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Test Environments to Analyse Methodological Improvements of Cost-benefit Analysis for Transport Interventions

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Abstract

Planners and policymakers are concerned that cost-benefit analysis (CBA) rankings are so sensitive that even minor adjustments in contentious input parameters might result in drastically different policy recommendations. Although there is a need for methodological improvement, CBA seems to retain its role as the most coherent and robust framework available for project appraisal. Based on the mentioned need for improvement, this paper aims to create a test environment to analyse possible methodological advances in transport CBAs. This test environment consists of three different models based on typical transport interventions. The models have different levels of complexity and computational need. The sensitivity of each model was tested, and the most critical factors were identified. The majority of the economic benefits come from travel time savings, so the value of time was identified as the five most sensitive factors for all cases.

Keywords

transport appraisal, cost-benefit analysis, sensitivity, test environment

1 Introduction

Improvement of transport infrastructures is predominantly carried out through public investment. Having a general scarcity of public funds, it is crucial to ensure the efficiency of interventions. Therefore, project appraisal has a vital role in assessing the viability and value for money.

One of the most used appraisal tools is Cost-Benefit Analysis (CBA), a framework used to assist the decision on the viability of a possible investment (Bristow and Nellthorp, 2000; Grant-Muller et al., 2001; Mackie et al., 2014). Such decisions can be considered both from a financial and economic aspect (Zoldy et al., 2022), and they are made based on indicators like the net present value (NPV) or the benefit-cost ratio (BCR) (Hansson, 2007; O'Mahony, 2021). Financial analysis regards only actual cash flows (inflows and outflows), whereas economic analysis also uses the concept of shadow prices to reflect the social values (European Commission, 2014). Transport projects are usually financially not viable (hence the need for public funding), while economic viability should only guarantee the funding of socially efficient projects. Therefore, social CBA in transport planning assists investment decisions, project ranking and allocation of funds primarily based on economic viability indicators. So the CBA framework and its values are essential not just in their own right but also because they confer legitimacy to contested decisions (Mackie et al., 2014).

As van Wee and Börjesson (2015) state, a CBA for a transport project considers many variables such as expected infrastructure costs, baseline traffic volumes, and the changes in travel behaviour affecting such volumes. Changes in travel times and traffic performances are calculated by transport models. Then specific costs are used to convert model outputs into monetary values to consider changes in consumer and producer surplus and to account for external effects such as casualties and environmental impacts. Therefore, CBA quality is heavily influenced by the transport model and the monetarisation process.

There are many debates on methodological issues of CBA. O'Mahony (2021) states that some of these debates have focused on improving environmental impact valuation and discounting future impacts to present values. Studies questioning the robustness of CBA methodologies are not uncommon either, since its outcome is filled with many kinds of uncertainties (Börjesson et al., 2014). Other studies have found that ambiguity about the economy's

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future is a significant source of uncertainty (Rodier and Johnston, 2002; Thompson et al., 1997). Another commonly discussed problem of the CBA methodology, according to Hansson (2007), is the assignment of a monetary price to (the loss of) human life and the contingent valuation based on stated preferences. Determining what is valued causes conflict since various people (or groups) value things differently (Dennig, 2018). de Jong et al. (2007) concluded that many studies analysing uncertainty in CBA results target errors in transport model outputs (de Jong et al., 2007; Hugosson, 2005; Zhao and Kockelman, 2002). Hansson (2007) and Mackie and Preston (1998) explore the ambiguity of results from neglected effects, model mistakes, input assumptions, and evaluations. Moreover, Flyvbjerg (2007) work is often cited, highlighting that appraisal of public projects often fails to account for cost overruns and demand shortfalls.

Planners and policymakers are concerned that CBA rankings are so sensitive that even minor adjustments in contentious input parameters might result in drastically different policy recommendations. As a result, Odeck and Kjerkreit (2019) state that such analyses tend not to influence policy decisions due to these incoherences in the CBA framework. However, besides improvements in valuations, recent progress has also been made to measure the uncertainties associated with dubious valuations and scenario assumptions (Börjesson et al., 2014; Eliasson and Fosgerau, 2013; Holz-Rau and Scheiner, 2011), leading to better approaches and refined methodologies. Nonetheless, there is still a need for methodological improvement as, besides other metrics predicting the economic return of investments, CBA seems to retain its role as the most coherent and robust framework available for project appraisal. At the same time, clarity, consistency and quality of analysis are also required (Laird et al., 2014).

A test environment can be built to test possible methodological improvements for transport CBAs. It should be based on prevailing appraisal techniques and the specific needs of typical interventions such as road, rail and urban projects. Such a test environment should fulfil the following requirements:

- have a consistent model structure for different projects in line with general appraisal methods (e.g. discounting, fiscal correction factors, calculation of residual value) and traffic forecasting (e.g. mode and route choice models);
- include all relevant parameters of the investment (e.g. investment and operating costs) and the appraisal (e.g. value of time, real GDP changes);
- make it possible to change the parameters (e.g. specific costs or charges) or calculation methods of inputs (e.g. replacement of a specific cost with a cost distribution).

A very limited number of similar experiments have been done concerning CBA calculations, e.g. (Miller and Szimba, 2015; Salling and Leleur, 2011) and outside the CBA scope (e.g. Fielbaum et al., 2017) to create a parametric city for normative analysis of transport systems.

In such a coherent CBA framework sensitivity analyses could be performed to reveal the most sensitive input parameters. Since 1998, 509 research papers have dealt with transport infrastructure CBA sensitivity analysis based on the Scopus and ScienceDirect database, and there is an increasing tendency in the number of annual papers, which is similar to the tendencies of the road transport related research papers.

Based on the need for improvement, this paper aims to provide a test environment to analyse possible methodological advances in transport CBAs. It outlines a consistent model structure for the most typical interventions with a gradually increasing complexity. Section 2 presents the setup of these models. Section 3 demonstrates the CBA results of each model type compared with actual results of similar Hungarian interventions and the sensitivity of the model parameters. Conclusions are drawn, and further research steps are drafted in Section 4.

2 Methodology

2.1 Model structures of typical interventions

The CBA models and the connecting traffic forecast models to be developed aim to analyse methodological relations and to test possible improvements. Therefore, the starting point should be the typical applications of transport CBAs. Based on the European practice, a sectorial segmentation of appraisal can be witnessed based on the type of the analysed intervention. The main areas of investment are the following:

- road interventions: upgrade of existing connections, new motorway or road sections to make up for missing links, creation of bypasses;
- rail interventions: upgrade of existing connections, new – mostly high-speed rail – network elements;
- urban interventions: complex projects including measures on public transport, passenger car, bicycle, pedestrian and freight traffic;
- other interventions, including waterborne and air transport investments.

Of the above, road, rail and urban interventions are the most typical. Therefore, three models have been selected to represent each of them. The research objective is to create structures that characterise the typical application and underlying fundamental relations of input variables in their detailedness. It is also intended to show the staggered complexity of CBA models and have a structure of test models with a gradually increasing complexity.

The simplest spreadsheet model is for road interventions, for which a bypass creation has been selected as a unique and frequent case of adding a new link to the network. It can depict the effect that a quicker – but usually longer – route can cause. The upgrade of an existing route has been selected as the rail transport case, a slightly more complex spreadsheet model. The most complex one is the urban spreadsheet-VISUM model, which is about building a new bridge and extending the public transport network.

The model consists of input variables that feed the successive transport and CBA sub-models. The internal utility functions are the same for all modelling steps. Eventual model results can be interpreted through the conventional three economic indicators of the CBA (Economic Net Present Value (ENPV), Economic Rate of Return (ERR), Benefit-Cost Ratio (BCR)).

2.2 General assumptions and parameters

The social CBA has the following fundamental assumptions mainly based on the Hungarian CBA guide (TRENECON, 2016), which was created in coherence with the European guidelines (European Commission, 2014):

- calculation method: an incremental case – comparing do-nothing and do-something scenarios;
- length of the analysis period: 30 years;
- economic discount rate: 5%;
- marginal cost of public funding: 5%;
- annual real GDP growth: 3% in the first five years, then 1.5%;
- elasticities to GDP change: passenger traffic – 70%, freight traffic – 90%, travel time/vehicle operating/accident/environmental cost – 100%;
- fiscal correction factor on personnel costs: 26%;
- the fuel tax rate is 37.5%;

The investment cost structure, residual value calculation (based on remaining life-spans), specific operational and social costs, relative injury ratios and speed-dependent vehicle operating cost (VOC) calculation parameters have also been adopted from the Hungarian CBA guide (TRENECON, 2016). The average travel time (VOT) for passenger transport is 8.56 EUR/h. The average VOC for 50 km/h is 0.16 EUR/km.

2.3 Bypass Model (BM) description

The Bypass Model is primarily based on Hungarian EU funded road projects such as the upgrades of main road No. 32, 51, 55, 61, 62 and 471. The simplified study area has a road between two cities that goes through another city. There is a regular bus service between these cities. A new road bypass connection and an optional refurbishment of connecting road sections are the content of the analysed investment (see Fig. 1).

The road length is 34 km, with a 4 km long inner section. The bypass is 5.5 km long. The maximum speed is 90 km/h for cars and 80 km/h for buses and trucks in the outskirts. Speed on worn road sections has an 80 km/h maximum. Within city limits, the maximum attainable speed is 45 km/h. The speed of trucks is 90% of that of cars.

The specific cost of road building is 1 million EUR/km, while refurbishment is 60% of that. The last refurbishment of the road was seven years ago. The total investment cost is therefore 25.9 million EUR. Construction lasts for three years: 1 year for planning and two years for works. There is a 30% time loss due to the construction works for these two years.

There is a single ticket for the bus which costs 1 EUR per trip. Buses operate with an average 15-minute headway (140 bus journeys per day). The bus capacity is 80 passengers.

The passenger trip demand is fixed in the model (25,400 trips per day for the nine origin-destination pairs with zero internal travel). Besides the 'no travel' option, there are two alternative modes of transport: private car and public bus. Freight trips served by HGVs are also included in

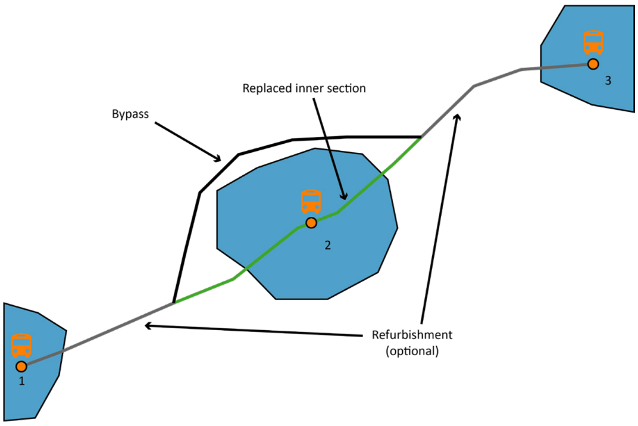


Fig. 1 Overview of the Bypass Model network

the model (1,880 trips per day). A standard logit model is responsible for mode choice without utility scaling parameters (Ortúzar and Willumsen, 2011). Car availability influences the possible choices of 80% of the population.

In the do-something case, there is a route choice logit model for origin-destination pairs 1–3 and 3–1 with two alternatives for cars: through the bypass or the city. Transit HGVs must use the bypass while buses stop midway in the city.

Travel speeds and, therefore, journey times depend (iteratively) on the saturation of road sections. The volume-delay function is a standard BPR (Ortúzar and Willumsen, 2011) with the following parameters: $a = 0.25$ (coefficient), $b = 2.5$ (exponent). Road capacity for outer road sections is 27,000 PCU/day and 22,000 PCU/day for inner road sections. PCU factor for trucks and buses is 2.5.

The following impedance functions are used for benefit calculations (logsum method) and the transport model. The impedance is used at the demand distribution, the mode choice and the route choice steps. We designed the impedance functions in a way that they are in Euro.

Equation (1) is the impedance function for cars in the Bypass Model, where the vehicle operating cost element is elaborated in Eq. (2):

$$Imp_{car} = \mathrm{VOT} \times T_{cur} + \frac{\mathrm{VOC}_{LV} \times Dist}{Occ}, \tag{1}$$

$$\mathrm{VOC}_{LV} = a - b \times V_{cur} + c \times V_{cur}{}^{2} + a_1 + \frac{b_1}{V_{cur}}, \tag{2}$$

where:

- VOT is the value of time: 8.56 (EUR/h);
- T_{cur} is the congested travel time (h);
- VOC_{LV} is the vehicle operating cost for light vehicles depending on the speed (EUR/vehicle km);
- V_{cur} is the congested speed (km/h);
- *Dist* is the distance (km);
- *Occ* is the car occupancy 1.3 (person/vehicle);
- a, b, c, a_1, b_1 are cost parameters from the Hungarian guide (TRENECON, 2016).

Equation (3) is the bus impedance function in the Bypass Model, where the perceived journey time element is elaborated in Eq. (4):

$$Imp_{bus} = \mathrm{VOT} \times \mathrm{PJT} + Fare + \mathrm{ASC}, \tag{3}$$

$$\mathrm{PJT} = \mathrm{IVT} + \frac{\mathrm{HW}}{2} + \mathrm{AT}, \tag{4}$$

where:

- VOT is the value of time: 8.56 (EUR/h);
- PJT is the perceived journey time (h);
- *Fare* is the fix fare for bus, like single ticket (EUR);
- ASC is the alternative specific constant (mode-specific disutility, mode penalty): 2.5 EUR;
- IVT is the in-vehicle time (h);
- HW is the headway for the buses (h);
- AT is the access time: 1/60 (h).

Equation (5) is the impedance function for the No travel option in the Bypass Model:

$$Imp_{NT} = 12. \tag{5}$$

Equation (6) is the impedance function for heavy goods vehicles in the Bypass Model, where the vehicle operating cost element is elaborated in Eq. (7):

$$Imp_{HGV} = \mathrm{VOC}_{HV} \times Dist, \tag{6}$$

$$\mathrm{VOC}_{HV} = a - b \times V_{cur} + c \times V_{cur}^{2} + a_1 + \frac{b_1}{V_{cur}}, \tag{7}$$

where:

- VOC_{HV} is the vehicle operating cost for heavy vehicles depending on the speed (EUR/vehicle km);
- *Dist* is the distance (km);
- V_{cur} is the congested speed (km/h);
- a, b, c, a_1, b_1 are cost parameters from the Hungarian guide (TRENECON, 2016).

2.4 Rail Model (RM) description

The Rail Model is primarily based on Hungarian EU funded rail projects such as the upgrade of railway line No. 1 (Biatorbágy-Tata), 2 (Budapest-Esztergom), 15–21 (Sopron-Szombathely-Szentgotthárd), 29 (Szabadbattyán-Aszófő), 30a (Budapest-Székesfehérvár). The simplified study area has a road and a rail connection between two cities. The road bypasses another town in the middle. A regular bus service connects these cities. A rail station is somewhat further away from the central city, but it is possible to transfer to a perpendicular bus line and reach the city. The analysed investment upgrades the railway line by increasing its speed (Fig. 2).

The length of the road, which is a motorway, is 32 km. The bypassed section is 7 km long: 4 km main road and 3 km inner section. The maximum speed is 110 km/h for cars and 100 km/h for buses on the motorway, 90 km/h and 80 km/h on the main road, and 45 km/h and 40 km/h on urban roads, respectively. The length of the railway line

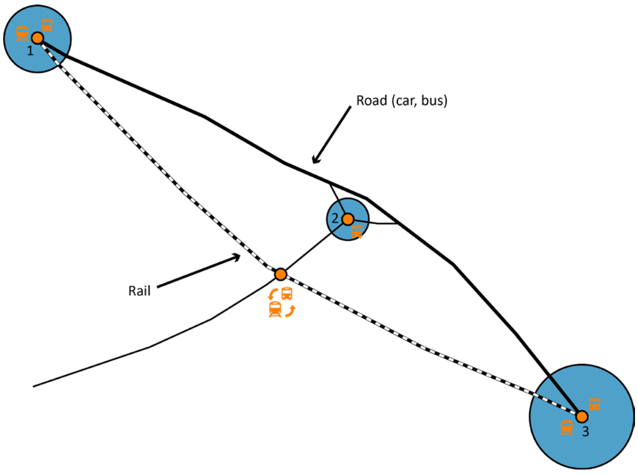


Fig. 2 Overview of the Rail Model network

is 30 km, and the connecting bus leg is 5.5 km long. Rail speed is 80 km/h in the do-nothing case and 100 km/h after the investment.

The specific cost of rail improvement is 3.5 million EUR/km. The last refurbishment of the railway line was 10 years ago. The total investment cost is therefore 105 million EUR. Construction lasts for three years: 1 year for planning and two years for works. There is a 40% time loss due to the construction works for the rail users.

The distance-based bus fare is 0.03 EUR/km and 0.05 EUR/km for rail. Buses operate with an average 30-minute headway (70 bus journeys per day). Rail service frequency is 20 minutes (105 rail journeys per day). Bus capacity is 72 passengers, while a train can carry 200 passengers.

The passenger trip demand is fixed in the model (54,000 trips per day for the nine origin-destination pairs with zero internal travel). Besides the 'no travel' option, there are three alternative modes of transport: private car, public bus or rail (including the rail and bus transfer for origin-destination pairs 1–2 and 2–1). A standard logit model is used for mode-choice without utility scaling parameters (Ortúzar and Willumsen, 2011). Car availability influences the possible choices of 75% of the population. Freight transport is excluded from the model.

This model has no route choice decisions: transit car trips use the motorway. However, travel speeds and road travel times depend on the saturation level. The volume-delay function and capacities are identical to the ones used in the Bypass Model. Road capacity for motorway 64,000 PCU/day. Mode-choice and road saturation are interdependent processes with in-built iterations to find equilibrium.

In terms of how users perceive the disutility of travel times – unlike in the Bypass model – the value of reliability (VOR) is also included. That is quantified through the average delay or lateness and the standard deviation of travel times.

The following impedance functions are used for benefit calculations (logsum method) and the transport model. The impedance is used at the mode choice step. The impedance functions were designed in a way that they are in Euro.

Equation (8) is the impedance function for cars in the Rail Model:

$$\begin{aligned} Imp_{car} &= \mathrm{VOT} \times \left(T_{cur} + T_{cur} \times L \times \mathrm{LF} + T_{cur} \times \mathrm{SD} \times \mathrm{RR} \right) \\ &+ \frac{\mathrm{VOC}_{LV} \times Dist}{Occ}, \end{aligned} \tag{8}$$

where:

- VOT is the value of time: 8.56 (EUR/h);
- T_{cur} is the congested travel time (h);
- L is the average lateness: 0.06 based on previous projects;
- LF is the average lateness factor: 2;
- SD is the standard deviation factor of the travel time: 0.2656 based on previous projects;
- RR is the reliability ratio: 0.4;
- VOC_{LV} is the vehicle operating cost for light vehicles depending on the speed corresponds with the road model [EUR/vehicle km];
- *Dist* is the distance [km];
- *Occ* is the average car occupancy 1.3 [person/vehicle].

Equation (9) is the impedance function for buses, while Eq. (10) is for rail in the Rail Model, where the perceived journey time is elaborated in Eq. (11). The reliability of travel times is represented based on the authors' previous research (Mátrai, 2013):

$$\begin{aligned} Imp_{bus} &= \mathrm{VOT} \times \begin{pmatrix} \mathrm{PJT} + \mathrm{IVT} \times L_b \times \mathrm{LF} \\ + \mathrm{IVT} \times \mathrm{SD}_b \times \mathrm{LF} \times \mathrm{RR} \end{pmatrix} \\ &+ Fare_b \times Dist + \mathrm{ASC}_b, \end{aligned} \tag{9}$$

$$\begin{aligned} Imp_{rail} &= \mathrm{VOT} \times \begin{pmatrix} \mathrm{PJT} + \mathrm{IVT} \times L_r \times Dist \times \mathrm{LF} \\ + \mathrm{IVT} \times \mathrm{SD}_r \times Dist \times \mathrm{LF} \times \mathrm{RR} \end{pmatrix} \\ &+ Fare_r \times Dist + \mathrm{ASC}_r, \end{aligned} \tag{10}$$

$$\mathrm{PJT} = \mathrm{IVT} + \frac{\mathrm{HW}}{2} + \mathrm{AT}, \tag{11}$$

where:

- VOT is the value of time: 8.56 (EUR/h);
- PJT is the perceived journey time (h);
- IVT is the in-vehicle time (h);

- L_b is the average lateness for buses: 0.06 based on previous projects;
- L_r is the average lateness for rail [h/km]: 0.000583 and 0.00025 for the do-nothing and do-something cases, respectively, based on previous projects;
- LF is the average lateness factor: 2.5;
- SD_b the standard deviation of the travel time for buses: 0.2656 based on previous projects;
- SD_r the standard deviation of the travel time for rail (h/km): 0.0002 and 0.000183 for the do-nothing and do-something cases, respectively, based on previous projects;
- RR is the reliability ratio: 1.4;
- *Fare* is the km based fare (EUR/km);
- ASC is the alternative specific constant (mode-specific disutility, mode penalty): −0.3 EUR for buses, 0.8 EUR for rail;
- HW is the headway for buses and rail (h);
- AT is the access time: 1/60 (h).

Equation (12) is the impedance function for the 'No travel' option in the Rail Model:

$$Imp_{NT} = 10. \tag{12}$$

2.5 Urban Model (UM) description

The Urban Model is based on building a new bridge in a capital city, which was modelled based on the Hungarian capital, Budapest. The simplified transport network is arranged in a radial structure with three-ring roads. The city is connected to other areas through 6 cordon zones located outside the outer ring. These cordon zones represent each sector of the suburban area (northeast, east, southeast, southwest, west, northwest). A river goes through the middle of the study area, dividing it into two parts. The western part of the area is hilly; therefore, transport provision is exiguous. The outer motorway ring is roughly 12–14 km away from the city center (100 km/h, 2 × 2 lanes). The ring road has a lower rank and attainable speed (50 km/h, 2 × 1 lanes). Roads within the city limits have 2 × 2 lanes. Motorway connections (70 km/h) are provided to the middle ring of main urban roads (50 km/h). The middle ring is around 5 km away from the center but does not proceed to the western part of the city. The inner ring road encircles the city center with a radius of around 2 km.

There are interconnecting main roads in a north-south relation on both flanks of the river and an east-west relation. Within the inner ring, roads are calmed to a moderate speed of 30 km/h. There are public transport stops around each cordon zone and at each junction of roads. Rail connections are provided from suburban zones except in the western sector, where there is only a bus connection. Railway lines go into three terminal stations, but their connectedness is limited. Five tram lines create an urban public transport network: a middle half ring, two north-south lines on both sides of the river, a southbound connection and an east-west one. The analysed investment is to build a new bridge in the south and extend the middle tram ring to the south-western part of the city (Fig. 3).

The specific cost of building the new bridge (and connecting roads) with the tram line is 180 million EUR/km. The length of the new section is 3.15 km, so the total investment cost is 565 million EUR. Construction lasts for three years: 1 year for planning and two years for works.

The public transport fare is trip-based; it costs 0.8 EUR for the urban part of the network and 1.2 EUR if it includes suburban services. Service frequency varies between 4 and 12 minutes for the urban and 6 and 15 minutes for the suburban network. Bus capacity is 72 passengers (with 28 seats), while a train and a tram can carry 200 and 350 passengers (with 64 and 110 seats), respectively.

Traffic forecast procedures are implemented in the 2020 version of PTV VISUM, based on a conventional four-step modelling logic. Trip demand generation is based on structural data such as the number of inhabitants (2.4 million in total), workplaces in production (0.63 million in total) and services (1.08 million in total), and an indicator for other services. Specific production and attraction factors for the daily number of trips calculate daily travel demand, accounting for motorisation. Motorisation levels of zones vary between 300 and 600 cars/1000 residents. Freight

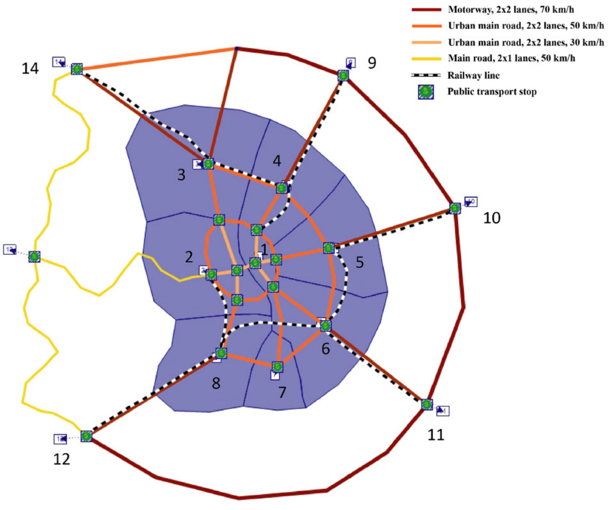


Fig. 3 Overview of the Urban Model network

transport is also taken into consideration. A standard logit model is used for trip distribution and mode choice without utility scaling parameters (Ortúzar and Willumsen, 2011). In the case of the distribution, matrices are balanced in a doubly constrained way. Besides the 'No travel' option, there are two alternative modes of transport: private car (for those who have access to a car) and public transport (buses, trams, and rail services). Structural data and network parameters are fixed for future years in the model.

Total passenger travel demand is around 1.71 million trips. The number of freight trips is 130,000 in total. In terms of route choice, private transport modes have an equilibrium based assignment, while public transport assignment follows a headway-based method. Travel speeds and, therefore, journey times depend on the saturation of road sections. The volume-delay function is a standard BPR (Ortúzar and Willumsen, 2011) with the following parameters: $a = 0.7$ (coefficient), $b = 1.5$ (exponent). Road capacity for motorways is 50 000 PCU/day, 42,500 PCU/day for main urban roads with 2 × 2 lanes, and 20,000 PCU/day for main roads with 2 × 1 lanes. PCU factor for trucks and buses is 2.5.

Regarding how users perceive the disutility of travel times, the value of reliability (VOR) is also included, but – unlike in the Rail model – only for private cars. That is quantified through the standard deviation of travel times. There is also a parking charge between 1 and 2.5 EUR for more congested zones, which is included in mode choice decisions. However, crowding of public transport services is an influencing factor for the value of in-vehicle time. Due to processing limitations, this option is not yet included in the model. The quality of service is assumed to be sufficient to avoid any passengers unable to board the vehicles.

The following impedance functions are used for benefit calculations (logsum method) and the transport model. The impedance is used at the demand distribution, the mode choice and the route choice steps. We designed the impedance functions in a way that they are in Euro.

Equation (13) is the impedance function for cars in the Urban Model, where the standard deviation element is elaborated in Eq. (14). This formulation of the SD comes from the A1.3 chapter of the English Transport Appraisal Guideline (Department for Transport, 2022), and it was designed to be calculated based on seconds as time units:

$$\begin{aligned} Imp_{car} &= \mathrm{VOT} \times \left(\frac{T_{cur}}{3600} + \mathrm{LF} \times \frac{\mathrm{SD}}{3600} \right) \\ &+ \frac{\mathrm{VOC}_{LV} \times Dist + \mathrm{PC}}{Occ}, \end{aligned} \tag{13}$$

$$\mathrm{SD} = 0.0018 \times T_{cur}^{\;2.02} \times Dist^{-1.41}, \tag{14}$$

where:

- VOT is the value of time: 8.56 (EUR/h);
- T_{cur} is the congested travel time (sec);
- LF is the average lateness factor: 0.4;
- SD is the standard deviation of the travel time (sec);
- VOC_{LV} is the vehicle operating cost for light vehicles depending on the speed corresponds with the road and rail model (EUR/vehicle km);
- *Dist* is the distance (km);
- PC is the parking charge for an average stay (EUR);
- *Occ* is the car occupancy 1.25 (person/vehicle);

Equation (15) is the impedance function for buses in the Urban Model, where the perceived journey time element is elaborated in Eq. (16):

$$Imp_{PuT} = \mathrm{VOT} \times \mathrm{PJT} + Fare, \tag{15}$$

$$\mathrm{PJT} = \mathrm{IVT} + 2 \times (\mathrm{OWT} + \mathrm{TWT}) + 3 \times \mathrm{NTR}, \tag{16}$$

where:

- VOT is the value of time: 8.56 (EUR/h);
- PJT is the perceived journey time (h);
- IVT is the in-vehicle time (h);
- OWT is the origin wait time (h);
- TWT is the transfer wait time (h);
- NTR is the number of transfers.

Equation (17) is the impedance function for the 'No travel' option in the Urban Model:

$$Imp_{NT} = 8. \tag{17}$$

Equation (18) is the impedance function for heavy goods vehicles in the Urban Model, where the vehicle operating cost element is elaborated in Eq. (7):

$$Imp_{HGV} = (\mathrm{VOC}_{HV} + \mathrm{RC}) \times Dist, \tag{18}$$

where:

- VOC_{HV} is the vehicle operating cost for heavy vehicles depending on the speed corresponds with the road model (EUR/vehicle km);
- RC is the road charge (EUR/km);
- *Dist* distance (km).

3 Results and discussions

Section 3 introduces the primary results of each model with the initial parameter sets. Main impacts on mode choice and other transport-related effects are discussed. CBA indicators are also presented as results of the test models, comparing them with actual ex-ante and ex-post results. A simple sensitivity test of input parameters is demonstrated as a preliminary analysis.

3.1 Bypass Model (BM)

In the case of the Bypass Model, the initial trip based modal share of cars is around 66%, bus services have around 33%, while no travel gives 1%. After implementing the bypass, car modal share increases by 1.6%, while bus and 'No travel' decrease by 1.3% and 0.3%, respectively. 72% of transit car travellers use the bypass. ENPV of the project is 7.75 million EUR, ERR is 6.3%, and BCR is 1.43. Table 1 compares this latter indicator with actual ex-ante and ex-post results. Based on the authors' experience with previous bypass road developments, the usual BCR is around 1.5, so our hypothetical model was tuned to provide similar results as a base case.

Table 1 Comparison of CBA indicators for road projects

Project	BCR
Hypothetical project of the Bypass Model	1.43
Rehabilitation of main road No. 32 (Hatvan-Szolnok) + Jászberény bypass (2011)	1.2–1.3
Rehabilitation of the main road No. 51 (Apostag – Baja) + Solt bypass (2013) - depending on different alternatives	1.5–2.7
Rehabilitation of main road No. 55 (Baja-Szeged) + Mórahalom bypass (2013)	1.1–1.5
Main road No. 61 Nagykanizsa bypass	1.4
Rehabilitation of main road No. 62 (M8-Székesfehérvár) + Perkáta, Szabadegyháza, Seregélyes bypasses (2011)	1.8–3.0
Rehabilitation of main road No. 471 (Debrecen-Mátészalka) + Hajdúsámson bypasses (2011)	1.4

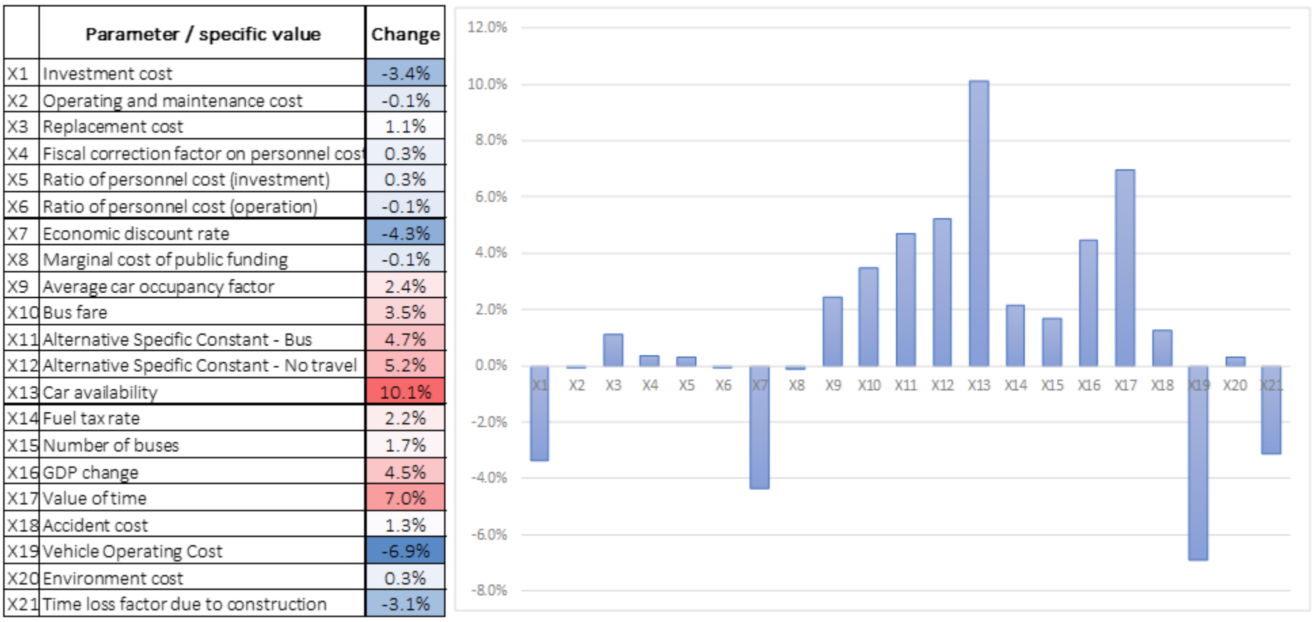
As a preliminary analysis, Fig. 4 shows the simple sensitivity of the ENPV indicator for +1% changes in significant input parameters. Conventionally, more than 1% sensitivity is considered critical, valid for most variables here. However, the most sensitive ones are car availability (+10.1%), VOT (+7.0%), VOC (−6.9%).

3.2 Rail Model (RM)

In the Rail Model, the initial trip based modal share of cars is around 55%, bus and rail services have around 13% and 28%, respectively, with 3% who choose not to travel. After implementing the rail investment, rail increased by 8.1%, car, bus, and the 'No travel' option decreased by 6.2%, 0.9% and 1.0%, respectively. ENPV of the project is 25.81 million EUR, ERR is 6.6%, and BCR is 1.36. Table 2 compares this latter indicator with actual ex-ante and ex-post results.

Table 2 Comparison of CBA indicators for rail projects

Project	BCR
Hypothetical project of the Rail Model	1.36
Rehabilitation of railway line No. 1 (Biatorbágy-Tata, 2015)	1.1–1.2
Rehabilitation of railway line No. 2 (Budapest-Esztergom, 2011)	1.4–1.5
Rehabilitation of railway line No. 15-21 (Sopron-Szombathely-Szentgotthárd, 2008)	1.2–1.3
Rehabilitation of railway line No. 29 (Szabadbattyán-Aszófő, 2017)	1.2–1.3
Rehabilitation of the main road No. 30a (Budapest-Székesfehérvár, 2011)	1.5–1.6



	Parameter / specific value	Change
X1	Investment cost	-3.4%
X2	Operating and maintenance cost	-0.1%
X3	Replacement cost	1.1%
X4	Fiscal correction factor on personnel cost	0.3%
X5	Ratio of personnel cost (investment)	0.3%
X6	Ratio of personnel cost (operation)	-0.1%
X7	Economic discount rate	-4.3%
X8	Marginal cost of public funding	-0.1%
X9	Average car occupancy factor	2.4%
X10	Bus fare	3.5%
X11	Alternative Specific Constant - Bus	4.7%
X12	Alternative Specific Constant - No travel	5.2%
X13	Car availability	10.1%
X14	Fuel tax rate	2.2%
X15	Number of buses	1.7%
X16	GDP change	4.5%
X17	Value of time	7.0%
X18	Accident cost	1.3%
X19	Vehicle Operating Cost	-6.9%
X20	Environment cost	0.3%
X21	Time loss factor due to construction	-3.1%

Fig. 4 Sensitivity analysis of the input parameters of the Bypass Model

Fig. 5 shows the simple sensitivity of the ENPV indicator for +1% changes in significant input parameters. Based on the standard 1% threshold of critical sensitivity only seven of the input parameters can be highlighted: investment cost (–3.5%), economic discount rate (–3.5%), average car occupancy rate (–3.2%), VOC (+2.2%), VOT (+1.9%), GDP change (+1.8%) and the number of trains (+1.5%).

3.3 Urban Model (UM)

In the case of the Urban Model, the initial trip based modal share of cars is around 34.5%, and public transport has 48.6%, with a high potential for induced demand (16.9% who choose not to travel). After building the new bridge and expanding the tram line, public transport share increased by 1.2%, while car and 'No travel' decreased by 0.4 and 0.8%. Around 62% of travelers using the new bridge travel through re-routing. The remaining 38% come from mode-choice (or induced trips). ENPV of the project is 1,377 million EUR, ERR is 19.7%, and BCR is 3.08. Table 3 compares this latter indicator with actual ex-ante results. Although the ex-ante results were slightly more conservative, we decided to build slightly more ambitious hypothetical scenario. Our experience with international projects shows higher returns than the Hungarian ones.

Table 3 Comparison of CBA indicators for urban projects

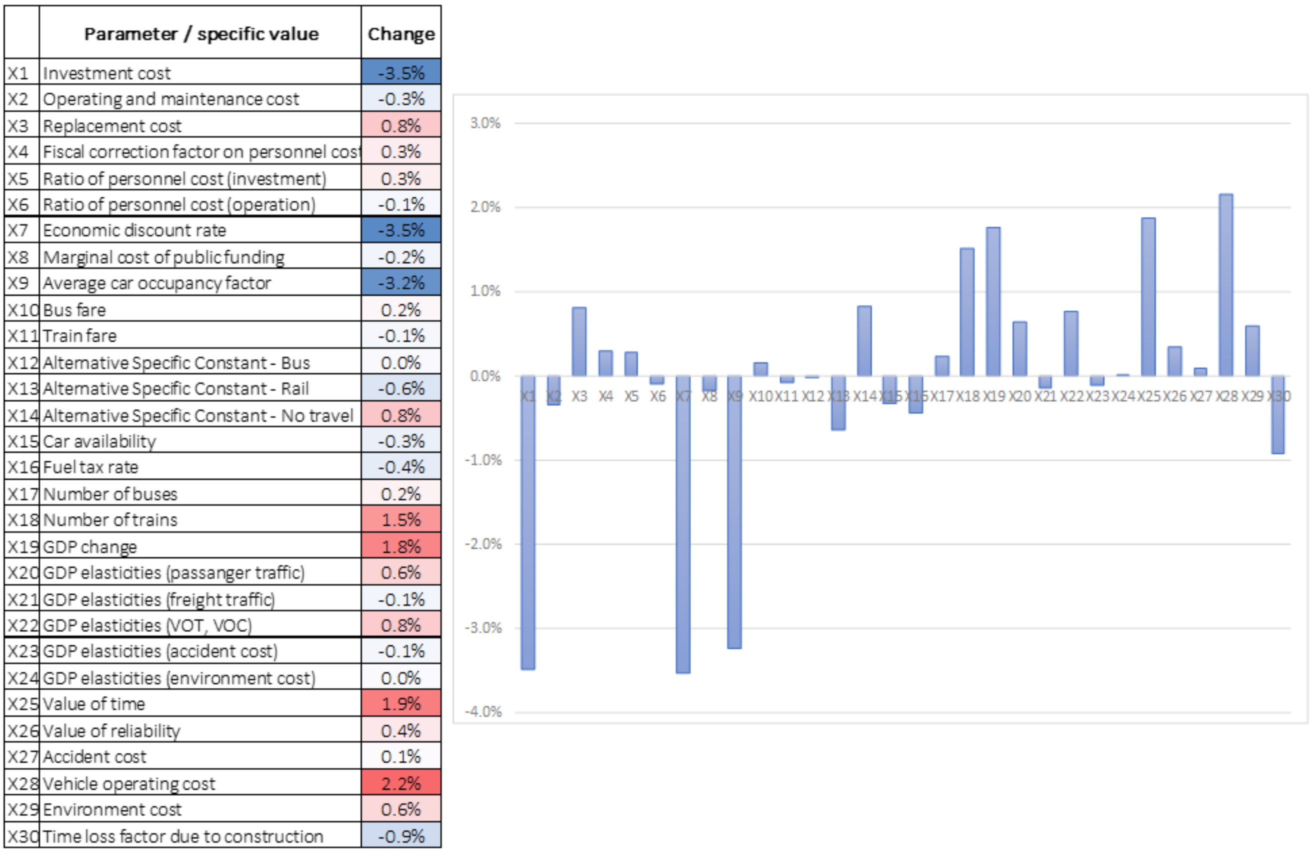
Project	Benefit-cost ratio
Hypothetical project of the Urban Model	3.08
Galvani bridge in Budapest (2014–2021)	0.8–1.2 (estimation based on different calculations)
Aquincum bridge (with the improvement of bus services) in Budapest (2022)	1.4–1.6 (depending on different alternatives)

Fig. 6 shows the simple sensitivity of the ENPV indicator for +1% changes in significant input parameters. Based on the standard 1% threshold of critical sensitivity, only five of the input parameters can be highlighted: average car occupancy rate (+1.7%), No travel ASC (–1.2%), motorisation (+2.6%), VOT (+3.9%), and the VOR (+2.0%).

4 Conclusions and further research

As the first step of an ongoing research project, a test environment to analyse possible methodological advances of transport cost-benefit analysis has been created. This test environment consists of three different models based on typical transport interventions. The models have different levels of complexity and computational need.

The first model (Bypass Model) is a typical road refurbishment project with a bypass road-building element. It represents the most basic functions related to the benefit



	Parameter / specific value	Change
X1	Investment cost	-3.5%
X2	Operating and maintenance cost	-0.3%
X3	Replacement cost	0.8%
X4	Fiscal correction factor on personnel cost	0.3%
X5	Ratio of personnel cost (investment)	0.3%
X6	Ratio of personnel cost (operation)	-0.1%
X7	Economic discount rate	-3.5%
X8	Marginal cost of public funding	-0.2%
X9	Average car occupancy factor	-3.2%
X10	Bus fare	0.2%
X11	Train fare	-0.1%
X12	Alternative Specific Constant - Bus	0.0%
X13	Alternative Specific Constant - Rail	-0.6%
X14	Alternative Specific Constant - No travel	0.8%
X15	Car availability	-0.3%
X16	Fuel tax rate	-0.4%
X17	Number of buses	0.2%
X18	Number of trains	1.5%
X19	GDP change	1.8%
X20	GDP elasticities (passanger traffic)	0.6%
X21	GDP elasticities (freight traffic)	-0.1%
X22	GDP elasticities (VOT, VOC)	0.8%
X23	GDP elasticities (accident cost)	-0.1%
X24	GDP elasticities (environment cost)	0.0%
X25	Value of time	1.9%
X26	Value of reliability	0.4%
X27	Accident cost	0.1%
X28	Vehicle operating cost	2.2%
X29	Environment cost	0.6%
X30	Time loss factor due to construction	-0.9%

Fig. 5 Sensitivity analysis of the input parameters of the Rail Model

	Parameter / specific value	Change
X1	Investment cost	-0.3%
X2	Operating and maintenance cost	-0.1%
X3	Replacement cost	0.0%
X4	Fiscal correction factor on personnel cost	0.0%
X5	Ratio of personnel cost (investment)	0.0%
X6	Ratio of personnel cost (operation)	0.0%
X7	Economic discount rate	-0.9%
X8	Marginal cost of public funding	0.0%
X9	Fuel tax rate	0.0%
X10	GDP change	0.6%
X11	GDP elasticities (passanger traffic)	0.2%
X12	GDP elasticities (freight traffic)	0.0%
X13	GDP elasticities (VOT, VOC)	0.3%
X14	GDP elasticities (accident cost)	0.0%
X15	GDP elasticities (environment cost)	0.0%
X16	Accident cost	0.1%
X17	Environment cost	0.0%
X18	Average car occupancy factor	1.7%
X19	Alternative Specific Constant - No travel	-1.2%
X20	Motorization	2.6%
X21	Value of time	3.9%
X22	Value of reliability	2.0%
X23	Vehicle operating cost	0.1%

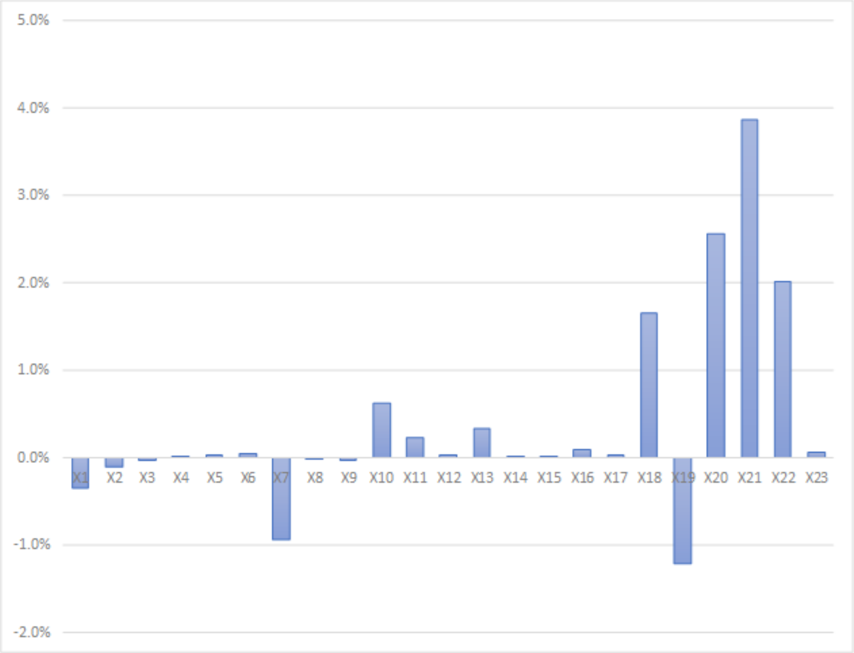


Fig. 6 Sensitivity analysis of the input parameters of the Urban Model

and cost elements. Furthermore, it only has a mode choice and a route choice problem with a fixed matrix which is easy to calculate in a spreadsheet. The impedance functions contain only the minimum required elements. Freight transport is included, but only for benefit calculations.

The second model (Rail Model) is a typical rail refurbishment project with a parallel competing road network element. It has a slightly more complex network and mode choice problem. The impedance functions include travel time variability. The average lateness model is used to represent the reliability of travel times. This model is still a spreadsheet one since it has minimal calculation requirements.

The third model (Urban Model) is the most complex one representing a bridge investment in an urban environment. The sample was created based on the specificities of Budapest, but it was highly simplified for this project. PTV VISUM was used for the transport modelling as it has a more complex network. A widely used four-step transport model was created and used, where the impedance functions are the same in all steps. The travel times' uncertainty was introduced as a standard deviation model for car traffic only. Freight transport is also included in the transport model but only used for benefit calculations. The development of this model was challenging since the CBA calculations, and the transport model had to be connected in an automated way to enable proper sensitivity analyses. It was implemented via a COM interface of the VISUM software and VBA in Excel.

With the presented test environment, the sensitivity of each model was tested, and the most critical factors were identified. The majority of the economic benefits come from travel time savings, so the value of time was identified as the five most sensitive factors for all cases.

The next step is to run a more advanced sensitivity test that can provide some information about the impact of the different input parameters on each other (e.g. Morris or Sobol methods). However, these tests are not trivial to implement since they require the simultaneous run of mathematical software (e.g. R) and Excel, and in the last case PTV VISUM. Based on the preliminary assumptions and tests, the computation times can be days since these methods usually require several runs.

The further goal of the research project is to determine whether the currently used point estimate value of time attributes can be replaced by distributions given the parameter's heterogeneous nature. The test environment presented in this article was designed to accommodate this complexity.

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