DEVELOPMENT OF DATA-SUPPORTED METHODOLOGY FOR CREATING DIGITAL CO_2 EMISSION CALCULATOR TO PROMOTE BEHAVIOURAL CHANGES IN PUBLIC TRANSPORT PASSENGERS

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Abstract. Within the framework of the research work, a reproducible, auditable and scalable data-supported methodology has been developed for the development of prototypes of a digital CO_2 emission calculator, which integrates behavioral, mobility, route and payment data in accordance with ISO 14083 and EN 16258 requirements. The methodology describes a selection of data sources, stratified sampling, data quality control, combining TTW (tank to wheel) and WTT (wheel to tank) components into WTW (wheel to wheel) results, providing verification procedures, such as unit tests, integration tests and validation. Experimental application in practice of a regular intercity passenger transport route (distance 220 km) demonstrates the practical application of a methodology, where at a representative average public transport load of 20/40/60 passengers, the calculated WTW CO_2e emission results for four transport type scenarios (R1-R4) are R1 (diesel) kg CO_2e 0.022 pax km^{-1}, R2 (electric bus) kg CO_2e 0.004 pax km^{-1}, R3 (B7-biogenic part 7%) kg CO_2e 0.021 pax km^{-1} and R4 (HVO100-biogenic part 100%) kg CO_2e 0.001 pax km^{-1}, which indicates the impact of public transport loads. The developed methodology provides a practical basis for the development of prototypes of digital calculators that can provide personalized feedback to passengers, support carriers in optimizing emissions, and promote a behavioural change of the public transport passengers.

Keywords: carbon footprint; CO_2 calculators; behavioural change of passengers; greenhouse gas (GHG) emissions.

Introduction

In Europe the transport sector remains one of the largest sources of emissions, accounting for almost a quarter of the EU greenhouse gas emissions; these emissions continue to increase, unlike other sectors where emissions are decreasing [1].

The European Commission transport decarbonisation policy intends to reduce transport emissions by 90% by 2050, and achieving this goal requires both technological and behavioural solutions, including digital tools that help users understand and reduce their CO_2 footprint [2]. The policy documents particularly highlight the importance of data, indicating that accurate emissions, accounting and behavioral change are essential prerequisites for climate neutrality.

The European Green Course and the Sustainable and Smart Mobility Strategy state that the transport system must be both green and digital, and that digital tools are a central instrument for reducing emissions, changing the mobility habits and engaging society [3]. The strategy provides for a significant increase in the use of data-supported mobility solutions by 2030, including personalised CO_2 calculators and digital platforms that ensure the users with feedback on the impact of their movements.

Despite the rapid increase in the data availability and the use of digital tools in the analysis of public transport passenger mobility in the recent years, the assessment of CO_2 emissions is still often based on generalized calculations that are not adapted for individual users or small and medium-sized businesses [4].

Several authors have shown that a large proportion of GHG emissions (60-70%) are related to personal consumption, which highlights the importance of individual decisions on the climate change mitigation and the importance of linking the climate changes with responsible consumption, both of which are included in the Sustainable Development Goals [5].

Several important directions have emerged in research that demonstrate the potential of digital data in the emissions analysis. For example, the data of the metro systems allow for the determination of the CO_2 emissions at the individual trip level, using smart card and operational data that accurately reflect the actual mobility of passengers [6]. This approach demonstrates that it is possible to develop personalized emissions indicators that can be integrated into the user-friendly digital tools. In turn, interpretive machine learning methods in multimodal mobility analysis allow for the identification of the main factors that determine the emissions of a particular trip, based on travel trajectory data, route

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choice, and transfer schemes [7]. Such models provide an opportunity to explain to the users how individual (particulas) behavioral choices affect their CO_2 footprint.

Analysis of the impact of personal decisions upon the GHG emissions is part of the growing concern about an individual's responsibility for the state of climate in parallel with governments, industry, or NGOs [8]. Among the various tools to improve the population awareness of climate change and the climate change mitigation measures, carbon footprint calculators (CFCs) have become a popular tool because they help educate about the impact of daily habits on GHG emissions [9; 10].

Several digital emission calculators already exist in the logistics sector, such as EcoTransIT World and CarbonCare, which ensure standardized calculations for various transport modes and comply with international methodological standards [11]. However, these tools are mainly focused on large companies and are based on the technical transport data (distances, tonne-kilometers, cargo characteristics), rather than on the merchants' daily financial or transactional data. This means that small and medium-sized transporers often lack practical, easy-to-use tools that would allow them to assess and reduce emissions using data already generated in the company's operational processes.

The authors of the review on the method for measuring the transport carbon dioxide emissions emphasize that harmonization of methodologies (e.g., ISO 14083 and EN 16258 frameworks) is essential in calculating transport emissions, as different approaches can lead to incomparable results and misleading policy indications [11]. But the authors of the study on transport emissions standardization point out that global or regional harmonization (CountEmissionsEU, ISO 14083, EN 16258) significantly improves data comparability and reliability, which is directly ensured by the TO-BE design [11-13].

International reports on transport emissions have drawn attention to the fact that without quality data and validation mechanisms, TO- BE solutions can create systematic errors in reporting [14].

In a study on modeling and the process analysis the authors have presented an in-depth theoretical basis for AS - IS modelling, indicating that the AS IS model plays an essential role in identifying the organizational weaknesses, the IT system and process deficiencies that create additional costs or delays, indicating that AS - IS modelling is resource-intensive, yet necessary to justify the development of TO-BE [15].

The analysis of the performed scientific publications indicates a significant research gap: although individual studies demonstrate possibilities to determine emissions at an individual level, to analyze the behavioral factors [6] or ensure standardized logistics calculations [12], there is a lack of integrated solutions that would combine behavioral data, payment/transaction data and emission modeling into a joint digital tool. There are also no tools available that would be suitable both for the public transport passengers and the logistics merchants at the same time, providing a personalized, everyday CO_2 assessment.

Most CO_2 emission calculators operate in Latvia as stand-alone tools (online platforms, banking applications, logistics APIs). The data entry is mainly based on the user's manually provided information (kind of transport, distance, consumed fuel, the user's habits). In order to find an optimal solution methodology for the creation of two digital CO_2 emission calculators, a comparative analysis of two AS-IS (a current process state) and TO-BE (a future process design) models was performed to select the optimal model.

Therefore, new solutions are needed that would allow society and businesses to move to a data-supported, user-friendly, and behaviour-changing approach to monitoring the environmental sustainability. The development and validation of such solutions is essential to promote climate-neutral mobility habits and provide practical support for reducing emissions at the level of everyday decisions.

The aim of the research is to develop a reproducible, auditable and scalable methodology for creating a digital CO_2 emission calculator that allows both the public transport passengers and the transport companies to assess and reduce their carbon footprint using behavioural, mobility, route and payment data. The developed methodology will serve as the basis for the development of prototypes of data-based CO_2 emission calculators, which will promote awareness among the public transport passengers, to improve the quality of the transport service choices, and facilitate environmental sustainability monitoring.

Materials and methods

The research is organized as a process of development and validation of a digital CO_2 emission calculator, covering both the public transport passengers and transporters. The methodology includes defining theoretical assumptions, selecting and validating data sources, choosing mathematical and statistical methods, as well as calibrating and testing the model to ensure accuracy and reproducibility.

The methodology is based primarily on the data integration, the emissions modelling, the algorithm development, and the users' testing, ensuring practical applicability of the calculators and compliance with the international emission calculation standards and methodologies.

The development of a practical application system (PAS) is focussed on the integration of the calculator model into a usable software tool, the development data processing flows, a user interface, a calculation module, and validation mechanisms that ensure the reliability and practical usability of the model in real-world operating conditions.

1. Development of a methodology for calculation of CO_2 emissions

The emission calculation according to the developed methodology includes the requirements of the ISO 14083 standard, both direct (TTW) emissions, which covers only the exhaust gases and direct energy consumption in the vehicle, and the indirect (WTT) emissions, which arise from the fuel or electricity production, the processing, transportation and delivery process to the vehicle tank, providing a full WTW emission report that combines WTT and TTW components. As an experiment, WTW is applied to a partcular public transport bus with comparing diesel and electric buses. The direct and indirect CO_2 emissions and energy consumption are analyzed in accordance with the development and validation process scheme of the CO_2 emission calculator (Fig. 1). The calculations include CO_2, CH_4 and N_2O emission components, expressed as CO_2 equivalent (CO_2e), in accordance with the requirements of ISO 14083 and EN 16258 [16; 17].

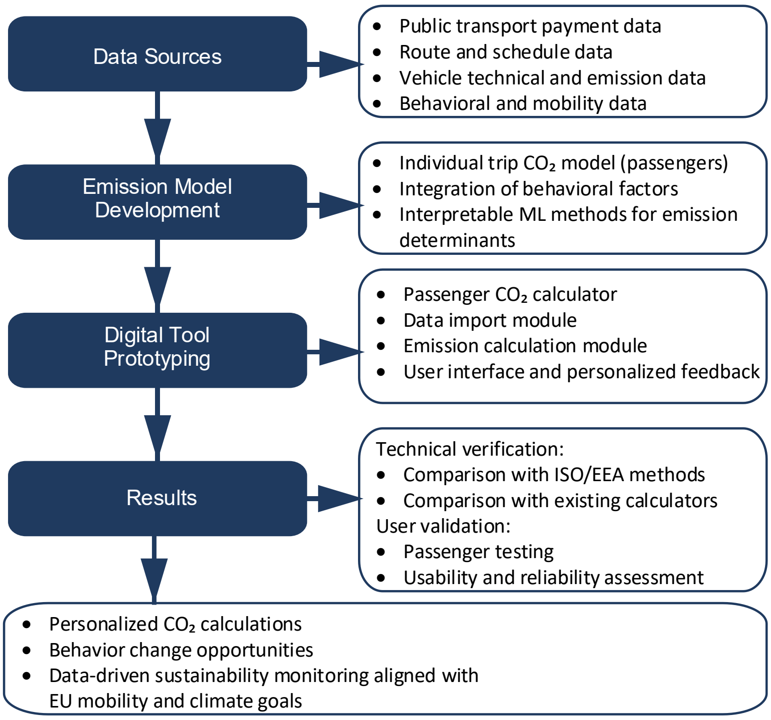

Fig. 1. **Scheme of CO_2 emission calculation development, verification and validation process**

2. Emission calculation methodology

The subsections of the methodology section for creating digital CO_2 emission calculators describe the principles of emission calculations, data quality assurance, verification, validation and reproducibility, based on ISO14083:2023, EN16258:2012, IPCC guidelines and international software quality standards [18].

Calculations are performed in the WTW system, separating the TTW and WTT components, as defined in ISO14083 [14; 16; 17].

2.1. The volume and definitions

The published methodology includes an experimental route of the public transport service provider and a definite period of time. The selection of the analyzed experimental route in the research is structured by the type of the route, the time of the day, and the season.

The key terms:

- public transport passengers (pax);
- distance travelled by passenger on the route (pax km^{-1});
- route distance (km);
- emission factor ($\text{kg CO}_2\text{e}\cdot\text{l}^{-1}$);
- AS-IS (the model of the existing state);
- TO-BE (the target state model);
- experimental inter-city route (EICR).

2.2. Data sources and sample selection

Data types used for analysis: e-ticket records, telematics data (GPS, CAN signals, travel times), lists of trips, payment transaction logs, passenger count data. Metadata are recorded for each record: the source, the time, the version of transformations, and the supplier identifier.

Sample selection is stratified by the route type (e.g. urban, regional), time of the day and the season. The inclusion and exclusion criteria, as well as the sample size (N), are clearly documented.

2.3. AS-IS audit (diagnostics) and TO-BE (the target model)

In the diagnostic (AS-IS) phase (Figure 2), a mapping of the existing process is performed using BPMN diagrams and semi-structured interviews with the public transport service provider, including the number of interviews and selection criteria. The data quality audit identifies the missing fields, the time synchronization problems, and the data interruptions. The AS-IS output artifacts: BPMN diagrams, the data quality report, and the risk lists.

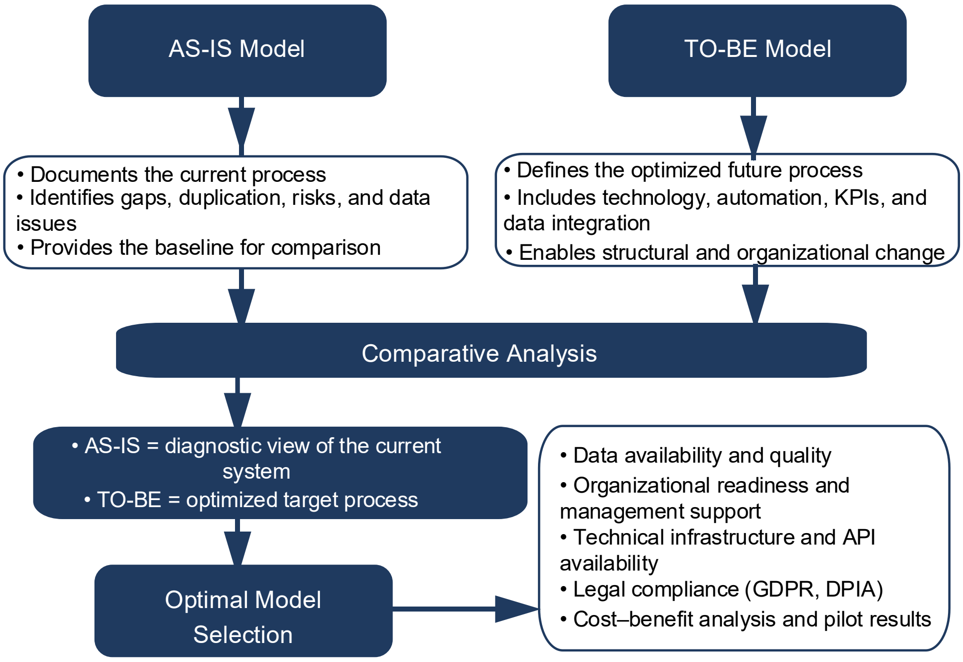

Fig. 2. **AS-IS audit (diagnostics) and TO-BE (the target model)**

In the optimization (TO-BE) phase (Figure 2), there are defined the target architecture, centralized data layer, API specifications for the data providers, data models, the calculation flow and KPIs (e.g. kg

CO_2 pax km^{-1}, kg CO_2 trip). TO-BE also includes a transition plan with phases, responsibilities and the required resources, as well as incorporating the GDPR requirements and the DPIA results into the design.

2.4. Data processing and quality control

Data validation, the missing value handling (inputation or exclusion depending on the field), unit conversions and time synchronization. All the sensitive fields are pseudonymized before the analysis. Each transformation is recorded in a metadata log with a version number, performer, and time. The version control ensures reproducibility. The data quality indicators (e.g., percentage of the missing fields, the number of time synchronization errors) are defined and monitored.

2.5. The calculation method and applied standards

The calculations are based on internationally recognized guidelines and standards, and their steps are documented with precise formulas and sources of the emission factors used [16; 17].

The fuel consumption F_c (1) is determined in absolute litres (l per 100 km^{-1}), based on the ISO defined units [16].

$$F_c = L \frac{F_{cb}}{100}, \tag{1}$$

where L – route length, km;
F_{cb} – fuel consumption base, l per 100 km^{-1}.

The total consumption of electric energy (C_{ee}) is determined by formula (2) [16]. The conditions of the public transport route must be taken into account, both frequent stops at bus stops and the road terrain features, which increase the consumption [19].

$$C_{ee} = L\, C_{be}, \tag{2}$$

where C_{be} – consumption base of electric energy, kWh·100 km^{-1}.

In the calculations of the biogenic fraction (B_f) and the proportion of the biogenic fraction in the fuel there are used certified and documented data, provided by the fuel supplier [16]. If the biocomponent is not specified, the value of the biogenic part is considered to be 0. In the case of using B7, the value of B_f is 0.07 (7%), but if only Hydrotreated Vegetable Oils (HVO) are used, which are produced by hydrogenating vegetable oils or other lipids, converting them into paraffinic hydrocarbons, then B_f = 1 (100%), and this value is used in the TTW/WTT calculation formulas [20; 21]. It is a "drop-in" alternative to diesel that is technically compatible with the existing vehicles [20].

Direct TTW CO_2 (kg) emissions, related to the fossil fuel component, are determined by formula (3).

$$CO_{2,fosil}^{TTW} = V \cdot (1 - B_f) \cdot EF_{TTW,fosils}, \tag{3}$$

where V – fuel volume (litres);
B_f = 1 – fuel considered as a biogenic (non-fossil) component; it is applied if the fuel fully complies with HVO;
$EF_{TTW,fosils}$ – TTW emission factor (kg CO_2e·V^{-1}).

Calculation of direct TTW emissions from the biogenic fuel fraction (4)

$$CO_{2,biog}^{TTW} = V \cdot B_f \cdot EF_{TTW,biog}, \tag{4}$$

where B_f – proportion of the biogenic part (0…1);
$EF_{TTW,biog}$ – TTW emission factor (kg CO_2e·V^{-1}).

Indirect WTT fossil CO_2e (kg) emissions, related to the fossil fuel component (extraction, processing, transportation), are determined using formula (5) [16].

$$CO_{2e,fosil}^{WTT} = V \cdot \left(1 - B_f\right) \cdot EF_{WTT,fosils}. \tag{5}$$

The calculation of biogenic CO₂e (kg) emissions (WTT) (6) is performed for the part, as a separate accounting, that relates to the production and supply of biogenic raw materials and is relevant for the comparison of ISO compliance [16].

$$CO_{2e,biog}^{WTT} = V \cdot B_f \cdot EF_{WTT,biog}, \tag{6}$$

where WTT – emission factor (kg $CO_2e \cdot L^{-1}$) of the biogenic fuel component, which includes all emissions arising from cultivation, collection, processing, production and logistics of the biogenic feedstock until the fuel reaches the vehicle tank, and must be accounted for separately in accordance with the requirements of ISO 14083 and EN 16258 [16; 17].

The combined WTW emission factor per litre, which weighs the TTW and WTT components according to the fossil and biogenic fraction, is determined by formula (7).

$$EF_{WTW} = \left(1 - B_f\right) \cdot \left(EF_{TTW,fosil} + EF_{WTT,fosil}\right) + \\ + B_f \cdot \left(EF_{TTW,biog} + EF_{WTT,biog}\right) \tag{7}$$

In the calculation of total WTW emissions (kg) (8), TTW and WTT components are summed, yielding the full CO_2e impact according to ISO14083 [14; 16].

$$CO_{2eWTT} = CO_{2,fosil}^{TTW} + CO_{2,biog}^{TTW} + CO_{2e,fosil}^{WTT} + CO_{2e,biog}^{WTT} \tag{8}$$

Emissions per passenger are defined (9) as total WTW emissions (kg CO_2e) divided by the actual number of passengers on the trip, and the results should be interpreted in conjunction with assumptions about the specific route load, pax km^{-1} and location principles. Calculations can also be made per pax km^{-1} (kg CO_2e pax km^{-1}), as this shows the impact of distance and allows for comparison of different routes [16; 17].

$$CO_{2e\,pax} = \frac{CO_{2eWTW}}{Pax}. \tag{9}$$

It should be considered that the result in kg CO_2e pax km^{-1} depends on the actual number of passengers, as empty trips may lead to incorrect high figures; therefore, in addition to this figure, it is necessary to simultaneously report kg CO_2e_{pax} and kg CO_2e_{km} [22]. Normalization of WTW emissions per pax km^{-1} (kg CO_2e pax km^{-1}) (10) by the number of passengers and the distance travelled (Pax_D) complies with the requirements of EN 16258 [17].

$$CO_{2e\,pax\,km} = \frac{CO_{2eWTW}}{Pax_D}. \tag{10}$$

The TTW emissions per pax km^{-1} are determined (11) to allow for the analysis of exhaust emissions without the WTT component [17].

$$CO_{2e\,pax\,km}^{WTW} = \frac{(CCO_{2\,fosil}^{TTW} + CO_{2\,biog}^{TTW})}{Pax_D}. \tag{11}$$

Activity is defined as pax km^{-1} or other appropriate unit of activity, depending on the purpose of the calculator. All assumptions and versions of the emission factors are documented in metadata.

2.6. Verification

Verification ensures that the implementation conforms to the TO-BE specification. The verification steps include unit tests for each computational function, integration tests for data flows, verification of the metadata and transformations, and peer-review of the code [18; 23; 24; 25].

The pass rate ($Pass_{rate}$) of the unit test is determined as the percentage of successful tests out of the total number of tests, with a target of ≥ 95%.

$$Pass_{rate} = \frac{N_p}{N_t} 100\%, \tag{12}$$

where N_p – number, indicating how many of the executed unit tests passed without errors;
N_t – total number of the operating unit tests.

2.7. Validation and prototype tests with statistical evaluation

The TO-BE prototype is tested on a selected route for a definite period of time. Validation includes comparison with the AS-IS baseline, using statistical methods (MAE, RMSE, t-tests), and a sensitivity analysis for the effects of emission factors and assumptions. Acceptance criteria (e.g. MAE < 5% against the verified data) are defined before the pilot project begins [24; 25].

The mean absolute error (MAE) between the measurements y_i and the simulated results $\hat{y}_i$ is determined by formula (13) [26; 27].

$$MAE = \frac{1}{N}\sum_{i=1}^{N} |y_i \tag{13}$$

Root Mean Square Error (RMSE) is used to quantify the error. Formula (14) is used to determine the average forecast error values [26; 27].

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (y_i - \hat{y}_i)^2} \tag{14}$$

The Mean Absolute Percentage Error (MAPE) is calculated according to formula (15) [26; 27].

$$MAPE = \frac{100\%}{N}\sum_{i=1}^{N} \left|\frac{(y_i - \hat{y}_i)}{y_i}\right| \tag{15}$$

A paired t test (statistical significance between AS - IS and TO - BE) is used to test whether the mean difference is statistically significant [16].

$$t = \frac{\bar{d}}{s_d/\sqrt{N}}, \tag{16}$$

where

$$\bar{d} = \frac{1}{N}\sum_{i=1}^{N} d_i \quad , \tag{17}$$

where $d_i = y_i^{AS} - y_i^{TO}$ – difference between related observations;
i – index of the ordered element;
$\bar{d}$ – average difference;
s_d – standard deviation between the differences;
N – number of observations.

Formulas (13)-(15) – MAE, RMSE, MAPE – quantify the error magnitude. Formulas (16)-(17) – a paired *t*-test – tests whether there is a statistically significant mean difference between AS-IS and TO-BE observations.

Results and discussion

Based on the developed methodology, the calculation of CO_2 emissions was performed using data from the public transport service provider for 2025 regular commercial trips of an experimental inter-city route (EICR) Liepaja-Riga, shown in Fig. 3.

The calculation uses the passenger carrier's operational data for a particular route in 2025, which the includes mileage, the number of passengers, the fuel or electricity consumption, and the type of the fuel used.

To assess the impact of different energy sources and fuel types upon the total WTW emissions, four scenarios (R1–R4) were defined and analyzed (Table 1), reflecting real and potential vehicle operation options on the Liepaja–Riga route: R1 (D) - a diesel bus (without biocomponent); R2 (E) - an electric bus; R3 (B7%) - a diesel bus with B7% (7% biocomponent); R4 (HVO) - a diesel bus with HVO100 (100% biogenic). [14; 16; 19]. The data for the HVO fuel were selected from the Neste manufacturer. The Neste manufacturer has indicated in its GHG reports 0.255 kg $CO_2e\cdot V^{-1}$ for HVO100 fuel [28].

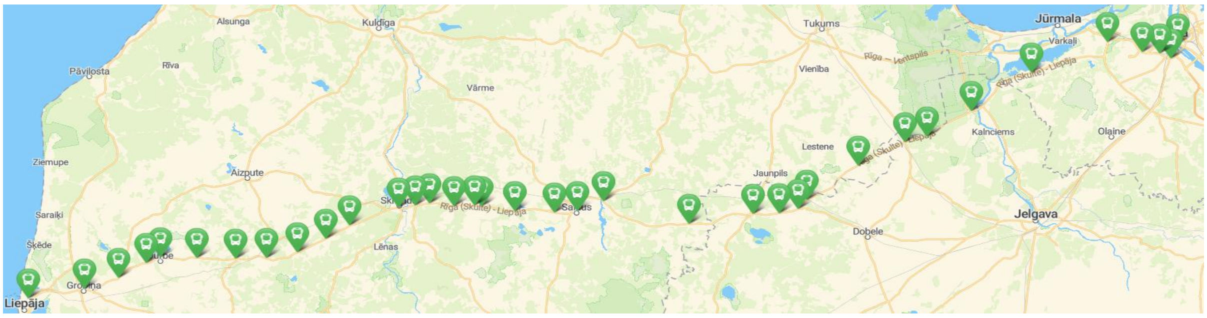

Fig. 3. **Experimental inter-city route scheme Liepaja-Riga**

Table 1

Input data table – EICR scenarios (R1-R4)

Scenario ID	Type of transport	Distance, km	Pax, (Qnt.)	Consumption base	Type of biogenic fraction, (%)
R1 (D)	Diesel	220	20/40/60	$28\ l\cdot 100\ km^{-1}$	None
R2 (E)	Electric	220	20/40/60	$130\ kWh\cdot 100\ km^{-1}$	None
R3 (B7%)	Diesel	220	20/40/60	$28\ l\cdot 100\ km^{-1}$	B7 (7%)
R4 (HVO)	Diesel	220	20/40/60	$28\ l\cdot 100\ km^{-1}$	HVO (100%)
Scenario ID	**Biogenic fraction**	**EF TTW fossils kg $CO2e\cdot l^{-1}$**	**EF TTW biog, kg $CO2e\cdot l^{-1}$**	**EF WTT fosils, kg $CO2e\cdot l^{-1}$**	**EF WTT biog, kg $CO2e\cdot l^{-1}$**
R1 (D)	0	2.68	-	0.52	-
R2 (E)	0	-	-	0	-
R3 (B7%)	0.07	2.68	-	0.52	0.5
R4 (HVO)	1	2.68	-	0.52	0.2

For all scenarios the emission calculation includes the conversion of CO_2, CH_4 and N_2O to CO_2 equivalent (CO_2e), using the IPCC AR5 GWP100 factors [14]. The CO_2e WTW values, obtained at load factors (20/40/60 passengers), are shown in Table 2.

Table 2

Results table - EICR scenarios (R1-R4)

Scenario ID	Pax	kg CO2e WTW	kg CO2e WTW pax	kg CO2e WTW pax km^{-1}
1/R1 (D)	20	197.1	9.9	0.045
1/R2 (E)	20	34.3	1.7	0.008
1/R3 (B7%)	20	185.5	9.3	0.042
1/R4 (HVO)	20	12.3	0.6	0.003
2/R1 (D)	40	197.1	4.9	0.022
2/R2 (E)	40	34.3	0.9	0.004
2/R3 (B7%)	40	185.5	4.6	0.021
2/R4 (HVO)	40	12.3	0.3	0.001
3/R1 (D)	60	197.1	3.3	0.015
3/R2 (E)	60	34.3	0.6	0.003
3/R3 (B7%)	60	185.5	3.1	0.014
3/R4 (HVO)	60	12.3	0.2	0.001

The results (Table 2) are normalized both per passenger and per pax km^{-1} according to EN 16258 [17]. WTW CO_2e values, obtained at a representative load level (20/40/60 passengers), are as follows: R1 (D) - 0.022 kg per pax km^{-1}; R2 (E) - 0.004 kg per pax km^{-1}; R3 (B7) – 0.021 kg per pax km^{-1}; R4

(HVO100) - 0.001 kg per pax km^{-1}. Compared to R1 (D), the percentage emission reductions are: R2 (E) - 81.8% (pax km^{-1}); R3 (B7) - 4.5% (pax km^{-1}); R4 (HVO100) - 95.5% (pax km^{-1}).

Comparison with public calculators and reviews indicates that the obtained ranges (approximately 0.001 - 0.022 kg CO_2e pax km^{-1} depending on scenario and load) are compatible with previously published values, provided similar emission factor sources and GWP100 basis are used [12; 14].

To assess the impact of the passenger load upon the CO_2 emissions, the pax km^{-1} of each scenario (R1–R4) was compared at the corresponding load (*N_pax*) (Figure 4).

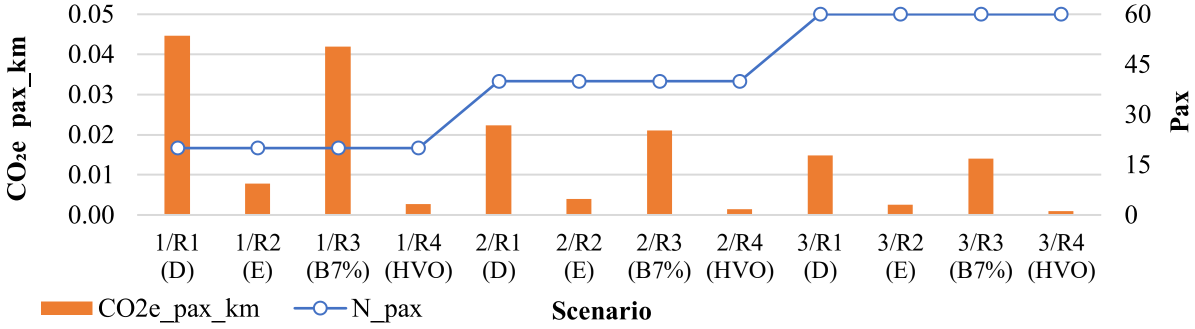

Fig. 4. **CO_2 emissions depending on the load**

From the results, presented in the graph (Fig. 4), it can be concluded that the R2 (E) scenario shows the lowest CO_2e pax km^{-1}, while R1 (D) shows significantly higher CO_2 emissions even at higher passenger loads.

To assess quantitatively the input parameters which most significantly affect the total CO_2 emissions, as well as to determine the optimal CO_2 emission reduction measures, a Tornado diagram was created.

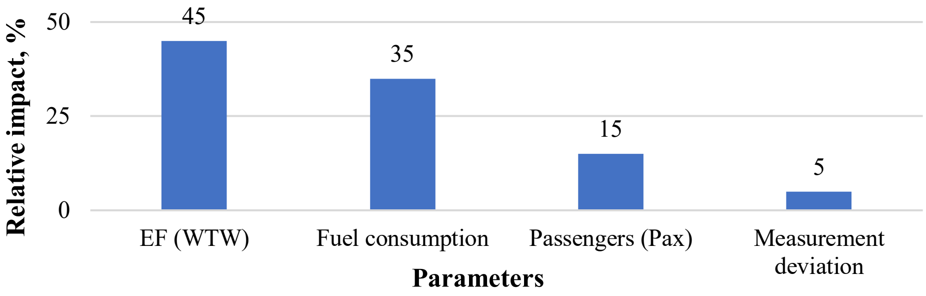

Fig. 5. **Relative impact of the input parameter on total CO_2 emissions**

The diagram (Fig. 5) shows which parameters have the greatest potential impact upon the result of the total CO_2 emissions.

Results are consistent with other studies showing that electric transport and fully biogenic fuels exhibit substantially lower WTW intensity compared with fossil diesel when both TTW and WTT components are taken into account [12; 14; 19].

Given the agreement with international standards and the published literature [7; 16; 17], this study provides a practical and reproducible basis for the development and further validation of CO_2e calculator prototypes.

Conclusions

1. The developed methodology, based on ISO 14083 and EN 16258, provides reproducible, auditable and scalable calculation of WTW CO2e emissions, both CO_2e_{pax} and CO_2e pax km^{-1}, thus creating a necessary basis for the development of prototype CO_2e emission calculation calculators.
2. The EICR calculations confirm the practical applicability of the methodology, for example, at an average load of 40 passengers, the WTW results are R1 (D) 0.022 kg CO_2e pax km^{-1}, R2 (E) 0.004 kg per pax km^{-1}; R3 (B7) 0.021 kg per pax km^{-1}; R4 (HVO) 0.001 kg per pax km^{-1}.

3. Compared to Scenario R1(D), Scenario R2 (E) CO_2e pax km^{-1} decreases by 81.8%, while Scenario R3 (B7) decreases by 4.5% and Scenario R4 (HVO) decreases by 95.5%, respectively, which shows that the energy source and biogenic fraction significantly determine the specific CO_2e pax km^{-1} intensity.
4. The results of the experimental route calculation confirm the importance of the passenger load, as CO_2e emissions decrease as the number of passengers increases, for example, R1 (D) at 20 pax CO_2e is 0.045 kg per pax km^{-1}, while at 60 pax CO_2e is 0.015 kg per pax km^{-1}, thus increasing the load is an efficient emission reduction measure.
5. The practical significance of the developed methodology lies in the fact that it provides basis for the development of prototypes of the CO_2e emission calculators, which, by integrating the behavioral, mobility, route and payment data, can provide personalized feedback for the passengers and action recommendations to the carriers, promoting a behavioral change among the public transport passengers.

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Author contributions

Indicate the contribution of each author: Conceptualization, V.D.; methodology, A.R. and V.D.; software, I.M., A.S; validation, A.R., AA and V.D; formal analysis, A.R, A.S and V.D..; investigation, V.D., A.R., P.S. and I.M.; data curation, A.R., V.D. and I.M. writing-original draft preparation, A.R., DV; writing-review and editing, A.R, A.A and I.M.; visualization, A.S., P.S.; project administration, A.R.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

References

[1] World Bank. Enhancing Transport Decarbonization in the European Union. Washington, DC: World Bank, January 2025. 72 p. [online] [25.01.2026]. Available at: https://documents1.worldbank.org/curated/en/099012125085536598/pdf/P5016401b3ed380a618fac1940454097e66.pdf

[2] European Commission. Transport Decarbonisation. Brussels: European Commission, 2025. [online] [25.01.2026]. Available at: https://climate.ec.europa.eu/eu-action/transport-decarbonisation_en

[3] European Commission. Transport and the Green Deal. Brussels: European Commission, 2025. [online] [25.01.2026]. Available at: https://commission.europa.eu/topics/transport-and-tourism/transport-and-green-deal_en

[4] Boulard C., Castellani S., Colombino T., Grasso A. “Assessing the Intent and Effectiveness of Carbon Footprint Calculators. Proceedings of 17th European Conference on Computer-Supported Cooperative Work, 2019. Doi: 10.18420/ecscw2019_ep12

[5] Burgui-Burgui M., Chuvieco E. Beyond Carbon Footprint Calculators. New Approaches for Linking Consumer Behaviour and Climate Action. Sustainability. vol. 12(16), 2020, 6529. DOI: 10.3390/su12166529

[6] Yu W, Wang T, Xiao Y, Chen J, Yan X. A Carbon Emission Measurement Method for Individual Travel Based on Transportation Big Data: The Case of Nanjing Metro. International Journal of Environmental Research and Public Health. vol. 17(16), 2020, 5957. DOI: 10.3390/ijerph17165957

[7] Wang G., Wang S., Li W., Yang H. What Determines Carbon Emissions of Multimodal Travel? Insights from Interpretable Machine Learning on Mobility Trajectory Data. Sustainability, vol. 17(15), 2025, art. 6983. [online] [25.01.2026]. Available at: https://www.mdpi.com/2071-1050/17/15/6983

[8] Paterson M., Stripple J. My space: Governing individuals' carbon emissions. Environ. Plan. D Soc. Space vol. 28, 2010, pp. 341–362. [online] [25.01.2026]. Available at: DOI: 10.1068/d4109?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

[9] Collins A., Galli A.; Hipwood T., Murthy A. Living within a one planet reality: The contribution of personal footprint calculators. Environ. Res. Lett. vol. 15, 2020, 025008. DOI: 10.1088/1748-9326/ab5f96?urlappend = %3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

[10] Salo M., Mattinen-Yuryev M.K., Nissinen A. Opportunities and limitations of carbon footprint calculators to steer sustainable household consumption-analysis of nordic calculator features. J. Clean. Prod. 2019, 207, pp. 658-666.

[11] Yaacob N.F.F., Mat Yazid M.R., Abdul Maulud K.N., Ahmad Basri N.E. A Review of the Measurement Method, Analysis and Implementation Policy of Carbon Dioxide Emission from Transportation. Sustainability, vol. 12, 2020, art. 5873, pp. 1-22. [online] [25.01.2026]. Available at: DOI: 10.3390/su12145873

[12] EcoTransIT World; CarbonCare. EcoTransIT World/CarbonCare - Emission calculator and methodology. [online] [25.01.2026]. Available at: https://www.ecotransit.org/en/emissioncalculator/

[13] Wild Peter. Recommendations for a future global CO2 calculation standard for transport and logistics. Transportation Research Part D: Transport and Environment, Volume 100, 2021, ISSN 1361-9209, DOI: 10.1016/j.trd.2021.103024

[14] IPCC (Jaramillo P., Kahn Ribeiro S., Newman P., et al.). Chapter 10: Transport. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report (AR6 WG3). Cambridge: Cambridge University Press, 2022, pp. 1049-1160. [online] [25.01.2026]. Available at: https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-10/

[15] Schwegmann A., Laske M. As-is Modeling and Process Analysis. In: Becker, J., Kugeler, M., Rosemann, M. (eds) Process Management. Springer, Berlin, Heidelberg, 2003. [online] [25.01.2026]. Available at: DOI: 10.1007/978-3-540-24798-2_5

[16] ISO 14083:2023. Greenhouse gases - Quantification and reporting of greenhouse gas emissions arising from transport chain operations. Geneva: International Organization for Standardization, 2023. Edition 1, 2023. 28 p.

[17] EN 16258:2012. Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers). Brussels: European Committee for Standardization, 2012. 72 p.

[18] Sargent Robert. Verification and validation of simulation models. Engineering Management Review, 2011, IEEE. vol. 37, pp. 166 - 183. DOI: 10.1109/WSC.2010.5679166

[19] Ji J., Bie Y., Zeng Z. et al. Trip energy consumption estimation for electric buses. Communications in Transportation Research, 2022. (version on Chalmers repository). [online] [25.01.2026]. Available at: https://research.chalmers.se/publication/533552/file/533552_Fulltext.pdf

[20] Gomes D.M., Costa Neto R., Baptista P., Pereira Ramos C., Borges Correia C., Rocha R. A review of advanced techniques in hydrotreated vegetable oils production and life cycle analysis. Biomass & Bioenergy, vol. 194, 2025. DOI: 10.1016/j.biombioe.2025.107689

[21] Kourkoumpas D.S., Sagani A.; Vallianatos A., Kiartzis S., Karellas S., Dedoussis V., Grammelis P. Life cycle GHG emission reduction of hydrotreated vegetable oil integration in an industrial petroleum refinery. Green Technologies and Sustainability, vol. 2, No. 2, 2024, art. 100076. DOI: 10.1016/j.grets.2024.100076

[22] Schmied M., Knörr W. Calculating GHG emissions for freight forwarding and logistics services in accordance with EN 16258 – Terms, Methods, Examples. Editor Friedl, C. European Association for Forwarding, Transport, Logistics and Customs Services (CLECAT), 2012. [online] [25.01.2026]. Available at: https://www.clecat.org/media/CLECAT_Guide_on_Calculating_GHG_emissions_for_freight_forwarding_and_logistics_services.pdf

[23] Witte, F. Test Case-Based Metrics. In: Metrics for Test Reporting. Springer, Wiesbaden. 2024. DOI: 10.1007/978-3-658-44006-0_15

[24] IEEE 29119-1. Software and systems engineering - Software testing - Part 1: Concepts and definitions. IEEE Standards. [online] [25.01.2026]. Available at: https://standards.ieee.org/standard/29119-1.html

[25] IEEE 29119-3. Software and systems engineering - Software testing - Part 3. Test documentation. IEEE Standards. [online] [25.01.2026]. Available at: https://standards.ieee.org/standard/29119-3.html

[26] Acar, G. The Role of Regression Testing Metrics in Software Quality. Nasdaq Technology AB, 2023. [online] [25.01.2026]. Available at: https://kth.diva-portal.org/smash/get/diva2:1799684/FULLTEXT01.pdf

[27] Montgomery, D.C. Introduction to Statistical Quality Control, 8th ed. Hoboken, NJ: Wiley, 2020. ISBN 9781119723097.

[28] Neste Corporation. Neste MY Renewable Diesel - Product Data Sheet/Technical information. Espoo: Neste, 2024. [online] [25.01.2026]. Available at: https://www.neste.com/products/all-products/neste-my-renewable-diesel