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Research Paper

A method of economic evaluation of noise mitigation measures in urban rail transit

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ABSTRACT

In addition to its many benefits, urban rail transit generates noise pollution that poses critical environmental and public health challenges. Traditional noise control strategies often rely on satisfying regulatory noise limits but do not take into account the social benefits of noise mitigation in the exposed areas. Moreover, conventional evaluation methods for railway transport infrastructure fail to provide a detailed analysis of the long-term socio-economic impact of noise reduction measures. This paper proposes a method for the economic evaluation of noise mitigation measures to enhance the sustainable development of urban rail transit, aiming to identify the most appropriate measures in terms of both cost efficiency and noise mitigation effectiveness. The main novelty lies in the combination of a single measure of life cycle cost (LCC) and monetized noise reduction to model the socio-economic impacts of the measures. The evaluation framework standardizes these impacts into measurable economic indicators, enabling direct comparisons between different measures. A case study involving a residential area adjacent to Beijing Subway Line 13 demonstrates the practical application of this approach. The cost-effectiveness of 4 m high noise barriers and rail grinding is analyzed and compared. Results show both measures have significant benefits: noise barriers incur higher initial costs but offer greater absolute economic benefits due to their superior noise reduction capabilities, and they are more suitable for densely populated areas, whereas rail grinding is recommended for extensive use in regular track maintenance due to its lower unit cost. The proposed evaluation method is verified by comparative analysis with existing methods. It provides a practical decision-making tool for urban rail noise abatement from the viewpoint of sustainability.

1 Introduction

With the rapid development of urban rail transit, there is increasing concern about railway vibration and environmental noise, which may have particularly severe impacts, including annoyance and potential damage to human health. Noise can cause irritability, sleeping problems, dizziness, and even heart disease, learning disabilities, and tinnitus (Tassi et al., 2013).

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According to the *China Noise Pollution Prevention and Control Report* (2023), noise nuisance accounted for 59.9% of all ecological and environmental pollution complaints and reports in 2022, ranking first among all environmental pollution factors in China. Among these, transport noise accounted for 4.3% (Ministry of Ecology and Environment of the People's Republic of China, 2023). In recent years, urban rail transit has become one of the most essential modes of transportation in mainland China. The total operational mileage reached 11 124 km, spreading across 116 lines. Large-scale construction and development of urban rail transit systems are still ongoing (Lu et al., 2025). Therefore, the regulation of noise control and pollution prevention has become necessary in the sustainable development of urban rail transit.

Various measures are commonly implemented to control noise in rail transit systems, including three main types: control of vibration and sound at source, which focuses on improving the properties of the vehicles and track structures to reduce noise generation; control in the propagation path, primarily achieved through noise barriers; and control at the receiver, such as improved sound insulation of windows. In practical railway engineering, their effectiveness is mainly assessed only by the technical indicator of the sound level, and hence, there is a lack of systematic assessment and decision-making programs. This approach has the following problems. (1) It leads to highly experience-dependent noise control modes, which generally aim only to adhere to the noise limits specified by standards and regulations. (2) Although many railway lines pass the environmental noise and vibration assessments in the planning phase, frequent noise complaints persist during operation. This shows that evaluating and understanding the noise impact on the population over the long term is needed. (3) As a kind of environmental pollution, railway noise generates social impacts, the quantification of which is not clear.

The economic technique of monetizing non-market goods as an externality provides an approach that can be used to quantify the social impacts of railway noise, which is beneficial to support the decisions on effective noise control. Various studies discuss evaluation methodologies and numerical results for the external valuation of noise; commonly used methods are the revealed preference (RP) and stated preference (SP) methods, categorized as direct methods. The European Union (EU) used the RP-based Hedonic Pricing (HP) techniques to evaluate the price depreciation in the noise-affected property market and quantified residents' willingness to pay (WTP) for lower noise based on the Noise Sensitive Depreciation Index (NSDI) (Navrud et al., 2006). Dekkers and van der Straaten (2009) investigated the effect of transport noise with multiple sources (including road, railway, and aircraft) on housing prices in an area around Amsterdam airport using the HP method. They concluded that a 1 dB (dB) noise reduction resulted in a total house price increase of 40 million Euros per year. Navrud (2002) summarized the road and aviation noise valuations obtained by the SP studies in France, Switzerland and Norway, expressed in the form of Euros (2001 prices) that each household was willing to pay per year for a reduction of 1 dB, with results ranging from €2 to €99 for road noise and €8 to €959 for aviation noise. Bellinger (2006) examined the residents' WTP for the elimination of train horn noise in a small town in the United States (U.S.) by the SP method, and estimated the increase in property values due to noise reduction by using regression analysis. In addition, a systematic overview of valuations of different transport noise sources is provided by Bristow et al. (2015) and Bruyn et al. (2018).

There are few studies, however, on noise valuation in China, and most of them focus on road noise. Li et al. (2009) estimated the WTP of road noise for a sample population in Hong Kong, China, using a discrete choice experiment and found that household income significantly influences an individual's WTP. The expected monthly WTP value per household for a 1 dB change increased from HK$5.0 at 55 dB(A) to HK$8.7 at 75 dB(A) for the higher income group, while it increased from HK$3.4 at 55 dB(A) to HK$5.9 at 75 dB(A) for the lower income group. Ma et al. (2021) later used the SP-based method to determine the value of road noise reduction in 12 residential areas in Tianjin, China, concluding that the mean WTP to eliminate noise annoyance of each household was CNY 162.64.

When the data required in the externality valuation process by the direct methods is not sufficiently available, an indirect method is adopted. The "benefits transfer" technique transfers the valuation estimates from an existing study to the target site, which could simplify the complex direct evaluation process, saving a lot of time and money. In order to improve the noise evaluation in the whole United Kingdom (UK), Nellthorp et al. (2007) transferred WTP from an established HP-derived Birmingham study to those in different places and years by adjusting the income, gross domestic product (GDP), inflation, and growth in the number of households. Xuan (2021) established a calculation model of noise externality for China's high-speed railways by transferring the transport-related noise cost in the EU to that in China.

The social and environmental impacts of the transport infrastructure, as non-monetary items, can also be economically evaluated by converting their externalities into financial terms using cost-benefit analysis (CBA), where life cycle cost (LCC) is generally adopted to take account of long-term financial expenditures (Browne and Ryan, 2011). Since these impacts can extend over a number of years, a discount rate is applied to convert the costs and benefits into present values, allowing for the aggregation of values from different years (Boardman et al., 2018). Ortega et al. (2018) applied CBA to evaluate the multiple economic impacts of the installation of under sleeper pads (USPs), assuming a discount rate of 3.5%. They concluded that USPs have proven benefits for all stakeholders although there was uncertainty and variability in the predictions. Armstrong et al. (2019) continued their CBA-based research on the economic effects of installing rail dampers and noise barriers. It was found that these two measures provided a much greater reduction of environmental noise than USPs, but with a much greater cost. A constant noise valuation of £20 per dB reduction was adopted in these studies without accounting for variations in noise reduction benefits across different initial noise levels. Moreover, LCC was not evaluated in the procedure.

An alternative method to evaluate the potential impacts of transport infrastructure is cost-effectiveness analysis (CEA), which aims at achieving a specific goal at the lowest possible cost without using externality monetization. To investigate the cost effectiveness of noise control measures for road noise and select the most appropriate ones, the Dutch evaluation method of CEA was proposed based on a system of so-called "reduction points" (representing the available budget for a range of noise control measures) and ''noise measure points'' (representing the costs of the noise control measures) (Faber and Lourens, 2015). Noise control measures are selected within the allocated budget of reduction points for a group of houses, prioritizing those with the highest total noise reduction. However, this method does not account for extra social benefits that arise from the noise reduction beyond the legal requirements (Peeters and van Blokland, 2018). CEA was also used to determine the most cost-effective height of a noise barrier for the road network in Denmark. This method adopted a score calculated based on the number of exposed dwellings and sound levels to quantify the noise impact on residential areas. However, for the calculation of cost-effectiveness, it evaluated only the construction costs of noise barriers without considering other associated expenditures (Conference of European Directors Roads, 2017). Additionally, CEA relies on the original evaluation units of dB for the noise reduction effect. There is no link between the noise reduction and the monetary cost, concealing the true economic impact.

The methods outlined above are useful tools in terms of measuring the potential impacts of transport projects, policies, or programmes (Browne and Ryan, 2011). However, they exhibit limitations when applied to the current purpose of effectively guiding practical decision-making on noise mitigation measures for a specific urban rail transit line or track section: CBA requires the monetization of all associated benefits and costs, which may vary for different measures; it thus introduces complexity and potential inconsistency in evaluating the impacts of various measures. On the other hand, CEA does not estimate the externalities in monetary terms, obscuring the economic trade-offs in the investment decision (Sartori et al., 2014; Browne and Ryan, 2011). These considerations prevent the two methods from providing a simple and direct selection process in terms of evaluating noise mitigation impact. It can also be seen from the previous work that LCC has not been included in the evaluation process of the noise mitigation measures, which means consistent information is not provided on the economic dimensions of sustainability, and cost-efficient strategies are not adopted (França et al., 2021). Moreover, the use of a constant noise valuation across different noise levels is a simplification in many studies. This neglects the variations in the noise impacts on the exposed population in practice (Ma et al., 2021; Nellthorp et al., 2007).

This study aims to provide a general framework to analyze the socio-economic impact of noise reduction measures in the long term for the sake of the sustainable development of urban rail transit when selecting the mitigation measures. A novel method is proposed to evaluate the economic impact of the noise control measures; it combines the LCC and the monetized noise reduction benefits derived from noise valuations, which enable the standardized economic quantification of various noise control measures with different technically useful lifetime and noise reduction performance, enabling a systematic assessment. The remainder of the paper is organized as follows: Section 2 introduces the proposed evaluation method. Specifically, the LCC of the measures and their noise reduction effect, including the classifications of population exposure, are standardized into monetary terms, which are then expressed as an appropriate index for direct comparison. In Section 3, an illustrative case study of Beijing Subway Line 13 is provided to demonstrate the applicability of the proposed method, with an assessment of the effects of rail grinding and 4 m-high vertical noise barriers at a specific residential area. Section 4 discusses the results of the case study, including a sensitivity analysis and comparative assessments with conventional methods. Finally, Section 5 summarizes the research conclusions.

2 Methodology

The method aims to analyze the costs of noise control measures in urban rail transit and their corresponding noise reduction performance in monetary terms, considering their whole-life performance; the optimal configuration is then proposed by balancing the two aspects. Key factors in the evaluation method are first defined, which are common necessities in estimating both the LCC and noise reduction benefits of different measures with various technical service life in a consistent time horizon. LCC is employed to capture all costs incurred throughout the entire lifespan of each measure. Meanwhile, noise valuation is carried out to monetize the noise mitigation effect from different initial sound levels. The noise reduction benefits are next obtained by multiplying the monetized noise reduction by the exposed population, classified and estimated in the study scope, which has been ignored in previous work. Finally, the LCC and monetized noise reduction benefits are integrated together as a framework to analyze the socio-economic impacts of noise mitigation measures, where the economic indicators are used to allow for a concise comparison of different measures. The detailed process of the method is shown in Fig. 1.

2.1 Key elements of the evaluation method

Noise mitigation measures vary in their technical lifespan. An appropriate appraisal period is hence essential to assess the economic viability of the measures in the long term. A period that is too short may fail to capture the full benefits of noise reduction, particularly if the benefits accrue gradually over time. Conversely, an excessively long period may introduce unnecessary uncertainties and overestimate the effectiveness. To ensure that all measures are adequately evaluated, the shortest technical service life of the options under consideration is adopted as the appraisal period, as recommended in (Nation Development and Reform Commission of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2006).

Certain measures will not be fully depreciated or exhausted at the end of the appraisal period. Measures with an operational lifetime extending beyond this appraisal period are therefore translated into their residual values, which are treated

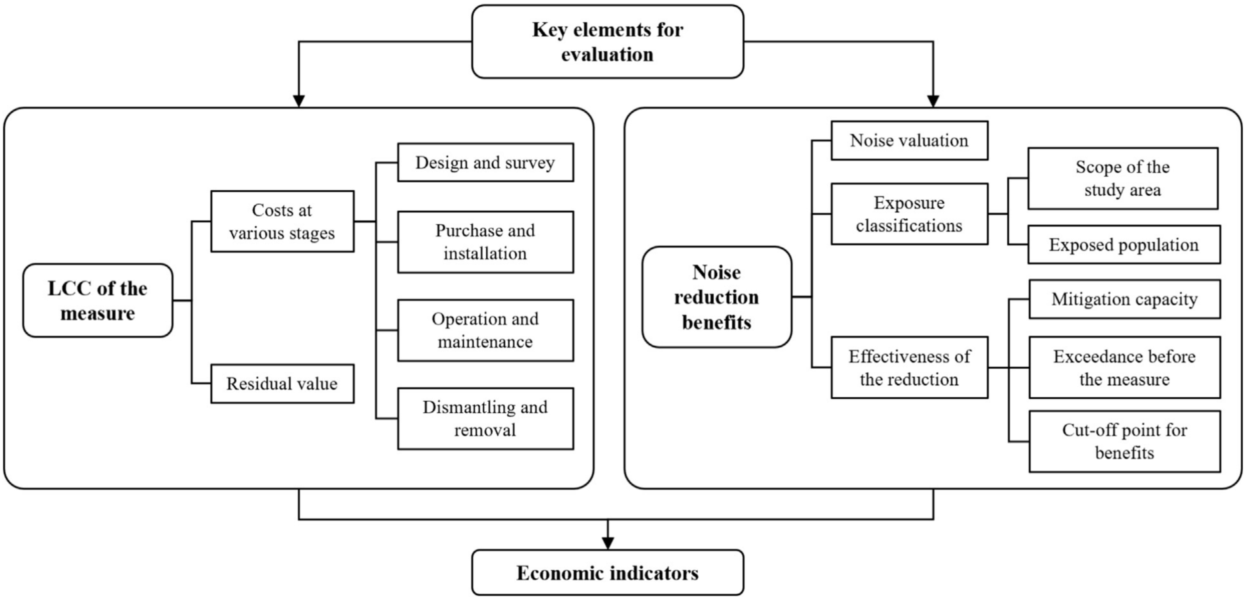


Fig. 1 Concept diagram of the evaluation method.

as cash inflows occurring at the end of the period for analysis, representing the capacity of the remaining service potential (Infrastructure Australia, 2022; O'Mahony, 2021). If a period equal to the economic lifetime of the asset is selected, the residual value will be zero or negligible (Sartori et al., 2014).

To ensure the impacts of the measures occurring in different years within the appraisal period have the same starting point for evaluation, the discounting approach is adopted to convert the benefits and costs to their present values (Boardman et al., 2018). The discount rate is uniformly determined and published by the national administrative authority. For urban rail transit projects with long benefit periods and significant forward benefits, the discount rate can be appropriately reduced, but no less than 6% in China (Nation Development and Reform Commission of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2006).

2.2 The LCC of the noise abatement measures

To integrate the costs of the noise abatement measures and thus achieve sustainable investment decisions, the LCC procedure is performed to take account of the costs from different phases in the appraisal period. The design and survey costs for renovation or new construction schemes, acquisition and construction costs of facilities and equipment, and operation and maintenance costs are included here. Additionally, the residual value at the end of the appraisal period must be considered, as the construction of rail transit infrastructure generates significant fixed assets with long economic lives. The present value of LCC for each measure is then calculated by discounting the costs from different phases and the residual value of these measures, as follows (Chen et al., 2010):

$$C_j = \sum_{t=1}^{T_1} \frac{C_{t1}}{(1+r)^t} + \sum_{t=T_1+1}^{T_1+T_2} \frac{C_{t2}}{(1+r)^t} + \sum_{t=T_1+T_2+1}^{T} \frac{C_{t3}}{(1+r)^t} + \frac{C_{t4}}{(1+r)^T} - \frac{R}{(1+r)^T}, \tag{1}$$

where C_j is the present value of the LCC of the measure j; t is the time index in years; T_1 is the number of years required for planning and designing the noise reduction measure; T_2 is the number of years for construction and installation; T is the length of the appraisal period; C_{t1}, C_{t2}, C_{t3},C_{t4} are the costs of designing and surveying, purchasing and installing, operating and maintaining, dismantling and disposing, respectively; R is the residual value of the project at the end of the appraisal period; and r is the discount rate.

2.3 The noise reduction benefits

Typically, better noise reduction performance is associated with higher costs, necessitating a trade-off to be balanced between them when formulating the noise reduction strategies. In the current work, this balance is achieved by comparing the economic investment, represented by the LCC, with the social benefits of the noise reduction. This subsection introduces the benefit assessment process of the noise mitigation effectiveness. Specifically, the noise valuation is first carried out to estimate the noise impact by converting the acoustical indicator into monetary units. Then, the exposed population within the studied area is categorized based on the initial noise levels, allowing for the evaluation of noise reduction benefits corresponding to different noise valuation categories. Finally, the total benefits at the target site are calculated by discounting.

2.3.1 Noise valuation

The external cost of noise is monetized to quantify the social benefits of noise reduction. The indirect transfer estimates from existing noise valuation research are adopted here as the valuation approach, in which available data from other countries or regions are used and adjusted for the application to the target study according to the local social and economic conditions. The noise valuations can then be estimated by applying the temporal and spatial factors to transfer the known noise valuation data to their values in the studied area. This effectively avoids the high costs and complexities associated with the valuation procedure required by the direct method.

The acoustical indicator proposed for noise valuation in the current study is the day-evening-night equivalent sound level, denoted as L_{den}, which provides a composite picture of the acoustic impacts at different times of the day and is commonly used in noise impact assessments (European Commission, 2002; Navrud, 2002). It is calculated as Eq. (2) (Brink et al., 2018; Navrud, 2002).

$$L_{\mathrm{den}} = 10 \cdot \lg\left(\frac{1}{24} \cdot \left(\sum_{H=7}^{18} 10^{0.1 \cdot L_{\mathrm{Aeq,H}}} + \sum_{H=19}^{22} 10^{0.1 \cdot \left(L_{\mathrm{Aeq,H}} + K_{\mathrm{e}}\right)} + \sum_{H=23}^{6} 10^{0.1 \cdot \left(L_{\mathrm{Aeq,H}} + K_{\mathrm{n}}\right)}\right)\right), \tag{2}$$

where H is the index for the hour of the day (e.g. $H = 0$ is the hour from 00:00 to 00:59:59); $L_{\mathrm{Aeq},H}$ is the averaged A-weighted yearly equivalent continuous sound pressure level within hour H; K_e and K_n are the penalty increments of 5 dB and 10 dB for the evening and night, respectively.

2.3.2 Exposure classifications

For practicality in the appraisal, the monetized noise values are simplified into different 5 dB(A) interval bands (Nellthorp et al., 2007). The exposed population influenced by the noise disturbance is counted within 200 m from the track centerline and classified into these 5 dB(A) interval bands (HJ 2.4–2021, 2021; Nellthorp et al., 2007). This use of a 200 m wide corridor for the evaluation refers to the most detailed evaluation procedures outlined in the *Technical Guidelines for Noise Impact Assessment* (HJ 2.4–2021, 2021). Since the environmental noise produced by the urban rail transit is expected to contribute significantly to the community noise levels affecting a large number of people, this scope can also ensure that the evaluation does not underestimate the extent and severity of the noise impact on the surrounding environment (GB 3096–2008, 2008).

2.3.3 Benefits of noise reduction

People's noise annoyance increases as the sound levels rise, hence not all sound pressure levels are included in noise valuation, and a threshold (termed the cut-off point for benefits) is defined for this purpose. When the sound level is below a certain threshold, it is considered to have minimal impact on daily life and work, and there is no need for additional expenditure to reduce the noise below this threshold value. Generally, a threshold of 50 dB(A) or 55 dB(A) is chosen for the noise reduction benefit calculation (Navrud, 2002; Nellthorp et al., 2007), assuming that noise below this level has few social costs and is not included.

It can thus be seen that the noise reduction benefits are achieved only when mitigation measures are implemented in the areas where the initial sound pressure level exceeds the defined threshold value. Accordingly, an effective noise reduction in each 5 dB(A) interval is determined by the threshold, the noise exceedance represented in terms of the 5 dB(A) interval and the mitigation capacity of the measure that varies at different sound receiver points. It is derived by

$$L_{\mathrm{eff},j} = \max\left(L_{\mathrm{after},j}, L_{\mathrm{threshold}}\right), \tag{3}$$

$$\bar{L}_{\mathrm{ij}} = \begin{cases} \frac{(L_{\mathrm{i2}}+L_{\mathrm{i1}})}{2} - L_{\mathrm{eff},j}, L_{\mathrm{eff},j} \leqslant L_{i1} \\ \frac{(L_{\mathrm{i2}}+L_{\mathrm{eff},j})}{2} - L_{\mathrm{eff},j}, L_{i1} < L_{\mathrm{eff},j} < L_{\mathrm{i2}} \\ 0, L_{\mathrm{eff},j} \geqslant L_{\mathrm{i2}} \end{cases}, \tag{4}$$

where i is the index of each noise interval from the low band to the high one; $L_{\mathrm{eff},j}$ is the minimum effective noise level achieved by measure j; $L_{\mathrm{after},j}$ is the noise level after applying the measure j; $L_{\mathrm{threshold}}$ is the threshold selected in the noise valuation process; $\bar{L}_{ij}$ is the noise reduction effectiveness of the measure j in the ith interval; L_{i1} and L_{i2} are the lower and upper limits of the ith interval, respectively. All quantities are expressed in dB(A).

Two example cases are shown in Fig. 2 to illustrate the evaluation method in Eqs. (3) and (4). In both cases, it is assumed that$L_{\mathrm{threshold}}$ = 55 dB(A) and the highest initial noise values fall within the range 60–65 dB(A). In Fig. 2(a), $L_{\mathrm{after,j}}$ =53 dB(A), while$L_{\mathrm{after,j}}$ = 57 dB(A) in Fig. 2(b). In each noise band, $\bar{L}_{ij}$ quantifies the noise reduction from the midpoint of the interval down to the effective noise level $L_{\mathrm{eff},j}$. The midpoint here is used as an approximate representative value of the noise band, simplifying the estimation process without significantly influencing accuracy. Note that $L_{\mathrm{after},j}$ varies depending on the noise measurement locations and should be analyzed on a case-by-case basis.

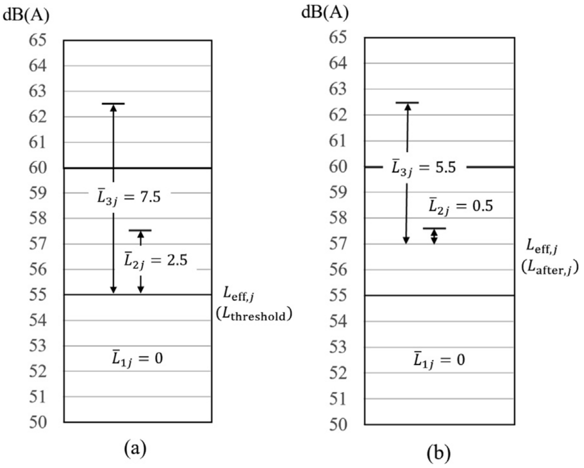


Fig. 2 Illustrative diagram of Eqs. (3) and (4).

The annual noise reduction benefit B_{jt} for the year t obtained by the measure j is derived and calculated as the aggregate of the monetized effective noise reduction across the entire exposed population within the studied area, which is given by:

$$B_{jt} = \sum_{i=1}^{k} p_{it} \cdot v_{it} \cdot \bar{L}_{ij}, \tag{5}$$

where k is the number of 5 dB(A) intervals; p_{it} is the exposed population in the ith interval for year t and v_{it} is the noise valuation of the ith interval for year t.

The total present value of the noise reduction benefits B_j obtained by the measure j is then calculated by discounting the annual benefit in the appraisal period, according to

$$B_j = \sum_{t=T_{1+}T_2+1}^{T} \frac{B_{jt}}{(1+r)^t}. \tag{6}$$

2.4 The economic performance indicators

The performance of different measures can be determined in the evaluation framework by using appropriate evaluation indicators after estimating their economic costs and social benefits. Two economic performance indicators widely used in transport project evaluations are economic net present value (ENPV) and benefit-cost ratio (BCR) (Nation Development and Reform Commission of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2006; Siciliano et al., 2016). The ENPV is the difference between the present value of the benefit and that of the cost, resulting in a total net benefit of a measure. The BCR is calculated as the ratio of these two values, which estimates the relative value of the average benefit generated per unit cost. They are expressed as Eqs. (7) and (8).

$$E_{\mathrm{ENPV}} = B_j - C_j, \tag{7}$$

$$B_{\mathrm{BCR}} = \frac{B_j}{C_j}, \tag{8}$$

where E_{ENPV} denotes ENPV and B_{BCR} denotes BCR.

By calculating and comparing the economic indicators of each noise mitigation measure under evaluation, the most socio-economically appropriate measure in the studied area can be identified, and the balance between social benefits and economic costs is also achieved. It can be seen that a measure is considered economically viable if ENPV > 0 or BCR > 1, with higher values indicating a higher priority for implementation.

3 Case study

This section presents a case study to illustrate the applicability of the proposed method, and then discusses the associated insights.

3.1 Case setup

An at-grade section of the Beijing Subway Line 13 is taken as the case study. Beijing Subway Line 13 is located in the northwest part of the subway network in Beijing with a total length of 40.74 km and a design speed of 80 km/h (China Academy of Railway Sciences Corporation Limited, 2019); its official operation began in 2003. This section has received frequent complaints due to severe environmental noise impacts, necessitating noise mitigation measures (Chen, 2017). The analysis will focus on mitigating the noise impact on the residents in two high-rise buildings between Guangximen Station and Liufang Station along a 180 m long section and within 200 m from the track centerline, where the noise has been measured at every two floors in the vertical direction. Referring to the noise measurement from (Chen, 2017), it is estimated that 28 people are exposed to 55–60 dB(A), 41 people to 60–65 dB(A), 387 people to 65–70 dB(A), and 17 people to 70–75 dB(A) at this location. An average household size of 2.62 persons is used to convert the residential units to population units (National Bureau of Statistics the People's Republic of China, 2021) required in the exposure classification process.

Two noise abatement measure options are considered here for the evaluation by way of example. These are vertical noise barriers with a height of 4 m and rail grinding, which represent a typical propagation path control measure and a source control measure for the environmental noise in urban rail transit. Although only these two representative noise control measures are considered for demonstration purposes, other commonly used mitigation techniques can also be analyzed within the proposed framework using their corresponding LCC and noise mitigation data. This could include dampers applied to the rail or wheel, enhanced fasteners and elastic pads, alternative heights of noise barrier, and noise insulation of buildings.

The appraisal period here is set as 25 years, corresponding to the lifetime of the noise barriers, with 2022 as the beginning year. The discount rate used is 6% as recommended in (Nation Development and Reform Commission of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2006). For simplification, the exposed population is assumed to remain constant over the 25-year appraisal period. Given that the noise reduction performance of both measures is assumed to remain stable throughout this period, and that any potential changes in population would have the same effect on the outcome for each measure, the relative comparison of their ultimate economic indicators would remain consistent.

The LCCs are determined using Eq. (1) by integrating the market prices of the measures in China and corresponding maintenance costs, the data for which are derived from the literature (Hemsworth, 2003; Feng et al., 2024), and listed in Table 1. For the noise barriers, the cost is the sum of all acquisition, maintenance, and removal costs, where the annual maintenance cost is simplified to correspond to 2% of the acquisition cost, and the dismantling cost to 10% (Hemsworth, 2003). The acquisition and maintenance costs of rail grinding are sourced from (Feng et al., 2024), based on costs associated with the GMC16A Rail Grinder used on Fuzhou Subway Line 1. Rail grinding is assumed to be implemented once per year to keep the noise within acceptable levels (Croft et al., 2023). Since the appraisal period is shorter than the 30-year lifetime of the grinding machine, a residual value of 16% of the equipment cost is included in the calculation (Florio and Vignetti, 2003; Xing, 2013). All costs are calculated based on the 180 m-length track section.

3.2 Noise valuation

The social impact of noise is monetized to quantify the economic benefits of noise abatement measures by using the noise valuation data. However, as there is no available data for rail transit in China, the benefit transfer method is used to calculate the unit noise costs in this case study. A cut-off threshold of 50 dB(A) is chosen based on the high background noise in China.

The EU's research on quantification of transport externalities started early and their data are relatively comprehensive. The original data are therefore derived from EU28 rail transit noise prices in 2016 (van Essen et al., 2019). Although economic and social conditions differ across regions, the fundamental mechanisms of railway noise generation, propagation, and impact are generally consistent across countries. Therefore, with appropriate adjustments, the values derived from EU studies provide a reasonable basis for estimation in the Chinese context (Xuan, 2021). Following the transfer steps proposed by (Nellthorp et al., 2007; Xuan, 2021), the original data of noise valuations are adjusted using three factors: purchasing power parity (PPP) based on GDP per capita, population density, and consumer price index (CPI). The first two facilitate the spatial transfer between the EU and China, while the last one accounts for temporal adjustments. The transfer factors and the noise valuations obtained by multiplying the original data by these factors are shown in Table 2 and Table 3. The calculated noise valuations in China will be the input data for the noise reduction benefits in the subsequent analyses.

3.3 Economic appraisal of the noise reduction

With the LCCs of the noise mitigation measures and the noise valuation per unit, the noise reduction benefits and the economic indicators in the study area can be calculated by using Eqs. (3)–(6), (8) and (9). Based on the previous noise reduction performance of the two measures, their noise abatement effectiveness in the study area is estimated as follows: noise barriers with a height of 4 m can achieve a noise reduction of 5–10 dB(A), while rail grinding can achieve a noise reduction of 0–5 dB(A) (Peeters and van Blokland, 2018; Scossa-Romano and Oertli, 2012; Tumavičė et al., 2016). These ranges of noise reduction are adopted here for the two measures to provide a reasonable, approximate assessment. A more accurate assessment could be provided by using more refined estimates of the noise mitigation effect; nevertheless, these 5 dB(A) ranges are

Table 1
LCCs of 4 m-high noise barriers and rail grinding.

Noise mitigation measure	Acquisition cost / CNY	Maintenance cost/ CNY	Removal cost / CNY	Residual value/ CNY	Present value of costs (PVC) / CNY
Noise barriers	720 000	14 000	72 000	–	860 000
Rail grinding	135 000	13 000	–	22 000	280 000

Table 2
Transfer factors between the EU28 and China.

Item	GDP per capita, PPP (World Bank, 2024a)/ current international USD	Population density (World Bank, 2024b)/(people·km^{-2})	Exchange rate in 2016 (China Foreign Exchange Trade System, 2016)	Transfer between 2016 and 2022	CPI (2010 = 100) (World Bank, 2024c)
EU28	40 552	111.5	–	2016	117.2
China	13 882	147.8	–	2022	131.9
Factor	0.34	1.33	7.31	Factor	1.13

Table 3
Original and transferred noise valuations.

L_{den}/(dB(A))	Original value in EU28(2016 price) (van Essen et al., 2019)/(EUR·dB^{-1}·person^{-1}·year^{-1})	Data transferred to China (2022 price)/ (CNY·dB^{-1}·person^{-1}·year^{-1})
50–55	17	63
55–60	32	119
60–65	34	127
65–70	63	235
70–75	67	250
≥75	72	269

selected here for compatibility with the 5 dB(A) ranges of the noise exposure data. The economic appraisal indicators for the two measures are presented in Table 4 and Table 5, respectively.

It can be seen that both mitigation measures exhibit socio-economic viability, with ENPV > 0 and BCR > 1, outperforming the ‘Do Nothing’ scenario. Noise barriers generate significant absolute benefits and are thus proven to be economically attractive measures. Despite their high costs, reflected by the PVC, these expenses are offset by better noise reduction performance, resulting in a higher ENPV. In contrast, rail grinding achieves a higher BCR due to lower unit costs but yields a significantly lower ENPV owing to its limited noise reduction capacity. These results suggest the great potential social benefits of implementing environmental noise mitigation measures in urban rail transit.

Although rail grinding has shown lower benefits in this case study and other related work (Hemsworth, 2003), this measure is crucial for the regular management of track maintenance. In addition to noise reduction, regular rail grinding improves wheel-rail profiles, extends rail life and reduces the vibration in the vehicle (Wang, 2020). These are the benefits that noise barriers cannot provide. However, the proposed method focuses on the mitigation of environmental noise, so these additional advantages of rail grinding have not been included in the quantification in the case study.

Table 4
Noise reduction benefit and economic indicators of noise barriers.

L_{den}/(dB(A))	Exposed population	Present value of benefits (PVB) in each interval/CNY	PVB/CNY	Present value of costs (PVC)/ CNY	ENPV/CNY	BCR
55–60	28	300 000	9 210 000	860 000	8 350 000	10.69
60–65	41	460 000				
65–70	387	8 080 000				
70–75	17	380 000				

Table 5
Noise reduction benefit and economic indicators of rail grinding.

L_{den}/(dB(A))	Exposed population	PVB in each interval/CNY	PVB/CNY	PVC/CNY	ENPV/CNY	BCR
55–60	28	100 000	3 070 000	280 000	2 790 000	11.12
60–65	41	150 000				
65–70	387	2 690 000				
70–75	17	130 000				

Alternative mitigation techniques can also be analyzed within the proposed framework. Moreover, a combination of multiple noise mitigation measures can also be considered, which typically has a better performance than single measures, especially where track treatment and noise barriers are combined (Zhang et al., 2021; Luo et al., 2023). This mixed approach can reduce the required heights of barriers, thereby lowering total costs and enhancing the cost-effectiveness (Royal Haskoning DHV, 2013).

4 Results and discussion

4.1 Sensitivity analysis

A single-factor sensitivity analysis is conducted to identify the influence of the underlying uncertainty in parameters on the findings and assess the robustness of the evaluation. The variables considered in the sensitivity analysis are the discount rate, noise valuations, and acquisition cost, which can vary depending on the data sources used. Each variable was adjusted by up to ±20% with 5% increments while all other variables were kept constant. The BCR and ENPV calculated for the analysis are presented in Fig. 3. Sensitivity coefficients for the different variables at the maximum magnitude of change (±20%) are also calculated and listed in Table 6 to show the sensitivity of the economic indicators to the different factors. Here, the sensitivity coefficient S_{AF} is adopted, and its formula is given as follows (Nation Development and Reform Commission of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2006):

$$S_{AF} = \frac{\Delta A/A}{\Delta F/F}, \tag{9}$$

where S_{AF} is the sensitivity coefficient; $\Delta F/F$ is the relative change of the variable F; $\Delta A/A$ is the relative change of the evaluation indicator A when F changes by ΔF. A positive sensitivity coefficient indicates that the evaluation indicator changes in the same direction as the variable, whereas a negative value indicates that it changes in the opposite direction. Parameters with larger values of $|S_{AF}|$ are more sensitive.

It can be seen from Fig. 3 and Table 6 that the discount rate and acquisition costs are negatively correlated with the two economic indicators. Conversely, noise valuations are positively correlated with these economic indicators. Noise barriers are more sensitive to all the variables analyzed compared with rail grinding. This is explained by the differences in the scale of benefits and the components of costs of the two measures.

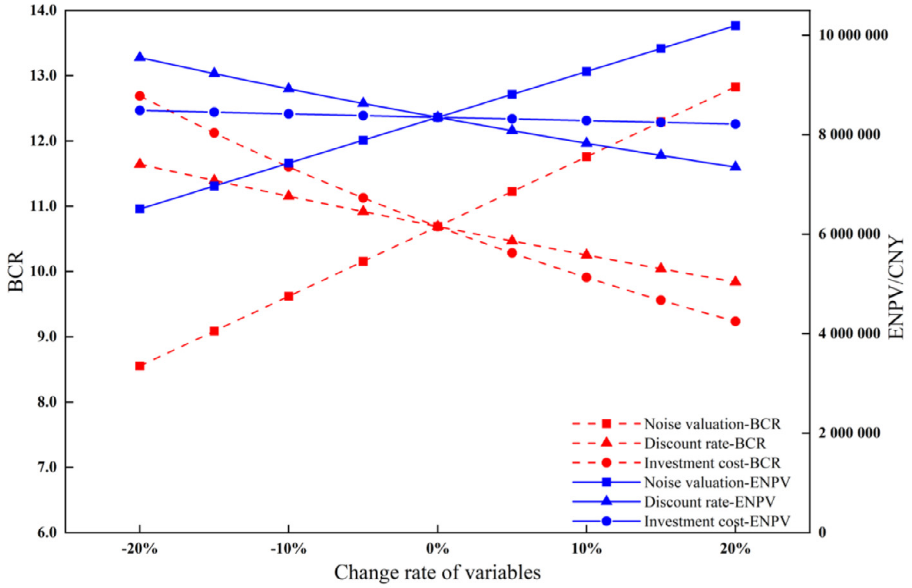
By comparing the slopes of the curves or the absolute values of sensitivity coefficients for different factors, it is evident that the noise valuations have the most significant impact on the evaluation indicators. This suggests that careful consideration should be given to the selection of monetization of noise to ensure that the noise reduction benefits remain within an acceptable range in practical applications. However, the method proposed in this paper aims to select the most economically feasible noise mitigation measures for a studied urban rail line section by comparing the economic indicators, focusing on the ranking of these indicators rather than their absolute values, and the ranking is fairly robust against the uncertainties.

It should be noted that the same noise valuation is applied within each 5 dB(A) band in the estimation of the noise reduction benefits in this work. These simplified values may lack precision but are consistent with the grouped noise exposure data. In practice, due to discrepancies between building-based measurements and population-based exposure, assigning a specific noise value to each exposure point is challenging. As a result, 3 dB(A) or 5 dB(A) bands are used in most noise valuation studies, whereas intervals refined to 1 dB(A) precision would result in additional work for apparently small gains in accuracy (Nellthorp et al., 2005).

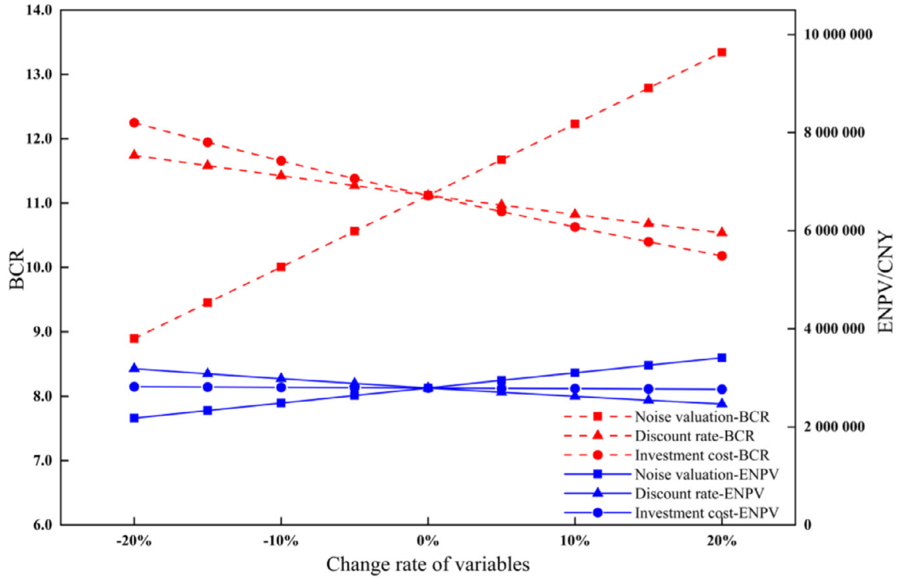
4.2 Comparison with conventional methods

For comparison with the proposed method, the CEA method and the CBA method are applied to the case study situation described in Section 3, with the results shown in Table 7. The CEA method is from reference (Conference of European Directors Roads, 2017), in which the noise exposure score (ΔNES) indicator is an expression of the accumulated noise reduction of all dwellings in the area. Cost-Effectiveness is then calculated as ΔNES divided by the acquisition cost. The CBA method is from reference (Armstrong et al., 2019), where other impacts of the measures are not taken into account in the estimation process, except that only the effect of environmental noise reduction is monetized here. The unit noise valuation used is the mean value 92 CNY$\cdot$dB$^{-1}\cdot$person$^{-1}\cdot$year^{-1} in 2022, which is converted from the price of 26 USD$\cdot$dB$^{-1}\cdot$household$^{-1}\cdot$year^{-1} in 2009 derived from the *meta*-analysis on SP studies in (Bristow et al., 2015). The ENPV is obtained here by subtracting the acquisition cost from the noise reduction benefit. Although these two methods both incorporate the monetary costs of mitigation measures in the evaluation, only the CBA method eventually delivers economic indicators.

Both the comparative studies indicate that the 4 m high noise barriers have greater effectiveness in noise abatement, as demonstrated by ΔNES in the CEA method, and by ENPV in the CBA method. Additionally, the CEA analysis regards the rail grinding as the measure with higher cost-effectiveness. This is because CEA is inherently aimed at achieving objectives at the least possible costs, using the indicator defined as the additional cost per additional unit of effectiveness (Peeters and van Blokland, 2018). However, it may fail to prioritize the option that generates the maximum net benefits, thereby ignoring the broader socio-economic advantages of noise reduction, represented by noise barriers in this case (Browne and Ryan,



(a) 4 m high noise barriers



(b) Rail grinding

Fig. 3 Sensitivity analysis of BCR and ENPV.

Table 6
Sensitivity coefficients S_{AF} of BCR and ENPV at ±20% change rate.

Range of variable changes	Variable	Noise barriers		Rail grinding	
		ENPV	BCR	ENPV	BCR
−20%	Discount rate	−0.72	−0.45	−0.70	−0.28
20%		−0.60	−0.40	−0.58	−0.26
−20%	Noise valuation	1.10	1.00	1.10	1.00
20%		1.10	1.00	1.10	1.00
−20%	Acquisition cost	−0.08	−0.94	−0.05	−0.51
20%		−0.08	−0.68	−0.05	−0.42

Table 7
Comparison of analytical estimation by using different methods.

Indicators	CEA		CBA	The current method	
	ΔNES	Cost-Effectiveness	ENPV/CNY	ENPV/CNY	BCR
Noise barriers	33	39	3 000 000	8 350 000	10.69
Rail grinding	15	55	1 010 000	2 790 000	11.12

2011; Swinburn et al., 2015). To mitigate this bias, the current method employs two economic indicators: the ENPV which identifies measures with the highest absolute net benefits, and the BCR which assesses benefits per unit cost, thus offering more applications for addressing different policy objectives and budget constraints in noise pollution control.

Compared with the CBA results, the current method produces the same relative ENPV values for the two measures. However, even though the LCC included in the current work gives a more conservative and realistic estimation of net benefits, the use of gradient-based noise valuations, which capture the substantial benefits of noise reduction in high-exposure areas, results in higher ENPV values. They are useful to distinguish between situations involving a small population exposed to high noise levels and a larger population experiencing minor noise impacts; this is important in reasonably allocating noise abatement resources, as higher noise intensities impose more severe effects on public health and well-being (Swinburn et al., 2015). This comparison confirms the necessity of employing the gradient-based noise valuations to reflect the true benefits of noise mitigation measures.

5 Conclusions

This paper proposes an economic evaluation method for noise mitigation measures in urban rail transit, integrating LCC analysis with monetized noise reduction benefits to balance technical efficacy and economic feasibility. The LCC captures the long-term cost of noise mitigation measures within the appraisal period, while noise valuation data and the exposed population are combined to quantify the benefits of noise reduction in monetary terms. ENPV and BCR are used as standardized indicators to directly compare different noise mitigation strategies.

A case study based on Beijing Subway Line 13 demonstrates the framework's applicability, comparing vertical 4 m noise barriers with rail grinding. The results show the economic viability of both measures: noise barriers, despite their high cost, yield higher absolute benefits in densely populated areas due to superior noise attenuation, justifying their common localized implementation, while rail grinding offers a more cost-effective measure although with a lower benefit. The use of noise valuations which increase with the original noise levels can capture the higher social benefits of noise reduction in noisier areas, aiding in allocating resources for noise mitigation more effectively. The reliability of the method is verified by a sensitivity analysis and a comparison with conventional CBA and CEA approaches.

Despite the robustness of the findings, certain limitations suggest directions for future research. While the original noise valuations from the EU are widely accepted and considered reliable, the sensitivity analysis indicates that the accuracy of evaluations would benefit from localized noise monetization data specific to the studied area. Refining externality valuations to smaller spatial scales, such as cities or even administrative districts, would enable more precise analyses. Additionally, to enhance evaluation accuracy and expand the scope to include a broader range of noise mitigation measures, the development of extensive and detailed studies on the LCC of railway transport is urgently needed. The proposed method provides a unified decision framework to balance sustainable mitigation for the community with corresponding economic cost. It is relevant for practical decision-making on urban rail noise remedies from the point of view of sustainability since the long-term economic cost and social benefit are considered.

CRediT authorship contribution statement

Xianying Zhang: Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Xiaoqing Hou:** Writing – original draft, Validation, Formal analysis, Data curation. **David Thompson:** Writing – review & editing, Methodology, Conceptualization. **Qi Li:** Writing – review & editing, Investigation. **Jianyue Zhu:** Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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