

Indicators	Physical description
Surface crack	surface cracks include bolt hole cracks, head longitudinal cracks, base cracks, etc.
Subsurface crack	subsurface cracks include over flaws, longitudinal vertical cracks, transverse cracks, etc.
Shelling	length ≥30 mm and depth ≥8 mm
Deformation	rail deformation includes plastic flow, tongue lipping, etc.
Rail end batter	≥5 mm
Corrosion	depth of edge of rail base ≤5 mm or depth of rail web ≤8 mm after cleaning
Rail wear	above the standard shown in Table 3

Table 2. Standards for severe rail wear defects
in the Beijing Metro

Type of rail [kg/m]	Vertical wear [mm]	Side wear [mm]
60	10	17
50	9	15
43	8	13

Table 3. Standards for broken rail defects
in the Beijing Metro

Indicators	Physical description
Cross-section	the cross-section has broken into two parts
Head crack	a crack has cut across the rail-head cross-section
Base crack	a crack has cut across the rail-base cross-section
Shelling	length ≥50 mm and depth ≥10 mm

3.2. Estimated service life

In this empirical analysis, 96 rail segments across four lines (Lines 1, 2, 10, and Yizhuang) in the Beijing Metro, in which severe or broken rail defects had occurred, were considered, as shown in Table 4.

Table 4. The 96 rail segments considered, from four lines
of the Beijing Metro

Line	Type of rail [kg]	Type of track	Average annual gross tonnage [Million Gross Tonnes (MGT)]	Number of rail segments
Line 1	50	jointless	38.14	15
Line 2	50	jointed	35.41	39
Line 10	60	jointless	36.54	25
Line Yizhuang	60	jointless	29.76	17

Based on the rail defect inspection data of these rail segments from January 2008 to March 2017, the values of λ^k and β^k for each rail segment were calculated using maximum likelihood estimation. Moreover, based on these estimated values, the service and residual lives of these rail segments were determined using the proposed method, as illustrated in Figures 3 and 4, respectively.

As shown in Figures 3 and 4, for the results calculated from the proposed method, both the service and residual lives for different rail segments are heterogeneous, which is consistent with the actual rail degradation. The deterioration of a rail segment is influenced by many factors, including spatial location factors (such as curves,
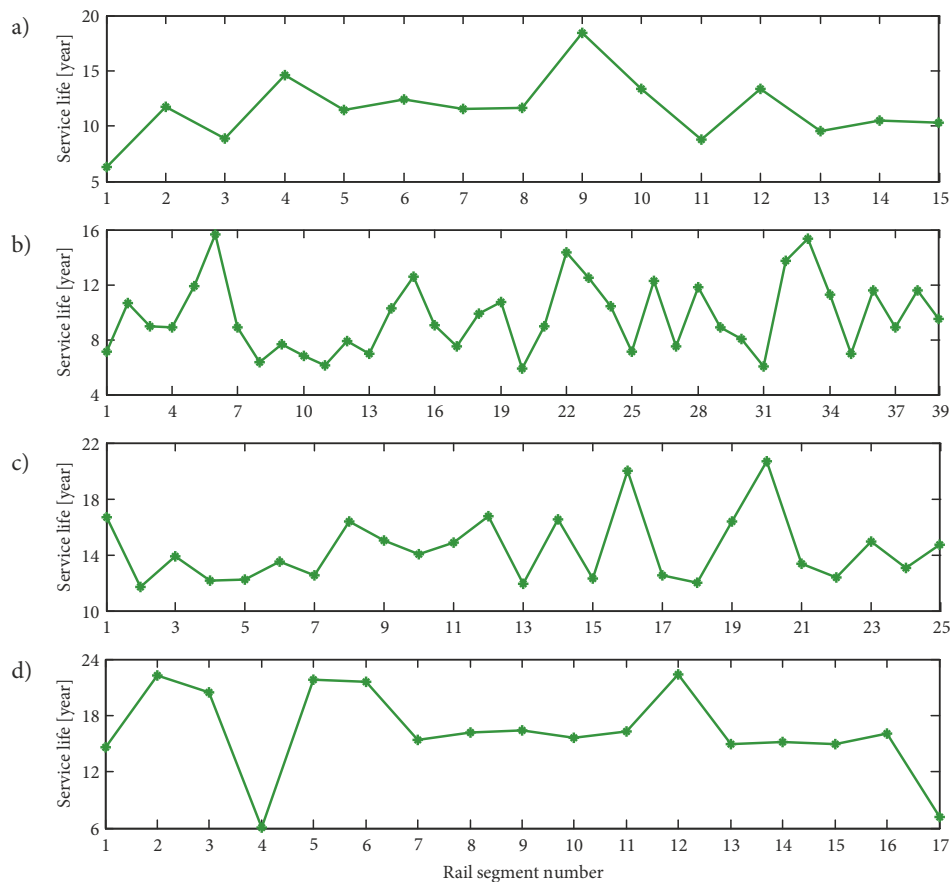

Figure 3. Estimated service lives of rail segments: a – rail segments of Line 1; b – rail segments of Line 2;
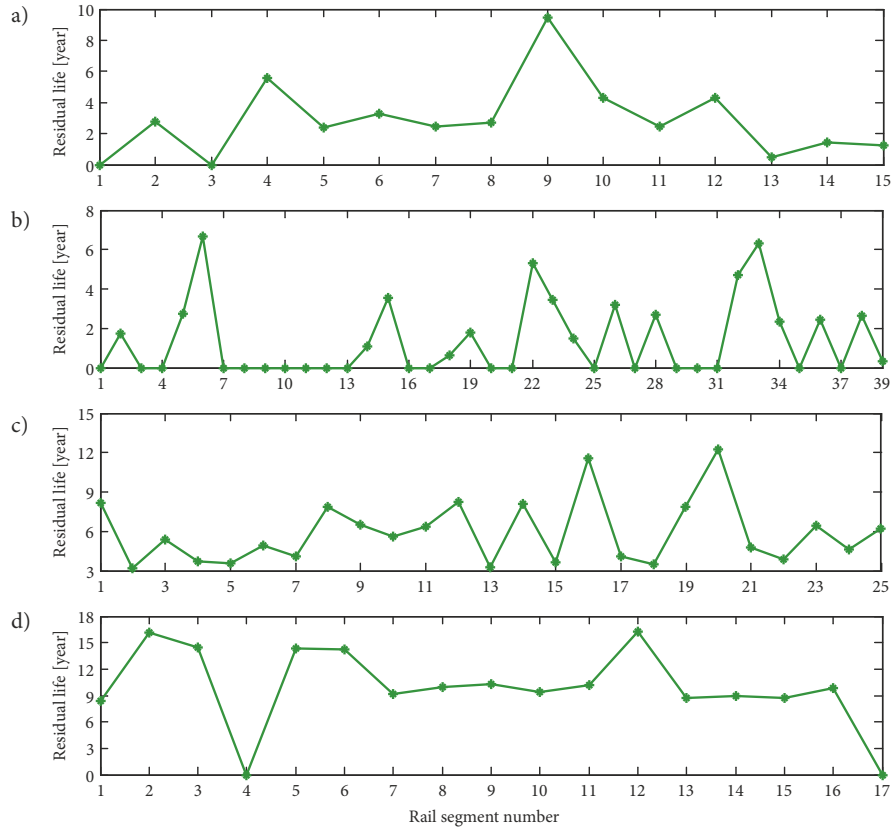c – rail segments of Line 10; d – rail segments of Line Yizhuang

Figure 4. Estimated residual lives of rail segments: a – rail segments of Line 1; b – rail segments of Line 2;
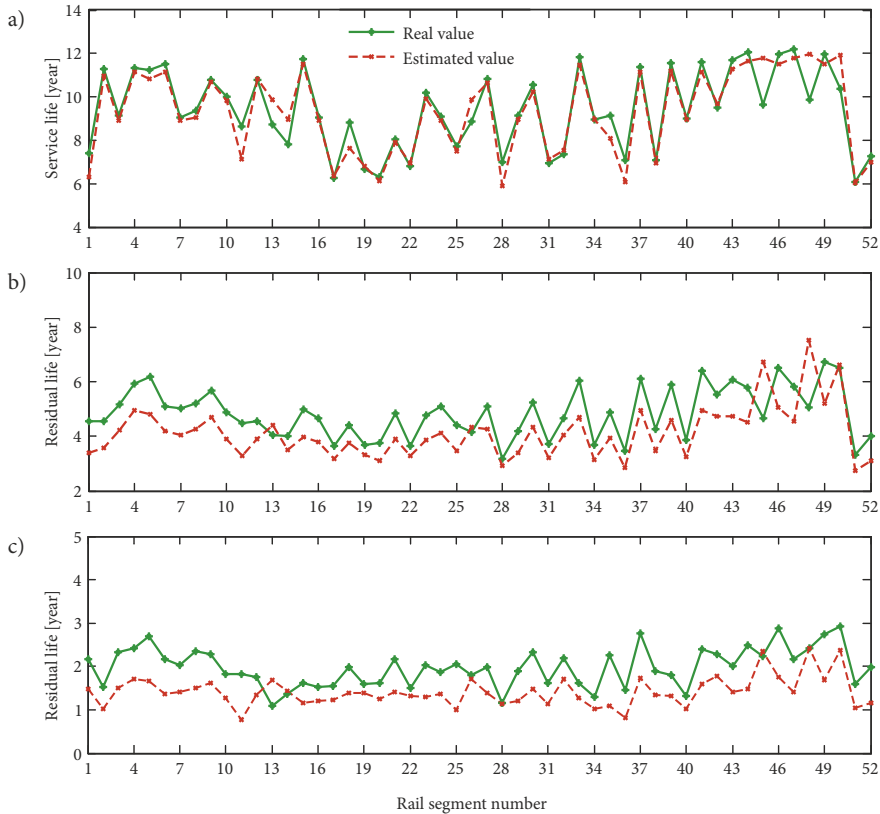c – rail segments of Line 10; d – rail segments of Line Yizhuang

Figure 5. Comparison of estimated and true values of the service and residual lifetimes of the 52 selected rail segments:
a – service life; b – residual life when one severe or broken rail defect occurred;
c – residual life when two severe or broken rail defects occurred

grades, and bridge–subgrade/tunnel–subgrade transitions), transportation factors (such as the type of rolling stock, cumulative gross tonnage, and train traffic speed/weight), design factors (such as the rail material and type or track bed type), track-associated facility factors (such as track regularity, curve smoothness, and ballast condition), maintenance factors (such as maintenance period and activities), and natural factors (such as temperature and humidity). The deterioration of different rail segments in separate locations is affected by different heterogeneous factors occurring at different rates over different rail renewal periods (Bai *et al.* 2015). The proposed method accounts for the uncertainty and heterogeneity in asset deterioration. Compared with the actual track maps, the rail segments, for which the service lives are relatively short, are mostly located on sharp curves and their deterioration rates are faster under the influence of rail wear.

3.3. Estimation error analysis

To evaluate the accuracy of the proposed model, 52 rail segments, in which severe or broken rail defects occurred more than three times, were selected from the 96 rail segments. Moreover, the estimated values of their service and residual lifetimes at each occurrence of a severe or broken rail defect (the first two times) were compared with the actual values, as illustrated in Figure 5. In this study, the actual service life for each rail segment is the time span from the date when the rail is put into use to the date when three severe or broken rail defects occurred.

Table 5 lists the comparison of the average estimated and actual values for the service and residual lifetimes of the 52 selected rail segments.

The results in Figure 5 show that the variation tendencies of the estimated values for different rail segments for, both the service and residual lives are consistent with the actual values and most of the estimated values are less than the actual values. In addition, as shown in Table 5, the average estimated value is less than the average actual value. This indicates that the results estimated using the proposed model can assist asset managers in developing rail renewal plans in advance, allowing them to address potential safety risks in the railroad before development.

To further analyse the error of the estimation results, the estimation errors of service life ε_s, residual life when one severe or broken rail defect occurs ε_r^1, and residual life when two severe or broken rail defects occurred ε_r^2 were analysed. The results are illustrated in Figure 6 and Table 6.

The results given in Table 6 indicate the following:
- for ε_s, the average and median results are −0.11 and −0.20 years, respectively, and the first and third quartile results are −0.39 and 0.03 years, respectively; further, 76.92% of $|\varepsilon_s|$ were less than a year;
- for ε_r^1, the average and median results are −0.72 and −0.91 years, respectively, and the first and third quartile results are −0.98 and 0.58 years, respectively; in addition, 73.08% of $|\varepsilon_r^1|$ are less than a year;

Table 5. Comparison of the average estimated and actual values of 52 selected rail segments

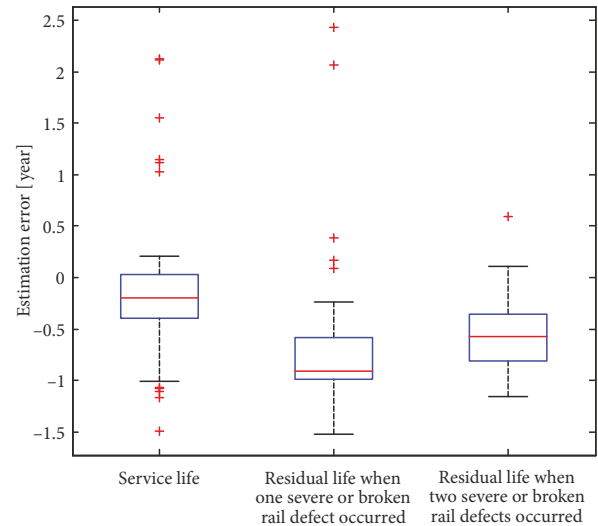| Item	Average estimated value [year]	Average actual value [year]
Service life	9.29	9.40
Residual life when one severe or broken rail defect occurred	4.13	4.85
Residual life when two severe or broken rail defects occurred	1.42	1.98

Figure 6. Box plot of estimation errors for service and residual lives

Table 6. Distributions of estimation errors

Item	Absolute value of estimation error ε [year]	Number of rail segments	Percentage [%]
Service life	$\|\varepsilon_s\| \leq 1$	40	76.92
	$1 < \|\varepsilon_s\| \leq 2$	10	19.23
	$\|\varepsilon_s\| > 2$	2	3.85
Residual service life when one severe or broken rail defect occurred	$\|\varepsilon_r^1\| \leq 1$	38	73.08
	$1 < \|\varepsilon_r^1\| \leq 2$	12	23.07
	$\|\varepsilon_r^1\| > 2$	2	3.85
Residual service life when two severe or broken rail defects occurred	$\|\varepsilon_r^2\| \leq 1$	44	84.62
	$1 < \|\varepsilon_r^2\| \leq 2$	8	15.38
	$\|\varepsilon_r^2\| > 2$	0	0.00

- for ε_r^2, the average and median results are −0.56 and −0.57 years, respectively, and the first and third quartile results are −0.80 and −0.37 years, respectively; in addition, 84.62% of $|\varepsilon_r^2|$ are less than a year.

Considering that the Beijing Metro track maintenance rules (QB(J)/BDY(A)XL 003:2009) require that rail renewal plans should be established 1…2 years in advance, the accuracy of the model proposed in this paper would allow management personnel to compose a reasonable renewal plan, providing sufficiently accurate estimation of the residual service life to support renewal decisions and a quantifiable, scientific basis for the allocation of resources.

3.4. Comparison with the existing renewal method

According to the current Beijing Metro track maintenance rules (QB(J)/BDY(A)XL 003:2009), the basis of rail renewal is its design working life, i.e., the accumulated gross tonnage, which is presented in Table 7. A comparison between the estimated service life values for the 52 selected rail segments obtained using the proposed method and accumulated gross tonnage and the actual values is shown in Figure 7.

The results presented in Figure 7 show the following:
– unlike the proposed method, the results calculated through the accumulated gross tonnage are consistent for rail segments on the same line and are heterogeneous for rail segments on different lines because of the similar accumulated gross tonnage of the rails on a given line; the determination of the service lives of rail segments through the accumulated gross tonnage disregards the uncertainties and heterogeneities in rail deterioration processes;

Table 7. Rail design working life of the Beijing Metro

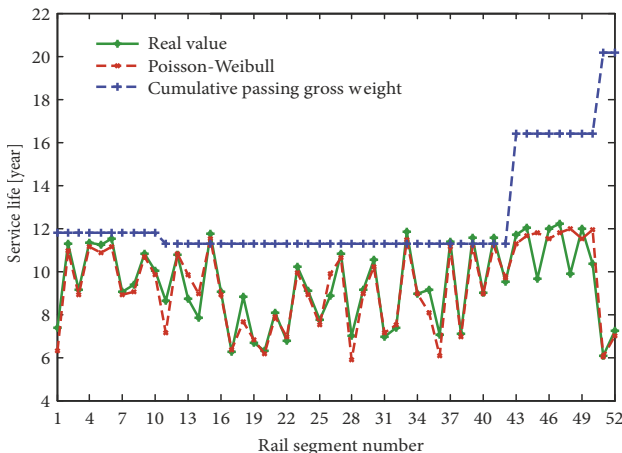| No.	Type of rail [kg/m]	Type of track	Accumulated gross tonnage [Million Gross Tonnes (MGT)]
1	60	jointless	600
2	60	jointed	500
3	50	jointless	450
4	50	jointed	400
5	43	jointed	150

Figure 7. Comparison between service lives of selected rail segments across methods

– the differences between the results calculated using the proposed method and the actual results for most of the rail segments examined in this study are smaller than those between the results calculated using the accumulated gross tonnage and actual results; this indicates that the proposed method is more effective than the accumulated gross tonnage method;
– the results calculated using the proposed method and the actual results for most of the rail segments are lower than the results calculated using the accumulated gross tonnage; this is because the selected rail segments in which severe or broken rail defects occurred more than three times are mostly located on sharp curves and their deterioration rates are faster under the influence of rail wear.

Consequently, managing rail renewal based on accumulated gross tonnage may lead to over-extended service of rails.

3.5. Discussion

In summary, the main advantages of the proposed model include the customized degradation rules and service life estimation model for each asset, considering the uncertainty and heterogeneity in deterioration. In addition, the estimated service life values of the various assets are more accurate, and the renewal demand and renewal period of each asset can be analysed quantitatively. Moreover, compared with the existing renewal method, the proposed method is more feasible and has higher efficiency. However, the application of the proposed method relies on detailed inspection and maintenance records for each asset. Based on the continued accumulation of these data, the estimation accuracy can be further improved.

Conclusions

Decision-making surrounding asset renewal is essential for the efficient use of renewal resources and the safe operation of urban rail transit. In this paper, the authors first analysed the asset renewal management methods for urban rail transit asset in countries with the same problems as China, that is, design working life and health condition are the major two bases of managing asset renewal. The main problems in the existing management methods were then summarized; these include the insufficient consideration of the uncertainty and heterogeneity in asset deterioration in the existing design-working-life-based renewal method and low efficiency and poor manoeuvrability of expert evaluation in the existing health-condition-based renewal method.

Secondly, in response to the existing problems, a renewal management framework based on the service life estimation was proposed to provide decision-making support for urban rail transit assets. In this framework, the cumulative failure frequency of an asset serves as its health condition indicator, and a Poisson–Weibull process model-based methodology was developed to estimate the ser-

vice and residual lives of each asset to analyse its renewal demand and renewal period quantitatively, considering the uncertainty and heterogeneity in the deterioration.

Finally, an empirical study of rail renewal was conducted in Beijing Metro to verify the effectiveness of the proposed method. In this case, continuous railway lines were divided into adjacent 1-km segments based on the actual management demand, and the service and residual lives of each rail segment were calculated using the proposed method based on historical rail inspection data from January 2008 to March 2017. Furthermore, the estimated values were compared with the actual values, and the estimation errors were analysed. The results demonstrated that the accuracy of the proposed model would allow management personnel to compose a reasonable renewal plan, providing a sufficient accurate estimation of the service life to support renewal decisions and a quantifiable, scientific basis for the allocation of resources. Further, a comparison was drawn between the estimated values obtained using the proposed method and accumulated gross tonnage, indicating that the proposed method avoids the main problems arising in the existing management methods, is more feasible, and has higher efficiency.

However, the application of the proposed method relies on detailed inspection and maintenance records for each asset. Based on the continued accumulation of these data, the estimation accuracy can be further improved. Several points that were not discussed in the current study may serve as topics for extending this study in the future:
– with so many kinds of urban rail transit assets, the threshold of the health condition indicator presented in this paper for each kind should be studied;
– the effects of heterogeneous factors on the deterioration processes of different assets, such as design factors and natural factors, should be examined.

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Disclosure statement

The authors declare that there are no conflicts of interest.

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