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Research article

Compliance indicator determination method to match electric buses with bus lines

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ABSTRACT

Urban bus service electrification is usually achieved using battery electric buses charged at the depot. However, due to the range limitation, a battery electric bus usually cannot replace a diesel-powered bus one-to-one in daily running. The compliance indicator determination method was developed using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to express the suitability of buses on a given bus line. Vehicle-specific (*maximum motor power*, *battery capacity*, *consumption rate*, *maximum charging power*) and route-specific (*topography*, *distance between stops*, *passenger load*) parameters were considered. The result is a vehicle ranking for a line. The method was applied as a case study in Budapest; 58 bus lines and 30 buses were analyzed. Buses with different vehicle parameters should be selected for lines with different route parameters; however, operating a diverse fleet is unnecessary, as among the 30 bus types analyzed, 9 buses were ranked in the first four positions. The most influencing vehicle parameters are the maximum engine power, average specific fuel consumption, battery capacity, passenger capacity, and vehicle weight; thus, the most influencing route-specific parameters are the roadway gradient, the number of stops, and passenger volume. Operators can use this method to decide which bus route an electric bus can operate without changing the daily bus schedule.

Table 0
List of abbreviations.

Abbreviation	Description	Used unit, SI unit
c_1	Braking loss	[kWh/km], [J/m]
c_1	Elevation loss	[kWh/km], [J/m]
c_3	Charging time	[h], [s]
c_4	Gradeability speed	[km/h], [m/s]
c_5	Passenger load	[%]
c_6	Number of trips	[−]
l	Serial number of bus line	[−]
p	Serial number of sensitivity test	[−]
r_1	Elevation	[m]

(*continued on next page*)

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Table 0 (*continued*)

Abbreviation	Description	Used unit, SI unit
r_2	Steepness	[°], [rad]
r_3	Trip length	[km], [m]
r_4	Number of stops	[–]
r_5	Speed limit	[km/h], [m/s]
r_6	Max. hourly passenger load in average	[pax/h]
r_7	Average speed	[km/h], [m/s]
v_1	Maximum power	[kW], [W]
v_2	Drivetrain efficiency	[–]
v_1	Consumption rate	[kWh/km], [J/m]
v_1	Battery capacity	[kWh], [J]
v_5	Maximum charging power	[kW], [W]
v_6	Passenger capacity in a vehicle	[pax]
v_7	Vehicle curb mass	[kg]
γ_ε	Strength factor	[–]
ε	Serial number of the serial factor	[–]

1. Introduction

Emissions and congestion are currently the most pressing challenges in big cities. Therefore, the electrification of the urban diesel-powered bus network is increasingly urgent. Several cities have committed to zero-emission vehicles; target dates for replacing their fleets have been set between 2025 and 2035 [1]. However, decision-makers have little information about these new types of vehicles. Therefore, very often, expensive and ad-hoc developments are implemented that do not serve optimal solutions at a system level.

The battery capacity and consumption of a battery electric bus (BEB) determine its daily range and the required charge level and, accordingly, its applicability. Four basic operational parameters influencing consumption are investigated primarily in specific literature: stop spacing ([2,3]), ambient temperature ([2–6]), topography ([6–8]) and passenger load. ([2,8]). However, these papers only estimate a few factors without revealing the correlations between basic technical parameters of BEBs and route parameters and, even though different buses may be suitable for steep mountain lines or downtown lines with several stops. Moreover, the scientific literature lacks comprehensive comparisons of BEBs or focuses solely on technical parameters while neglecting important line and operational characteristics, such as in Ref. [9].

Accordingly, the research question was: How can the compliance of a BEB for an urban bus line be determined considering relevant route and vehicle parameters? Accordingly, we aimed to determine the compliance indicator, which expresses the efficiency of using a

Table 1
Reviewed scientific publications.

Research topic	Article No.	Vehicle parameters				Route parameters			
		Max. engine power	Max. charging power	Battery capacity	Con-sumption rate	Topo-graphy	Stop spacing	Ambient tempera-ture	Passen-ger load
Consumption modeling	[2]	Yes	No	Yes	Yes	No	Yes	Yes	Yes
	[4]	Partly	Partly	Yes	Yes	Partly	Yes	Yes	Yes
	[5]	No	No	Yes	Yes	No	Partly	Yes	No
	[6]	Yes	No	No	Partly	No	No	Yes	Partly
	[8]	No	Partly	Yes	Yes	Yes	Yes	Yes	Yes
	[11]	Yes	Partly	Yes	Yes	Yes	No	No	No
	[12]	Yes	No	Yes	Yes	Partly	No	Yes	Yes
	[13]	Yes	No	Yes	Yes	No	No	No	No
	[14]	Yes	No	Partly	No	Partly	No	No	No
	[15]	Partly	Yes	Yes	Yes	No	Yes	Yes	No
HVAC analysis, control	[16]	No	No	No	Yes	No	No	Yes	No
	[17]	No	No	No	Partly	No	No	Yes	Yes
Acceleration control	[18]	No	No	No	No	No	Partly	No	No
	[19]	Yes	No	Yes	Yes	Yes	No	No	No
Regenerative braking	[20]	Yes	Partly	Partly	No	Yes	Partly	No	No
Energy saving	[21]	Yes	No	Yes	Yes	Yes	No	No	No
Bus selection	[9]	Yes	Yes	Yes	No	No	No	No	No
Battery sizing	[22]	No	Yes	Yes	No	Yes	Partly	Yes	Yes
Charging optimization, scheduling	[23]	No	Yes	Yes	No	No	No	No	No
	[24]	Yes	Yes	Yes	Yes	Yes	No	Partly	No
	[7]	No	Yes	Yes	Yes	No	No	Yes	Partly
	[10]	No	Yes	Yes	Yes	No	No	Yes	No
	[25]	No	Yes	Yes	Yes	No	No	Partly	No
	[26]	No	No	Yes	Yes	No	No	No	Partly

BEB in a bus line from a technical point of view. Accordingly, the buses can be ranked in order to select the best option for a line. As the vehicle scheduling and charging characteristics may differ significantly among different bus fleets [10], the best-fitted buses for a line should be selected first. The method present in this paper can be applied as an initial step during the electrification of the current bus fleet before the charging location and power selection. The method developed is a decision-making tool before purchasing BEBs or planning their daily operation.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a multi-aspect decision-making method, was adapted to define criteria derived from vehicle and route parameters. As a limitation, opportunity chargers at the stops or on-route chargers were out of the scope of this study. Moreover, as the aim was to determine the correspondences between technical parameters and route parameters, not to create a cost-benefit analysis, economic costs (e.g., capital, depreciation, maintenance, and energy costs) calculation were also neglected. This paper presents an extensive application case involving 58 bus lines, examining each line individually and collectively in both directions. The bus lines are grouped based on the route-based operational aspect; the hypothesis was that the same BEB type could be used for a bus line category. Furthermore, a sensitivity analysis was conducted to prove the independence of the variables (criteria) considered. As a limitation, the paper does not consider any economic factors and focuses only on the technical compliance of a BEB for a bus line.

The paper is structured as follows: Section 2 reviews the literature. Section 3 presents the method elaborated. The application case of the method is discussed in Section 4. The paper is completed with concluding remarks.

2. Literature review

Four vehicle-related and four route-related parameters describing consumption and energy use were identified during the review. The vehicle-related parameters are max. engine power, max. charging power, battery capacity, and consumption rate, while the route-related parameters are topography, stop spacing, ambient temperature, and passenger load parameters. Table 1 describes whether a parameter was investigated in the paper reviewed. We found that no paper had taken into account all the parameters. These parameters form the basis of this paper considering them during the compliance indicator determination.

The primary parameter determining the applicability of a BEB is the battery size. In general, the higher the battery capacity is, the longer the daily run is. However, the actual energy consumption depends on several factors. Optimizing energy use consists of consumption minimization while ensuring satisfactory acceleration and regeneration (e.g., ascents, re-reaching the traffic speeds) [20]. The consumption can be estimated based on the current road situation, driver behavior (aka route-specific parameters), vehicle parameters, and ambient temperature [27]. The driver's behavior and style, especially the acceleration, affect consumption [19,18,21]). Depending on the driving behavior, 35 % energy savings can be achieved. The dynamic parameters can be improved as a function of *maximum engine power* [12,13,14]. Considering the *topography*, an energy calculation was made, considering the effect of the rise and fall on the total consumption by Ref. [11]. It was found that the vehicle uses only 82 % of its consumption in generator mode. The *stop spacing* is also important for energy models, as frequent acceleration can enhance consumption [2,15,28]. The impact of the *ambient temperature* is high on the consumption because of the heating-cooling system (HVAC) operation [16,29], especially during heating in wintertime [30,31]. A poorly configured system can mean a 40–45 % reduction in range [17]. Moreover, the temperature may influence the charging power, especially if solar power is used for charging BEBs at the depot [25]. *Passenger load* also affects vehicle and HVAC system consumption, accounting for up to 5–6% of overall consumption [17]. Accordingly, on the one hand, the dynamic load of passengers has a high impact on consumption [2], but on the other hand, the higher the passenger load is, the smaller the cost of the bus trip per person is [32]. That can be seen in the consumption and cost analysis of electric buses and buses with alternative drives [33,34]. Besides the drivetrain and power output, the power intake, namely the *charging power*, is also a considerable aspect as it influences the re-applicability of a bus [22,23]. Furthermore, the available charging capacity at the charging stations can also influence the re-applicability and scheduling [26]. However, as a limitation, the management and scheduling of BEBs were neglected in this study.

Several Multi-Criteria Decision-Making (MCDM) methods have been used for selection in different transport systems. The general MCDM logic and the life-cycle assessment were combined to determine the optimal distribution of alternative propulsion in passenger cars [35]. In addition, fuzzy multiple-criteria decision-making was applied to solve the problem of alternative-fuel bus selection [36,37]. Moreover, descriptive comparison techniques were also used to analyze the alternative fuel types [38]. Considering 8–10 criteria for the evaluation of complete systems, the AHP method is the preferred technique, which includes the selection between options (e.g., trams [39], compressed natural gas (CNG) buses [40]. Overall, finding weights is arbitrary, so this technique can be used per se to select and discard a particular system. Therefore, it is not recommended on its own. Another technique is the matrix-based weights determination method, the TOPSIS method (Technique for Order of Preference by Similarity to Ideal Solution). Selecting the options that represent the real alternative is possible less arbitrarily and more professionally based on the pre-defined data. Accordingly, as our aim is to minimize arbitrariness, the TOPSIS method was chosen for the determination of the compliance indicator. However, determining the weight of TOPSIS is challenging; an ordinal priority approach or AHP is often included [9]. In our study, to handle this issue, we have developed several scenarios applying different weights. Previously, this method was used in the selection of vehicles [41], monorail technologies [42], electric buses [9], and rapid transit systems [43]. In Ref. [9], only technical parameters were compared. As a novelty, we verify the compliance of the BEB using bus line specific metrics.

Based on the literature, the aspects influencing consumption and, thus, the compliance of a BEB are comprehensive. Several route and vehicle parameters influence compliance. The TOPSIS method is an appropriate tool to integrate positive and negative aspects into a common decision-making process. Though TOPSIS does not determine the absolute best option, it identifies the best relative option among the known and available options; thus, it can support the decision-making processes.

3. Methodology

The steps of the developed compliance indicator determination method are depicted in Fig. 1. The number of boxes refers to the further sub-section describing a step. Based on the literature review, we identified vehicle-related and route-related parameters that can influence the compliance of a BEB in a line (Section 3.1). Criteria (Section 3.2) and Exclusions (Section 3.3) were formed to integrate the parameters and manage the outliers. The TOPSIS method was adapted to determine the compliance indicator of a BEB in a given line (Section 3.4). TOPSIS allows finding trade-offs between criteria with different performances; accordingly, the indicator given is more thorough and expressive. Moreover, based on the calculated compliance indicator, the options, namely the BEBs, can be ranked; thus, different BEBs can be compared quantitively. The TOPSIS method is not used to determine the absolute best option but to rank the vehicles considered. The best bus among the compared ones is determined. The alternative to be chosen is the shortest distance from the ideal solution and the furthest from the most useless solution. The ideal solution minimizes the cost (disadvantageous) criteria and maximizes the benefit (advantageous) criteria. In general, costs need to be reduced while benefits need to be increased [19]. Finally, a sensitivity analysis regarding the criteria dependency is concluded in Section 3.5.

As a limitation, only BEBs charged once a day are considered, and dynamic traffic characteristics (congestion, prohibited signs, etc.) are not considered. As a simplification, energy consumption calculation is based on an average and continuous acceleration and deceleration. The ambient temperature was considered only indirectly through the consumption rate. The ambient temperature influences the consumption, especially if the HVAC system is in operation. It is worth planning for the worst-case scenario. According to Ref. [31], the consumption rate is more considerable in lower temperatures (wintertime) than in higher temperatures (summertime).

3.1. Vehicle and route parameters

The basic v_α vehicle parameters of buses and r_β route parameters considered are summarized in Table 2. The maximum speed and the range are neglected as these data may be derived from the basic parameters.

v_1 *Maximum power:* The peak performance to complete the entire journey and take all the slopes. This parameter prescribes whether a bus is applicable for mountain routes. Either providing peak power on short slopes or delivering high power on a longer slope without overheating is necessary. Beyond these, if a vehicle travels at a similar load (the inclination angle is identical), it is worth scaling the electric motor to the operating point to keep energy consumption low.

v_2 *Drivetrain efficiency:* The energy utilized in percentage. The drivetrain efficiency depends on the drive system parts, clutch, differential, final gear, and all parts involved in the drive.

v_3 *Consumption rate:* Average energy a bus consumes per kilometer on a plane area, without stopping. Consumption data are measured by specified standard driving cycles.

v_4 *Battery capacity:* The total amount of electricity stored in the battery; the higher this value is, the greater the distance the bus can cover.

v_5 *Max. charging power:* The maximum power a BEB can be charged with. The charging power is decisive during the daily operation whether the fast charging option at the terminal is suitable or only normal charging can be used at the depot.

v_6 *Passenger capacity:* Maximum passenger a bus transports. The general aim is its maximization.

v_7 *Vehicle mass:* The unladen weight of the bus. The general aim is to keep the unladen (curb) weight of the bus as low as possible. A heavier bus may have higher consumption and energy consumption.

r_1 *Elevation:* The altitude difference of the highest and lowest point on the line. The energy consumption may depend on the altitude profile.

r_2 Steepness: Descriptive metric of the route; the angle of inclination of its steepest point.

r_3 *Trip length,* r_4 *Number of stops:* The average distance between stops is the quotient of the line length (r_3) and the number of stops (r_4).

r_5 *Speed limit:* The general speed limit allowed on the route.

r_6 *Max. passenger load:* The average number of passengers per trip in the busiest section at peak.

r_7 *Average speed:* The average speed of the bus during the trip according to the timetable.

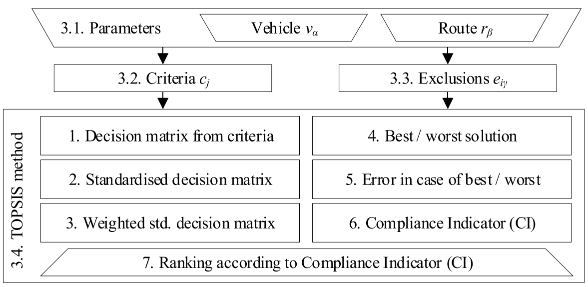

Fig. 1. Steps of the compliance indicator determination method.

Table 2
Vehicle and route parameters.

A	v_α vehicle parameter	β	r_β route parameter
1	Maximum power [kW]	1	Elevation [m]
2	Drivetrain efficiency [−]	2	Steepness [°]
3	Consumption rate [kWh/km]	3	Trip length [km]
4	Battery capacity [kWh]	4	Number of stops [−]
5	Max. charging power [kW]	5	Speed limit [km/h]
6	Passenger capacity in a vehicle [pax]	6	Max. hourly passenger load [pax/h]
7	Vehicle curb mass [kg]	7	Average speed [km/h]

3.2. Criteria

Common metrics are created to consider the route parameters as bus-related parameters; accordingly, the vehicle and route parameters form c_j criteria describing consumption and compliance. Cost and benefit criteria were determined whether the correlation between a criterion and the consumption per capita is negative or positive. The cost criteria are as follows: (1) Braking loss [kWh/km], (2) Elevation loss [kWh/km], and (3) Charging time. The benefit criteria are as follows: (4) Gradeability speed [km/h], (5) Passenger load, and (6) Number of trips [−]. The total consumption of the vehicle may be increased by a criterion (e.g., maximum capacity), but this criterion has a decreasing effect on the consumption per capita. Each consumed energy is determined for the whole line (inward and outward) based on the average consumption and the kinetic and potential energy of the bus.

3.2.1. Cost criteria

c_1 *Braking loss:* This is calculated from kinematic energy according to Eq. (1). In practice, deceleration and acceleration phases are included in each stop section.

$$c_1 = \frac{r_4 \cdot v_7 \cdot r_5^2}{r_3} \tag{1}$$

c_2 *Elevation loss:* The general metrics of the terrain define the maximal potential energy of elevation (Eq. (2)). This value is derived from the most significant height difference that the vehicle must overcome. The height difference is counted as a vehicle-specific criterion based on the potential energy considering the g acceleration of gravity [m/s^2].

$$c_2 = \frac{v_7 \cdot g \cdot r_1}{r_3} \tag{2}$$

c_3 *Charging time:* The re-availability, namely, the total charging time, influences the daily schedule of a bus. The charging time is calculated using the simplification expressed in Eq. (5).

$$c_3 = \frac{v_4}{v_5} \tag{3}$$

3.2.2. Benefit criteria

c_4 *Gradeability speed:* The gradeability speed on the slope of the steepest section is evaluated by Eq. (4). On a slope, the vehicle must travel with the least perceptible resistance on the steepest section of the slope; the speed loss due to the lack of torque must be as small as possible. Fluid resistance and rolling resistance shall not be considered.

$$c_4 = \frac{v_1}{v_7 \cdot g \cdot sin r_2 \cdot v_2} \tag{4}$$

c_5 *Passenger load:* The passenger load influences vehicle mass, thus the consumption. However, energy consumption per capita will be even lower if passenger load is considered. The average passenger load is calculated by Eq. (4) and defined as the average load of the daily operating period.

$$c_5 = \frac{r_6 \cdot r_1}{v_6} \tag{5}$$

Table 3
Exclusions.

k	e_{ik} exclusion	Example
1	Minimum gradeability speed [km/h]	$c_5 > 15$ km/h
2	Passengers to be transported [pax]	$v_6 <$ Max. momentary number of passengers
3	Maximum charging time [hour]	$c_3 < 8$h
4	Minimum number of trips [−]	$c_6 < 2$
5	Maximum vehicle mass [t]	$v_7 < 20$ t for single bus, $v_6 < 30$ t for articulated bus
6	Geometric clause [−]	an articulated bus cannot travel in narrow streets

c_6 *Number of trips:* The operation efficiency of a bus is expressed by the number of trips performed (Eq. (6)).

$$c_6 = \frac{v_4}{(v_3 + c_1 + c_2) \cdot r_4} \tag{6}$$

3.3. Exclusions

Some $e_{i\gamma}$ exclusions of i buses are applied to consider only the buses that can fulfill a minimum service expectation (Table 3). Example values describing minimum expectations were added.

e_1 *Minimum gradeability speed:* This is fundamental for keeping the schedule and vehicle dynamics.
e_2 *Passengers to be transported:* This value would be higher than the capacity to meet the demand.
e_3 *Maximal charging time:* The longer the charging time, the less likely the bus is to be ready for a shift.
e_4 *Minimum number of trips:* If the vehicle cannot complete turns, its applicability is low.
e_5 *Maximum vehicle mass:* The vehicle may be prohibited from running on the route over a given mass.
e_6 *Geometric clause:* Not all types can be run on a route (e.g., articulated buses cannot turn in a narrow street).

3.4. Adaptation of the TOPSIS method

Based on the general steps of the TOPSIS [44], we defined the following steps for the calculation of the compliance indicator of a BEB in a given line.

1. Decision matrix from defined vehicle and route-based criteria: Creating a decision matrix for ranking and decision making (Eq. (7)) where a mxn matrix consists of m rows connection to the optional BEBs (O_i where $i = 1.m$) and n columns connecting to the criteria (C_j where $j = 1.n$; in this paper, $n = 6$ as six c criteria are analyzed). The c_{ij} cell of the matrix represents the value of c_j criterion in the case of i BEB.

$$M = \begin{bmatrix} O_1 \\ O_2 \\ \vdots \\ O_i \\ \vdots \\ O_m \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1j} & \cdots & c_{1n} \\ c_{21} & c_{21} & \cdots & c_{2j} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ c_{i1} & c_{i1} & \cdots & c_{ij} & \cdots & c_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ c_{m1} & c_{m1} & \cdots & c_{mj} & \cdots & c_{mn} \end{bmatrix}; X = \begin{bmatrix} C_1 & C_2 & \cdots & C_j & \cdots & C_n \end{bmatrix} \tag{7}$$

2. Standardized decision matrix: Creating a standardized decision matrix $N(= n_{ij})$ (Eq. (8)).

$$n_{ij} = \frac{c_{ij}}{\sqrt{\sum_{i=1}^{m} c_{ij}^2}} \quad i = 1, 2, \ldots, m; j = 1, 2, \ldots 6 \tag{8}$$

3. Weighted standardized decision matrix: Weighting a standardized decision matrix $T(= t_{ij})$ (Eq. (9)) where w_j ($\Sigma\, w_j \equiv 1$) is the weight for C_j criteria, which is the same for each option, namely BEB (O_i). The w_j weight can be determined according to the different objective functions (e.g., in a hilly area, the gradability criterion has a higher weight).

$$t_{ij} = w_j \cdot n_{ij} \quad i = 1, 2, \ldots, m\,;\, j = 1, 2, \ldots 6 \tag{9}$$

4. Best/worst solution: Determining a positive ideal (O_{best} best BEB option, Eq. (10)) and a negative (O_{worst} worst BEB option, Eq. (11)) ideal solution.

$$O_{best} = \left\{ \langle \max_i \left(t_{ij} \middle| i = 1, 2, \ldots, m \right) \middle| j \in J_- \rangle, \langle \min_i \left(t_{ij} \middle| i = 1, 2, \ldots, m \right) \middle| j \in J_+ \rangle \right\} \equiv \left\{ t_{bj} \middle| j = 1, 2, \ldots, 6 \right\} \tag{10}$$

$$O_{worst} = \left\{ \langle \min_i \left(t_{ij} \middle| i = 1, 2, \ldots, m \right) \middle| j \in J_- \rangle, \langle \max_i \left(t_{ij} \middle| i = 1, 2, \ldots, m \right) \middle| j \in J_+ \rangle \right\} \equiv \left\{ t_{wj} \middle| j = 1, 2, \ldots, 6 \right\} \tag{11}$$

where: $J_+ = \{j = 1, 2, \ldots, 6|j\}$ is associated with the criterion having a positive impact; thus $J_- = \{j = 1, 2, \ldots, 6|j\}$ is associated with the criterion having a negative impact.

5. Error in case of best/worst: Determining the difference rate (square error) between the criteria of the given BEB and the criteria of the best BEB (d_{ib}, Eq. (12)) or the criteria of the worst BEB (d_{iw}, Eq. (13)).

$$d_{i,best} = \sqrt{\sum_j^n (t_{ij} - t_{bj})^2} \quad i = 1, 2, \ldots, m \tag{12}$$

$$d_{i,worst} = \sqrt{\sum_j^n (t_{ij} - t_{wj})^2} \quad i = 1, 2, \ldots, m \tag{13}$$

6. Compliance indicator: Determining the compliance indicator (CI), CI means the similarity to the O_{best} best BEB option (Eq. (14). $CI = 1$ only if a BEB option has the best criteria, and $CI = 0$ only if a BEB option has the worst criteria.

$$CI = \frac{d_{i,worst}}{d_{i,worst} + d_{i,best}}, 0 \le CI \le 1, i = 1, 2, \ldots, m \tag{14}$$

7. Ranking according to Compliance Indicator: Ranking the considered BEB options according to their similarity with the best BEB option.

Although one bus runs on the whole line, the steps are performed in both directions to determine the local optimum. The elevation loss (in the case of hillside lines), braking loss (based on different expressway directions, stopping order), and passenger load (due to alternative options, e.g., different trip, round trip); thus, the consumption may differ in each direction, and the operating environment may also differ in the two directions. The total CI is measured by taking the average of the original sequence numbers of the two directions and ranking the averages. This can result in BEB option 1 fitting uphill, BEB option 2 fitting downhill, and BEB option 3 fitting the whole line.

3.5. Sensitivity analysis

A sensitivity analysis was done to examine the independence of the criteria; the weight of the cost and benefit criteria was changed. Sensitivity regards the reactivity of the result's distortion. 24 nominal and 24 weighted sensitivity cases were formed. The original nominal and weighted cases are strengthened by a γ_ε strength factor where ε is the serial number of the serial factor $\varepsilon = 1 \ldots 4$ and $\gamma_\varepsilon \in [0; 0.75; 1.5; 3]$ according to Eq. (15).

$$w' = \gamma_\varepsilon \bullet w_j \tag{15}$$

The deviation of the rankings from the original nominal or weighted case can be calculated for all 48 cases and each bus. The deviation of the serial number of the given vehicle must be looked at in absolute value. The deviation in the serial number is calculated according to Eq. (16). The value shifts were normalized by the number of bus types selected per line.

$$\Delta_j = \sum_l \sum_{p=(\varepsilon-1)\bullet j+1}^{\varepsilon\bullet j} \frac{|ranking_{l,i,0} - ranking_{l,i,p}|}{i} \Bigg|_{nom/wgt} \tag{16}$$

where l is the bus lines, i is the number of bus models, p is the serial number of sensitivity test; p is the following according to the criteria: braking loss c_1, $p = 1 \ldots 4$; elevation loss c_2, $p = 5 \ldots 8$; charging time c_3, $p = 9 \ldots 12$; gradeability speed c_4, $p = 13 \ldots 16$; passenger load c_5, $p = 17 \ldots 20$; number of trips c_6, $p = 21 \ldots 24$.

The final ranking is derived from summating these rankings as a negative ranking. The best one is where the rankings are the smallest.

4. Result and discussion

4.1. Application case

Budapest was selected as an application case as most of the bus network has not been electrified. There are only a half dozen electric buses in the city center and a few in the suburbs. Therefore, at this initial stage, the proper selection of BEBs can contribute to efficient electrification.

The capital of Hungary has flat and hilly areas. It has an extended public transport network. In the inner city, 7 out of 10 people use public transport; in the outer districts and suburbs, this ratio is 3 out of 10. In Budapest, more than 1.3 billion passengers travel on the public network yearly, and the average number of passengers per workday is 3.1 million [45]. Besides underground and tram lines, there are 244 bus lines on a 3000 km network and 15 trolleybus lines on an almost 100 km network with a catenary system. Bus lines have different characteristics (e.g., express, feeder, and on-demand). The number of people traveling by bus is significant; more than

50 % of the trips are done by bus. This was 673 million in 2018 before the Covid crisis [46]. In addition, the number of people traveling by trolleybus is also significant; this sector carries 100 million passengers every year. Furthermore, 430 million people travel by tram, and more than 200 million passengers travel on the metro lines yearly [47].

Data sources: The route parameters were retrieved from Google Maps and Elevation Finder - Free Map Tools; scheduling and passenger load data were provided by the BKK Centre for Budapest Transport. Vehicle parameters were given by the eBus Report implemented in the European Commission's ZeEUS program [48]. This report published real operational data on electric buses running in different cities.

To conclude general consequences, bus lines were categorized according to *length*, *average stop distance*, *average speed, topography, and passenger load.* In each aspect, 2–4 sub-aspects can be distinguished; theoretically, 216 categories can be formed. Table 4 summarizes the categories, sub-categories, and considered category values; the number of lines that fit into a category is given in the last column.

Category values may differ in the application fields. The trip length is a primary parameter [2,15], and it is related to the endurance of the bus. Topography describes the characteristics of the bus line (height differences, max. steepness) [16,19,20,21]. Passenger load is described by the hourly average number of passengers during operation hours [2,15,29]. During the application case, the hypothesis was that the six criteria mentioned above could be used to determine the order in which the best option for a given bus line would be selected. In Budapest, bus lines can be classified into 21 categories. In order to prove the hypothesis, 58 bus lines were further analyzed. In most categories, at least 2 lines were analyzed. In addition, 30 buses were evaluated (8 midi, 18 single, 4 articulated) to provide a comprehensive and multi-optional analysis of bus types (options).

4.2. Compliance indicator

The compliance indicator was determined for each route, considering all buses. Two bases of the tests were distinguished.

- nominal: the weights are equal; $w_j = 1/6$. ($j = 1 \dots 6$)
- weighted: the weights are $w_1 = w_2 = w_5 = 1/10$, $w_3 = w_4 = 2/10$, and $w_6 = 3/10$. These weights highlight the importance of the number of trips a bus performs (w_6), passenger comfort, and consumption (w_3, w_4).

In both cases, directions "A" and "B" were also calculated. As a limitation, the efficiency of the drivetrain from the battery to the wheels v_2 is assumed to be constant for each vehicle ($v_2 = 0.7$).

As an example, the result for bus line 21 is detailed. Main characteristics: middle length, middle stop distance, slow average speed, hillside, and high passenger load (crowded). The considered r_β route parameters are: elevation $r_1 = 341$ m, steepness $r_2 = 7.6°$, trip length $r_3 = 11$ km, the number of stops $r_4 = 22$, speed limit $r_5 = 30$ km/h, and max. passenger load $r_6 = 59$ pax/h. Table 5 contains the criteria (step 1) according to directions for each BEB considered. The general vehicle parameters considered are given in the Appendix. Only midi and solo buses were analyzed as the γ_6 geometric limitation. There are a few differences in braking loss c_1; the range is from 0.2 to 0.4 kWh/km, depending on vehicle weight. The elevation loss c_2 varies between 1.0 and 1.5 kWh/km. It is noticeable how much higher these values are if the bus line is a long hillside one. The gradeability speed c_4, which expresses the actual peak power of the engine, varies from 15 to 28 km/h on the steepest section. In the downward "B" direction, the gradeability speed permitted on the line is considered 80 km/h. As buses drive on a slope for almost the entire trip, the maximum speed can be maintained in any case. In the case of passenger load c_5, the differences are given by the maximum allowed number of passengers on the bus. There are considerable differences in charging time c_3, depending on the battery capacity and the charging infrastructure. Charging times vary from 9 min to more than 4 h. Accordingly, the number of trips c_6 varies from 2.5 to 10 trips. Although the BEB-22 weighs less, the BEB-04 has four times more energy storage.

Table 4
Categorization aspects of bus lines.

Aspect	Sub-aspect	Value	Number of lines (in Budapest)
Length	short	$r_2 \leq 5$ km	27
	middle	5 km $< r_2 <$ 20 km	189
	long	$r_2 \geq 20$ km	28
Average stop distance	short	$r_3/r_4 \leq$ 0,35 km	27
	middle	0,35 km $< r_3/r_4 <$ 0,8 km	187
	long	$r_3/r_4 \geq$ 0,8 km	30
Average speed	slow	$r_7 \leq 20$ km	33
	middle	20 km/h $< r_7 <$ 30 km/h	156
	fast	$r_7 \geq 30$ km/h	55
Topography	flat	$r_1 \leq 20$ m	47
	hillside	$r_1 > 20$ m	197
Passenger load	sparse	$r_6 \leq 50$ pax/h	15[a]
	middle	$50 < r_6 \leq 125$ pax/h	22[a]
	crowded	$125 < r_6 \leq 250$ pax/h	10[a]
	overcrowded	$r_6 > 250$ pax/h	8[a]

[a] Only 58 investigated bus lines were categorized due to the availability of the passenger data.

Table 5
Criteria calculated of buses considered on bus line 21.

Bus variant	Direction "A" (uphill)						Direction "B" (downhill)					
	c_1	c_2	c_3	c_4	c_5	c_6	c_1	c_2	c_3	c_4	c_5	c_6
BEB-01	0.23	1.3	4:21	38.2	29.3 %	11.28	0.23	−1.3	4:21	80.0	27.8 %	11.28
BEB-02	0.24	1.4	2:34	21.8	31.9 %	12.20	0.25	−1.4	2:34	80.0	30.3 %	12.20
BEB-03	0.35	2.0	5:31	20.9	22.2 %	10.51	0.35	−2.0	5:31	80.0	21.1 %	10.51
BEB-04	0.24	1.3	4:08	27.2	30.9 %	11.72	0.24	−1.4	4:08	80.0	29.3 %	11.72
BEB-05	0.22	1.3	1:24	21.0	37.6 %	3.52	0.23	−1.3	1:24	80.0	35.6 %	3.52
BEB-06	0.25	1.4	1:13	17.9	29.3 %	5.90	0.25	−1.4	1:13	80.0	27.8 %	5.90
BEB-07	0.28	1.6	3:45	19.1	34.7 %	10.32	0.28	−1.6	3:45	80.0	33.0 %	10.32
BEB-08	0.22	1.2	0:09	24.5	34.7 %	2.84	0.22	−1.2	0:09	80.0	33.0 %	2.84
BEB-09	0.27	1.5	1:37	27.1	32.7 %	6.54	0.27	−1.6	1:37	80.0	31.0 %	6.54
BEB-10	0.25	1.4	3:17	18.0	47.9 %	5.50	0.25	−1.4	3:17	80.0	45.5 %	5.50
BEB-11	0.25	1.4	2:18	28.5	35.2 %	8.35	0.25	−1.4	2:18	80.0	33.4 %	8.35
BEB-12	0.34	1.9	1:30	41.7	20.3 %	8.08	0.34	−1.9	1:30	80.0	19.2 %	8.08
BEB-13	0.25	1.4	2:18	18.6	33.9 %	6.83	0.26	−1.5	2:18	80.0	32.2 %	6.83
BEB-14	0.25	1.4	0:32	29.2	30.9 %	8.56	0.25	−1.4	0:32	80.0	29.3 %	8.56
BEB-15	0.38	2.1	0:32	21.1	21.5 %	5.78	0.38	−2.2	0:32	80.0	20.4 %	5.78
BEB-16	0.23	1.3	0:32	21.6	42.8 %	6.26	0.23	−1.3	0:32	80.0	40.6 %	6.26
BEB-17	0.21	1.2	1:08	16.5	30.9 %	6.25	0.22	−1.2	1:08	80.0	29.3 %	6.25
BEB-18	0.25	1.4	0:10	31.6	30.9 %	2.17	0.25	−1.4	0:10	80.0	29.3 %	2.17
BEB-19	0.20	1.1	1:40	29.2	42.8 %	7.51	0.20	−1.2	1:40	80.0	40.6 %	7.51
BEB-20	0.25	1.4	0:48	20.4	34.3 %	4.23	0.25	−1.4	0:48	80.0	32.6 %	4.23
BEB-21	0.26	1.5	0:40	17.9	37.1 %	5.83	0.27	−1.5	0:40	80.0	35.2 %	5.83
BEB-22	0.24	1.3	0:15	19.1	26.5 %	2.89	0.24	−1.4	0:15	80.0	25.1 %	2.89
BEB-23	0.26	1.5	2:48	22.8	28.7 %	13.75	0.26	−1.5	2:48	80.0	27.2 %	13.75

The compliance indicator considering the nominal final ranking according to the cases and directions is summarized in Table 6 for each BEB. In the case of bus line 21, direction "A" means a steep direction going up the mountain, in which the engine must hold fast on the steep slope. Direction "B" means the returning, descending direction, where the absorption losses are adverse, i.e., the vehicle can gain energy from the slope for its trip. These indicate that the engine mode is less important in this section, and the recuperation is significant because of the generator mode. Considering both directions, the average of the results of both directions was calculated. In summary, the best bus among the compared single and midi buses is BEB-14 for the nominal test and BEB-23 for the weighted test. In addition, 7 bus types were excluded because of insufficient passengers to be transported (e_{i2}) and the number of trips (e_{i4}) criteria.

The bus line categories were merged based on the ranking if at least three ranking positions were the same. This resulted in 14 categories out of the original 21 categories. Table 7 describes the primary characterization of the categories, giving examples from Budapest. The main reason for merging the categories was the speed, as there is no significant difference between low and medium-

Table 6
Compliance indicator and ranking on bus line 21.

Bus variant	"A" nom.		"B" nom.		"A" wgt.		"B" wgt.	
	CI	Rank	CI	Rank	CI	Rank	CI	Rank
BEB-01	0.4806	19	0.4178	22	0.6617	③	0.6019	4
BEB-02	0.5830	8	0.6003	7	0.6709	②	0.7128	②
BEB-03	0.2881	23	0.3278	23	0.4847	10	0.5518	7
BEB-04	0.4654	20	0.4447	21	0.6373	4	0.6301	③
BEB-05	0.5472	16	0.5516	17	0.3519	22	0.3243	23
BEB-06	0.5618	15	0.5943	10	0.4144	16	0.4247	17
BEB-07	0.4335	22	0.4578	19	0.5440	9	0.6000	5
BEB-08	0.6073	4	0.6021	7	0.3859	18	0.3543	19
BEB-09	0.5799	11	0.5876	13	0.4598	12	0.4526	13
BEB-10	0.4370	21	0.4478	20	0.3508	23	0.3463	21
BEB-11	0.5803	10	0.5671	16	0.5511	7	0.5305	9
BEB-12	0.5943	7	0.5878	12	0.5671	6	0.5506	8
BEB-13	0.5050	18	0.5320	18	0.4248	15	0.4414	15
BEB-14	0.7032	①	0.6999	①	0.6050	5	0.5907	6
BEB-15	0.5429	17	0.6063	6	0.3961	17	0.4698	12
BEB-16	0.6532	③	0.6736	②	0.4768	11	0.4737	11
BEB-17	0.5805	9	0.6066	5	0.4407	13	0.4404	16
BEB-18	0.6000	6	0.5865	14	0.3812	19	0.3409	22
BEB-19	0.6555	②	0.6194	4	0.5496	8	0.4965	10
BEB-20	0.5790	12	0.5997	9	0.3784	20	0.3725	18
BEB-21	0.6019	5	0.6497	③	0.4270	14	0.4501	14
BEB-22	0.5684	14	0.5853	15	0.3576	21	0.3488	20
BEB-23	0.5718	13	0.5891	11	0.6988	①	0.7456	①

Table 7
Bus line categories in Budapest.

No. of cat.	Line	Stop	Speed	Topography	Passenger load	Bus lines
I.	short	short	slow/middle	flat	sparse/crowded	181, 199, 220
II.	short	short/ middle	slow/middle	hillside	sparse/middle/ crowded	16A, 16, 27, 39, 116, 149
III.	short/ middle	middle	fast	hillside	sparse	65A, 65
IV.	middle	short	middle	flat/gentle hillside	sparse/middle	38, 102, 156, 194
V.	middle	middle	slow/middle	flat	sparse/middle/ crowded	9, 26, 30, 30A, 40, 40B, 87, 105, 109, 194B
VI.	middle	middle	slow	hillside	middle/crowded	11, 21, 53, 108E, 139, 178, 22, 212, 221
VII.	middle	middle	fast	flat	sparse/middle	10, 84E, 113, 113A, 161, 187
VIII.	middle/long	long	fast	flat	middle/crowded	40E, 101E, 161E, 200E
IX.	middle/long	middle/long	middle	flat	middle	46, 217E, 284E
X.	middle/long	middle/long	middle	flat	middle/crowded	66E, 148
XI.	long	middle/long	slow/middle/ fast	flat	crowded/very crowded	7, 7E, 133E, 97E
XII.	long	middle	middle	flat	very crowded	5
XIII.	long	middle	middle	hillside	very crowded	8E
XIV.	extra long	long	fast	flat	crowded	100E

speed lines.

Table 8 contains the top three bus types in each direction and the aggregated results for each bus line category in the weighted test. In the top three positions, nine bus types are distinguished. The most common bus type in the ranking is BEB-23, which was on the podium in 90 % of the cases and took first place in 83 % of the cases. BEB-02 is the second most frequent bus type appearing on the podium in 71 % of the cases, and it was ranked second place in 62 % of the cases. The third most suitable bus type is the BEB-04 model, which appears on the podium in 40 % of all cases and which is ranked 3rd position in 33 % of all cases.

Table 9 contains the main vehicle parameters of the best buses. These are real data, given by the technical data sheet of the manufacturers. The homogenisation of the fleet may also be a very important technical aspect not addressed in the study (e.g. homogenisation by charging powers, - by manufacturers), but the primary aim of the developed method was to provide an elementary selection tool for operators. We concluded that a fleet containing nine different BEB types from seven manufacturers is enough to serve the whole bus network in Budapest.

Considering and highlighting the two directions differently via different weights is possible. In the current research, the weight of the two directions is 50-50 %. However, we took the elevation-related criteria (climbing loss c_2, gradeability speed c_4) as 0.2–0.2; this highlighting helps ensure that the buses go up the slope more smoothly. In addition, the number of trips c_6 criterion was considered with a weight of 0.3, ensuring that the buses can make more trips.

Table 8
Top three BEBs in each bus line category.

No.	Direction„A"			Direction„B"			Direction „A+B"		
	①	②	③	①	②	③	①	②	③
I.	BEB-23	BEB-02	BEB-04	BEB-23	BEB-02	BEB-04	BEB-23	BEB-02	BEB-04
II.	BEB-23	BEB-02	BEB-30	BEB-23	BEB-02	BEB-30	BEB-23	BEB-02	BEB-30
III.	BEB-01	BEB-23	BEB-02	BEB-23	BEB-02	BEB-30	BEB-23	BEB-02	BEB-01
IV.	BEB-23	BEB-02	BEB-30	BEB-23	BEB-02	BEB-30	BEB-23	BEB-02	BEB-30
V.	BEB-23	BEB-02	BEB-04	BEB-23	BEB-02	BEB-04	BEB-23	BEB-02	BEB-04
VI.	BEB-23	BEB-02	BEB-01	BEB-23	BEB-02	BEB-04	BEB-23	BEB-02	BEB-04
VII.	BEB-23	BEB-02	BEB-30	BEB-23	BEB-02	BEB-30	BEB-23	BEB-02	BEB-30
VIII.	BEB-23	BEB-02	BEB-04	BEB-23	BEB-02	BEB-04	BEB-23	BEB-02	BEB-04
IX.	BEB-23	BEB-30	BEB-02	BEB-23	BEB-30	BEB-02	BEB-23	BEB-30	BEB-02
X.	BEB-23	BEB-04	BEB-14	BEB-23	BEB-04	BEB-14	BEB-23	BEB-04	BEB-14
XI.	BEB-23	BEB-02	BEB-04	BEB-23	BEB-02	BEB-04	BEB-23	BEB-02	BEB-04
XII.	BEB-03	BEB-15	BEB-12	BEB-03	BEB-23	BEB-01	BEB-03	BEB-23	BEB-15
XIII.	BEB-12	BEB-03	BEB-15	BEB-12	BEB-03	BEB-15	BEB-12	BEB-03	BEB-15
XVI.	BEB-23	BEB-12	BEB-01	BEB-23	BEB-12	BEB-01	BEB-23	BEB-12	BEB-01

Table 9
Details of the best BEBs.

Bus variant	Bus categories and rank	Type	v_1 [kW]	v_3 [kWh/km]	v_4 [kWh]	v_5 [kW]	v_6 [pax]	v_7 [kg]
BEB-01	III; XIV. ③	single	300	1.29	348	80	95	11540
BEB-02	I-VIII; XI.② IX. ③	single	250	1.35	450	135	51	15583
BEB-03	XII. ①	articu-lated	250	1.275	414	75	125	19500
BEB-04	X. ②, I; V; VI; VIII; XI. ③	single	220	0.85	311	75	90	12000
BEB-12	XIII. ①	midi	180	1.28	385	150	87	12300
BEB-14	X. ③	single	250	0.9	240	450	90	12880
BEB-15	XIII. ③	articu-lated	270	1.3	240	450	129	21228
BEB-23	I-XI; XVI. ①, XII. ②	single	200	1.1	422	150	97	13300
BEB-30	IX. ②, II; IV; VII.③	single	250	1.35	450	135	51	15583

4.3. Sensitivity analysis

The dependency among the considered six criteria ($c_1..c_6$) was analyzed on four different bus lines; two hillside and two flat lines. Bus line 21 overcomes a significant height difference, while line 16 climbs just a small hill. Bus line 100E is an express line with two stops over a long distance, while line 181 is a short line with short stops at a low speed. Table 10 shows the main route parameter of the selected bus lines. According to directions ("A" and "B"), there are two different average speeds; thus, two values are given.

24 nominal and weighted sensitivity cases were defined; in each sensitivity cases a criterion is strengthened by the $\gamma_\varepsilon \in [0; 0.75; 1.5; 3]$ strength factor. With the strengthening, for example, in the first nominal case, the overemphasized criterion c_6 will be $3/6 = 0.5$, while considering the second nominal case, this value will be $9/10 = 0.9$. The test categories are.

a) 24 nominal sensitivity cases based on the original nominal case,
b) 24 weighted sensitivity cases based on the original weighted case,
c) 24 weighted sensitivity cases based on the original nominal case.

Table 11 shows the deviation in rankings aggregating the results of the four considered bus lines.

We concluded that the number of trips, charging time, and passenger load are the most sensitive parameters as the results, namely the rank of a bus, differ significantly in each sensitivity case. This means that counting the number of trips provides an important basis for the ranking; this proved the application of the original weighted case, where $w_6 = 0.3$ was used. In addition, the charging time and passenger load are the second and third most sensitive criteria. Accordingly, this study considered a weight of 0.2 for elevation loss and gradeability speed, ensuring the grade performance of mountain vehicles.

The sensitivity of the criteria in the case of bus line 21 is depicted according to 14 BEBs only for the direction "A"; Fig. 2 deals with the nominal test – a) test category, and Fig. 3 deals with the weighted test – c) test category. Depending on the cases (x-axis), the place occupied in the ranking was represented on the y-axis. The sensitivity cases are as follows in the figures.

- neglect a criterion ($\gamma_\varepsilon = 0$): cases 1, 5, 9, 13, 17, 21
- underestimate a criterion ($\gamma_\varepsilon = 0.75$): cases 2, 6, 10, 14, 18, 22
- slightly overestimate a criterion ($\gamma_\varepsilon = 1.5$): 3, 7, 11, 15, 19, 23
- significantly overestimate a criterion ($\gamma_\varepsilon = 3$): 4, 8, 12, 16, 20, 24

Each case shows a deviation from the original nominal case. There are criteria where the change in the ranking is significant (see the high volatility considering the sensitivity cases in the figures), like charging time, number of trips, and passenger load.

Table 10
Selected bus lines for sensitivity analysis.

Bus line	Line category	Type	r_1 [m]	r_2 [°]	r_3 [km]	r_4 [-]	r_5 [km/h]	$r_{6,\text{"A"}}$ [pax]	$r_{6,\text{"B"}}$ [pax]	$r_{7,\text{ave}}$ [km/h]
21	V	single	341	7.6	11	22	30	27.79	26.37	25.15
16	II	midi	50	3.0	4.7	9	30	19.72	16.36	21.69
100E	XIV	articulated	22	<1.0	25.6	2	50	46.45	37.84	49.69
181	I	single	4	<1.0	3	9	30	11.49	14.43	15.00

Table 11
Sensitivity ranking according to the criteria.

Test category	Braking loss		Elevation loss		Gradeability speed		Passenger load		Charging time		Number of trips	
	Dev.	Rang	Dev.	Rang	Dev.	Rang	Dev.	Rang	Dev.	Rang	Dev.	Rang
a) nominal sensitivity– original nominal	14	⑥	14	⑤	17	④	32	③	66	②	67	①
b) weighted sensitivity– original weighted	3	⑥	3,3	⑤	9,5	④	24	③	43	②	45	①
c) weighted sensitivity– original nominal	119	①	119	②	119	③	117	④	80	⑥	107	⑤
Overall	⑥		⑤		④		③		②		①	

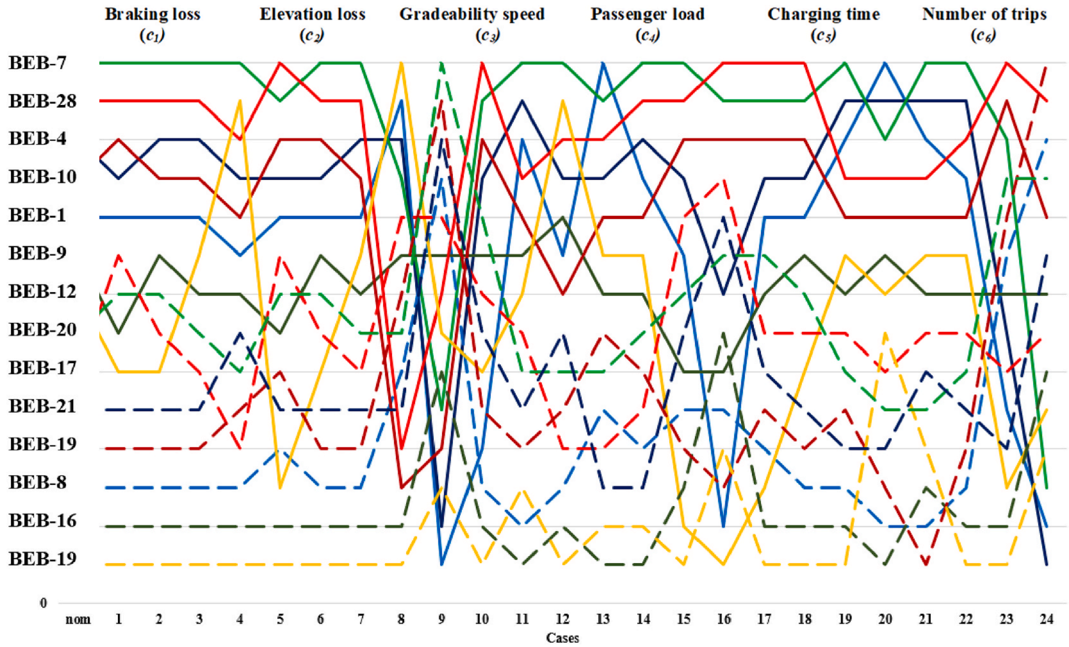

Fig. 2. Sensitivity analysis in the case of bus line 21 for 14 BEBs – a) test category.

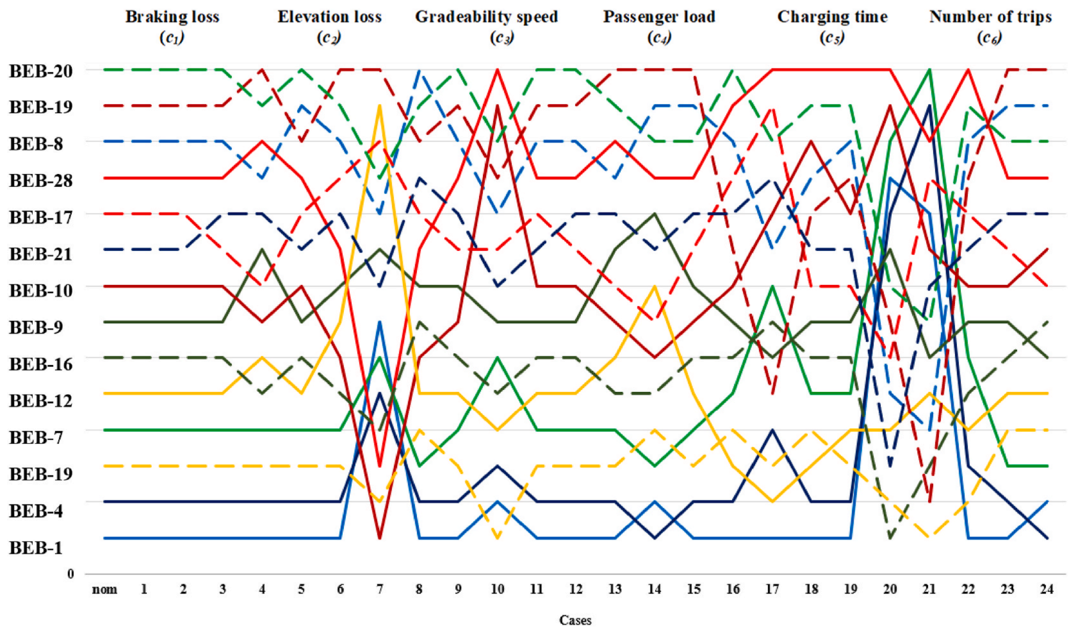

Fig. 3. Sensitivity analysis in the case of bus line 21 for 14 BEBs - c) test category.

Furthermore, there are criteria where the change in the ranking is less significant (see the smoother volatility considering the sensitivity cases in the figures), like breaking loss, elevation loss, and gradeability loss. We can conclude that each criterion is independent, as a change in each criterion leads to a large change in the ranking.

4.4. Discussion

The compliance indicator introduced applies to cities where the electrification is planned by BEBs charged at the depot at night. BEB is currently the most favorable as it requires less investment in charging infrastructure. The operators like this type as the buses provide high flexibility; the buses are not tied to bus lines where the charging infrastructure along the route is available (e.g., terminal charger, catenary network).

Budapest was chosen to test the methodology as the morphology of the city is peculiar, and several different line categories are available. The sub-aspects of bus lines were defined to cover not only the typical lines in Budapest but also the typical lines in European cities. Cities with comparable topography and bus networks to Budapest can benefit the most, such as Prague and Cracow. Completely flat (e.g. Amsterdam, Copenhagen) or mostly hilly (e.g., Grenoble, Sintra) cities can also apply the result of this study, but only the results for flat or hilly line categories should be considered.

The sensitivity analysis showed that the variables are independent. Excluding one of them results in different results. Although the result of the application case can be used as an initial solution for a city, the result can be refined by considering the network characteristics in the given city and choosing the weight values according to the operators' priority.

Compared with [9], we identified route parameters besides vehicle technical parameters during the criteria definition. Accordingly, it is not the pure performance of the buses but their compliance with a route that can be determined. The studies [36,38] compare alternative drives. However, consideration of urban emissions is weak, though diesel-powered buses pollute a lot in the acceleration phase (after stops or junctions). Based on these, electric vehicles should be preferred for operation [49].

5. Conclusion

The main contribution of the paper is the compliance indicator determination method for a battery electric bus on a given bus line. The novelty of the determination method is the consideration of the correspondence between vehicle and route parameters via the TOPSIS method. This can support decision-making and multi-criteria evaluation of different electric buses; the developed method ranks the buses for a line.

The applicability of the method was demonstrated in Budapest, Hungary. Bus lines are categorized according to the characteristics of the route. The investigated 58 lines were divided into 14 categories. The key finding was that buses with different vehicle parameters should be selected for lines with different route parameters. We found that the most influencing parameters regarding the vehicle selection are maximum engine power, average specific fuel consumption, battery capacity, passenger capacity, and vehicle weight as vehicle-related parameters, and roadway gradient, the number of stops, and passenger volume as route-specific parameters. In the Budapest case study, the fleet will not be very heterogeneous as the same bus types proved to be the best for several bus lines; among the 30 bus types analyzed, 9 buses were ranked in the first four positions in all the 14 analyzed line categories.

The lessons learned suggest that performing exclusions is necessary; in their absence, the buses selected may distort the result (e.g., because of the tight road curves, the bus cannot run on the route). Furthermore, the first option selected may not be the best for a given city. The final option should be selected based on the operational needs and the aftersales opportunities of the best bus. In addition, the vehicle characteristics were given from a general database in the study. Considering the drivers' skills and habits, the temperature, and other environmental-related factors, the vehicle characteristics, significantly the consumption rate, may change. However, testing all buses in all lines is not possible. Accordingly, the proposed BEB options may give a good approximation.

For future studies, the method can be improved by incorporating additional organizational and maintenance criteria. Furthermore, electric charging solutions can also be included in the metrics. In addition, dynamic traffic characteristics such as congestion and average speed can be included in future calculations. Moreover, economic cost calculation will be involved in the methodology to define whether the operation of BEBs is rentable. Accordingly, capital cost, depreciation, maintenance, and energy costs calculation will be considered. The methodology developed will be included in decision support software for bus service providers.

CRediT authorship contribution statement

Péter Ákos Szilassy: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dávid Földes:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

In connection to our submission entitled 'Compliance indicator determination method to match electric buses with bus line', we, the authors, have no conflicts of interest to disclose. The authors declare that they have no competing interests. Each author has contributed substantially to conducting the research and drafting this manuscript.

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Appendix

Table A
Investigated bus types.

Bus variant	Type	v_1 [kW]	v_3 [kWh/km]	v_4 [kWh]	v_5 [kW]	v_6 [pax]	v_7 [kg]
BEB-01	single	300	1.29	348	80	95	11540
BEB-02	single	180	1.28	385	150	87	12300
BEB-03	articulated	250	1.28	414	75	125	19500
BEB-04	single	220	0.85	311	75	90	12000
BEB-05	midi	160	0.70	84	60	74	11050
BEB-06	single	150	1.20	182.5	150	95	12540
BEB-07	single	180	1.50	376	100	80	14560
BEB-08	single	180	1.11	79	480	80	10560
BEB-09	single	250	1.6	243	150	85	14220
BEB-10	single	150	0.51	138	42	55	11300
BEB-11	single	240	0.88	230	100	79	12628
BEB-12	articulated	480	1.15	300	200	137	18684
BEB-13	single	160	1.40	230	100	82	13024
BEB-14	single	250	0.90	240	450	90	12880
BEB-15	articulated	270	1.30	240	450	129	21228
BEB-16	midi	170	0.80	160	300	65	11580
BEB-17	single	120	1.10	172	150	90	10380
BEB-18	single	270	1.50	75	450	90	12880
BEB-19	midi	200	1.10	200	120	65	9580
BEB-20	single	170	0.97	120	150	81	12492
BEB-21	single	160	1.65	216	320	75	13645
BEB-22	single	155	0.83	76	300	105	12000
BEB-23	single	200	1.1	422	150	97	13300
BEB-24	articulated	240	2.40	70	600	142	19344
BEB-25	single	180	0.95	21	150	91	12812
BEB-26	single	200	0.95	32	340	91	12812
BEB-27	midi	160	0.62	144	60	55	10350
BEB-28	single	150	0.67	138	42	58	12480
BEB-29	midi	380	1.00	170	55	55	9760
BEB-30	single	250	1.35	450	135	51	15583

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