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Towards the electrification of freight transport: A network design model for assessing the adoption of eHighways

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ABSTRACT

The development of new technological innovations for eco-friendly vehicles combined with the usage of renewable energy sources is essential for mitigating the environmental impact of freight transport. In this context, this paper investigates the opportunities for implementing the eHighway system, a novel recent technology designed to supply new hybrid trucks. This technology uses overhead catenary heavy-duty vehicles that are supplied with electric energy from overhead power lines through a pantograph that is positioned at the top of the truck. A novel bi-level multi-objective network electrification design (BM-NED) model is proposed to assess the environmental benefits and opportunities of adopting eHighways, considering the limited budgetary resources for road infrastructure electrification. Still, the implementation of eHighways requires collaboration between public and private stakeholder interests. The upper level considers multiple objectives aiming at minimizing the total travel cost, infrastructure, and environmental costs and maximizing the average traffic density of OC hybrid trucks on electrified arcs, whereas the lower level is the traffic assignment model. The Elitist multi-objective Genetic Algorithms are used as a solution approach for the multi-objective optimization and the Pareto front of the non-dominated solutions have been generated. Results of the model, tested on a part of a motorway network in the Veneto region in Italy, show that the implementation of the eHighway system can lead to an average emission reduction of about 66%, considering all Pareto-optimal solutions. Furthermore, a sensitivity analysis has been carried out by giving different weights to the objective functions that can be a basis for decision-makers regarding the adoption of this new technology.

1. Introduction

The transportation sector has the highest share of Europe's emissions. Road transport is the largest contributor with approximately 70% of overall transport emissions (EEA, 2023). Since 2017, light- and heavy-duty vehicles produced around 15% and 5% of total carbon dioxide (CO_2) emissions in Europe, respectively (EC, 2021). To overcome these shortcomings, the new EU regulations set light- and heavy-duty vehicle CO_2 emission targets to 15%, and more than 30% reduction from 2025 to 2030, respectively. Only in 2023, an EU regulation has been intended for reducing heavy-duty vehicles' CO_2 emissions of up to 90% by 2040, with the intermediate targets of 45% for 2030 and 65% for 2035 (EC, 2023). The implementation of these targets, towards an emission-free transport system, encouraged the expansion of eco-friendly vehicles, mainly because the largest transportation' emission rate comes from Internal Combustion Engine (ICE) vehicles. Hybrid technologies for heavy-duty trucks represent a valid alternative to conventional diesel trucks, either by the means of power-to-weight ratio, the range level and battery cost, the life cycle performance, or the possibilities for different powertrain technology applications in road freight transportation (Yan et al., 2021). While Electric Vehicles (EVs) have been acknowledged to show limited autonomy in traversed distances due to the current battery duration, the combination of ICE with an electric engine in hybrid vehicles' technology offered the possibility for overcoming these issues, mainly through better energy efficiency and energy recovery on short and long-haul distances (Zhuang et al., 2020). These have been widely supported by public authorities through the deployment of charging infrastructures and incentives for buying zero-emission vehicles. Furthermore, the study by Niestadt and Bjørnåvold, 2019 estimated that zero-emission vehicles could contribute to the steady growth of vehicles' market share by up to 23% in 2030.

To meet these targets, some studies analysed the application of the Electric Road System (ERS), and, in particular, the performance of vehicles equipped with continuous electricity supply while driving on

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electrified road segments (Jelica et al., 2018; Taljegard et al., 2017). The variations among ERS approaches are due to the power transfer from the power grid to the vehicles: i) conductive power supply through overhead catenary wires (overhead catenary ERS); ii) conductive power supply through electric rail in the road; iii) the inductive power supply with no physical contact through electric coils in the road. Different ERS approaches have been showing variations in terms of cost evaluation and vehicles' autonomy, but what is common for all is the presence of additional propulsion sources since some road parts might not be possible/convenient to electrify. Since the conductive power supply in the road might show higher vulnerability due to safety requirements and infrastructure maintenance, the overhead catenary ERS, the so-called "eHighway" system, tends to be a more efficient solution (Schulte and Ny, 2018). In the eHighway system, Overhead Catenary (OC) hybrid trucks receive current from the overhead wire through an active pantograph that is positioned at the top of the vehicle and allows the automatic connection/disconnection from the overhead wires. The main feature of a pantograph is to ensure safe automatic connection/disconnection and power transmission from the overhead wires while driving or overtaking on the electrified segment. Besides the high investment costs, dynamically power-supplied OC hybrid trucks in the eHighway system operate with a less-sized battery which gives the opportunities for various applications in freight transportation such as transport for distances up to 50 km (Siemens, 2018). Certainly, ERS technologies are conceived to electrify the segments with higher traffic flows, which makes them more suitable from an environmental point of view. At the same time, vehicles running on electric propulsion while travelling on eHighway segments have been proven to contribute to the reduction of both fuel consumption and CO_2 emissions. For example, the application of ERS on five Swedish roads with the highest traffic flows resulted in a 20% reduction in CO_2 emissions (Jelica et al., 2018). Accordingly, the case study analysed by Taljegard et al. (2019) highlighted that the electrification of all roads in both Norway and Sweden could cover up to 70% of CO_2 emissions from all heavy-duty traffic flows. Also, according to the study proposed by Plötz et al. (2018), the fleet of 60000 heavy-duty trucks (65% electric drive fraction and 35% diesel) with 190 gCO_2eq/kWh (considering reference scenario for 2030) can result in GHG savings of 37 tCO_2/y per vehicle. Moreover, Qiu et al. (2022) predicted the good emission and energy prospect of eHighways by considering the estimated range of driving cost (i.e., break even selling price of electricity) for OC hybrid trucks from 0.242 to 0.666 $/km.

To the best of our knowledge, most of the related works dealt with eHighways by focusing on aspects related to OC market penetration and battery sizing, energy demand generation, configuration, and dimension of traction substations, etc. The paper proposes a novel multi-objective bi-level Network Design Model (NDM) for assessing the eHighway system adoption considering the interests of both public authorities and transportation companies. The upper level of the model involves multiple objective functions, i.e., the minimisation of the total travel cost, the total costs needed for capacity expansion of electrified arcs, the environmental costs, electrification costs, and the maximization of the average traffic density of OC hybrid trucks on electrified arcs, while the lower level is the traffic assignment model. Consequently, the decision variables of the multi-objective optimization problem are referred to the set of links to be electrified, as well as the optimal placement of traction substations. The selection of the links to be electrified in the eHighway system application is subject to budget limitations. Moreover, the proposed model also deals with the capacity expansion that is intended as a potential improvement for electrified links. In this way, increasing the capacity of a subset of electrified arcs ensures the flexibility of the eHighway system regarding a possible demand increase of OC hybrid trucks, as well as the possibility of improving traffic flow conditions. To assess the impact of the eHighway system, the proposed model has been tested on a part of the motorway network in the Veneto region in Italy. Elitist multi-objective Genetic Algorithm is used as the solution approach and a sensitivity analysis is performed by acting on the weights associated with each objective. In this way, the proposed model can be useful for decision-makers in determining to find the best compromise in evaluating the opportunities for implementing eHighways.

The structure of this work is given as follows. Section 2 explores the research studies on the eHighway system application and electrification network design, while the overview of the eHighway system is described in Section 3. The problem description as well as the mathematical formulation of the proposed model is shown in Section 4. Section 5 reports the results, sensitivity analysis of applying the proposed model to a real-scale case study, as well as discussion. The conclusions and further developments are reported in Sections 6.

2. Related studies

An overview of research works related to the eHighway system is given in the following subsections. First, we present the projects that have investigated the opportunities for the eHighway implementation. Secondly, we explore the scientific literature on eHighway from a technical, energy, and environmental point of view. Thirdly, we report the relevant works regarding road electrification network design. Finally, we highlight the contribution of this work regarding the existing literature.

2.1. eHighway test projects

The eHighway concept was first introduced in 2012 within a series of successfully performed trials, where the major tasks were the design of electric infrastructure and substations, the definition of the voltage level, and the configuration of the energy system (Grunjes and Birkner, 2012). In recent years, several countries launched "test" projects for demonstrating the performance of the eHighway system and investigating the opportunities for future large-scale implementation (Siemens, 2018). In 2016, the first eHighway project, thanks to the collaboration between Scania and Siemens, was realised on the E16 highway road with a 2 km of distance in the city of Gävle, Sweden (Insideevs, 2016). In 2017, the integration of advanced pantograph into three class-8 trucks was examined on Alameda Street in Carson, California, demonstrating to be more suitable for zero-emission freight technology than plug-in hybrid electric trucks, and resulting in more than 20% of zero-emission miles (Lehmann 2018; Impulitti and Lehmann, 2019). In 2018, the installation of the eHighway system started in Germany on an A5 federal autobahn between Frankfurt Airport and the Darmstadt/Weiterstadt interchange. The first goal was to gather driving behaviour data and the effects of the eHighway system on traffic flows; the study confirmed that most of the users' categories are not negatively influenced by the eHighway system implementation, e.g., the overtaking behaviour of car drivers will not change significantly (Wauri and Boltze, 2019). According to Siemens (2019), the electrification of 30% of truck traffic on German highways through the eHighway system using renewable energy sources, would lead to 7 million tonnes of CO_2 savings per year. Similarly, the eHighway project in California predicted an annual saving of 6 million tonnes of CO_2. Furthermore, the UK government planned an investment for the electrification of 65% of road freight movements and estimated 13.4 $MtCO_2$ savings per year. According to the report provided by the Centre for Sustainable Road Freight, the electrification of 7.500 km of UK highway roads would cost around 19.3 billion £ and it would lead to 5% emission mitigation, and fuel cost savings for transportation companies of around 20 000 € per 100 000 km (Ainalis et al., 2020). Also, Italy started the experimentation of the eHighway system in the north of Italy on the A35 Brebemi motorway (Green Car Congress, 2018). The project involves the realization of a 3 km eHighway system in the region of Lombardy, where the Brebemi motorway connects Brescia, Bergamo, and Milano (Melis and Rigoni, 2019). Accordingly, the proposed study could support the above-mentioned projects in evaluating the opportunities of eHighways implementation.

2.2. Studies on non-ERS network optimization

There have been several studies in the literature devoted to the problem of road network design for EVs, and in particular, the placement of recharging infrastructure and stations capacities for ERS technologies (see Table 1.). Most of these studies focused on the optimal station location design from both user and system perspectives by enhancing the maximization of users' utility and demand coverage under budged and cost limitations.

Qiu et al. (2020) proposed a mathematical model for optimising facility locations in road network design by taking into account the routing and recharging behaviour of EV drivers. Micari et al. (2017) proposed a two-level model applied to the Italian highway network for calculating the position of EV charging stations, in the first level, and the number of charging stations, in the second level. Wang et al. (2018) investigated the problem of fast charging location in a highway network for plug-in EVs through a capacitated flow refuelling location model, where the expected utility theory was used for analysing drivers' charging behaviour. Other studies focused on the optimal design of charging lanes. Napoli et al. (2020) investigated the optimal dimensioning and location of charging infrastructure along a highway network for EVs. Wei et al. (2017) proposed an optimal traffic-power flow model for transportation network electrification from both transportation and electricity network perspectives. Liu and Song (2018) developed a multi-class multi-criteria equilibrium model for the optimal deployment of dynamic charging lanes for Plug-in Hybrid Electric Trucks. He et al. (2020) optimized the location of wireless charging lanes considering their effects on road capacity and traveller's route choice. Shoman et al. (2023) applied trip chain model for estimating charging infrastructure demand of long-haul Battery Electric Trucks (BETs) in Europe in 2030 by simulating truck travel distances, stop locations, durations, and energy requirements. The outcomes of the study showed almost five times higher requirements of the number of overnight chargers (50–100 kW), compared to the number of megawatt chargers (0.7–1.2 MW), for supporting a 15% of BET share in long-haul operations. In addition, Liimatainen et al. (2019) estimated the potential of BETs in Switzerland and Finland by applying commodity-level analysis. The study demonstrated that 71% of Switzerland's and 35% of Finland's road freight transport tonne-kilometres may be electrified by using BETs.

2.3. Studies on the eHighway

The relevant papers in the literature analysed the attraction of the eHighway system by considering energy, technical and environmental points of view, as reported in Table 2. Several studies focused on the required electricity demand, market diffusion and energy generation of the eHighway system. Bottger et al. (2018) reported the outcomes of different eco-friendly market diffusion scenarios, where the assumption of a 75% market share of eHighway trucks resulted to be cost-efficient in all scenarios regarding heavy-duty freight transportation. Also, Plötz et al. (2019) analysed the impact of OC hybrid trucks on market diffusion, the European electricity system, and CO_2 emissions. Even though the expansion of OC hybrid trucks in the eHighway system would require extra energy demand, the study showed that the additional 30 Mt of CO_2 emissions in the electricity production would lead to a 40–50 Mt CO_2 reduction in road transport. Certainly, the connection of renewable energy sources in the study would lead to more promising

Table 1
Studies on road network electrification design.

Station location network design					
Authors	Study aim	Mathematical formulation	Objective function	Constraints	Solution approach
Qiu et al. (2020)	Finding locations for road electrification considering routing and recharging behaviour of EVs drivers	Mathematical program with equilibrium constraint model	Minimize the total driving time of EVs	Budget limitation	Active Set Method
		Routing choice Path-constrained network equilibrium	Minimizing total electricity and travel time costs	Driving range, energy consumption and charging rate	Shortest useable path solution framework
Wang et al. (2018)	Investigating the siting and sizing problem of fast charging stations in a highway network	Capacitated flow refuelling location model	Maximizing the charged PEV flows	Station capacity, construction and infrastructure cost limitation, location sizing limitations	Genetic and Heuristic algorithms
		Routing choice Random utility theory	Analysing the drivers' strategies for selecting charging stations	PEV range constraint and driver charging logic	Iterative approach
Charging line network design					
Authors	Study aim	Mathematical formulation	Objective function	Constraints	Approach
Liu and Song (2018)	Investigating the optimal deployment of dynamic charging lanes for PHETs	Robust optimal deployment problem of charging lanes for PHETs	Minimizing the total system travel time, fuel and emission costs	Budget limitation	The heuristic algorithm and cutting-plane scheme
		Routing choice Multi-class multicriteria equilibrium	Minimizing generalized driving costs as electricity and diesel consumption, actual and recharging travel time, and battery level	Energy consumption, battery level limitation, relationship between charging and travel time	Column generation algorithm
Wang et al. (2019)	Integrating link-based discrete credit charging scheme into the discrete network design problem to improve the transport performance	Mixed-integer nonlinear bilevel programming model	Finding the optimal network design strategy and credit charging level for minimizing the total system travel time	Budget limitation, number of added lanes	Genetic algorithm
		Routing choice Traffic network user equilibrium	Minimize generalized travel cost (the travel time and the value of the credit charged for using the link)	Credit distribution scheme determined by the transport authority	Frank–Wolfe algorithm

Table 2
Studies on the eHighway system.

	Authors	Study aim	Approach
Energy aspect	Bottger et al. (2018)	Comparing different scenarios considering the share of controlled charging vehicles and the availability of eHighway trucks.	Dispatch optimization model “SCOPE” for determining energy supply system
	Plötz et al. (2019)	Analysing European market penetration of OC trucks and their impact on the electricity system and CO_2 emissions, considering electricity demand and optimal power plan investment.	ALADIN (Alternative Automobiles Diffusion and Infrastructure) model and PERSEUS-EU energy system model
	Taljegard et al. (2017)	Investigating the impact of road electrification on the energy demand variation and stationary electricity system, assuming different electrification options and drivetrains.	A vehicle model
Technical aspect	Mareev and Sauer (2018)	Investigating the energy consumption of OC trucks and its comparison with conventional diesel trucks on German highways	Vehicle simulation model
	Felez et al. (2018)	Determining the minimum size of the batteries by modelling the mechanical and electrical behaviour of the eHighway truck	A Model Predictive Control (MPC) approach
	Sachse and Gräbner (2014)	Providing an insight into the intelligent traffic control of the eHighway system using V2X-communication equipment	The advanced Traffic Control Centre with V2X
Environmental aspect	Talebian et al. (2018)	Examining the potential of road freight transport electrification for achieving the 2040 year’s target for GHG emission reduction	Business as usual (BAU) scenario, Current legalization fulfilment (CLF) scenario
	Breuer et al. (2021)	Investigating the potential of fuel cell-electric, battery-electric and overhead catenary trucks for reducing GHG emissions and air pollution, considering the infrastructure investments	Bottom-up transport model
	Lajevardi et al. (2019)	Quantifying the well-to-wheel GHG emissions, total ownership costs and abatement costs for 16 different heavy-duty truck drivetrains, including those powered by natural gas, electricity, and hydrogen	Monte Carlo simulation

results as 691 MT CO_2 reduction from total road transport emissions. Nicolaides et al. (2018) investigated the prospects for Electric Freights Vehicles (EFVs) where the main challenges remain in the high cost of the batteries, the limited range, the long battery recharging times, and the lack of public charging infrastructure. Also, authors developed four case studies for assessing the feasibility of electrification of various road freight operations; the outcomes showed the opportunity of shifting to EFVs as well as the possibility to achieve up to 73% of CO_2 emission reduction to 2030.

Another group of studies addressed the technology aspect of eHighway system and questions related to the configuration, and dimension of traction substations, as well as the definition of a voltage level and catenary power system. For example, Deshpande et al. (2023) analysed the impact of ERS system installation by providing cost breakeven analysis. The outcome of their analysis estimated the economic feasibility of ERS; the results of 20-year breakeven period showed that up to 47%, 72% and 38% of the total road freight could be electrified using ERS in England, France, and South Africa, respectively. Also, the study proposed by Gidofalvi and Yang (2020) analysed the concepts and aspects related to a route based ERS network optimization model which showed the potential cost savings of up to 75%.

Taljegard et al. (2019) applied a cost-minimisation investment model and an electricity dispatch model to Scandinavia and Germany to investigate the influence of new electricity generation to 2050, and the dispatch of the electricity generation portfolio to 2030. Mareev and Sauer (2018) estimated the energy consumption of OC trucks on German highways for long-haul transportation, as 1.66 to 1.82 kWh/km based on different configurations of traction battery and catenary power system. Sachse and Gräbner (2014) provided insight into the eHighway system components, and functionality of the V2X-communication intelligent traffic control for increasing safety, road capacity, and exchanging all necessary information between eHighway users. Also, Felez et al. (2018) used Model Predictive Control for designing the minimum size of the battery considering the mechanical and electrical behaviour of OC trucks in the eHighway system. The proposed work is an extension of a preliminary study by Colovic et al. (2022) where a single-level multi-objective network design model was developed to estimate the benefits of eHighway system considering an application to a test network.

2.4. *Strengths and weaknesses of the eHighway*

The proposed study considered the main features of the eHighway system related to the infrastructure, traction substations and energy distribution, that were implemented from the strategic planning perspective. Since we are only dealing with prototypes of eHighway system technology today, there are still some issues that need to be addressed before implementation. From an economic point of view, one of the main limitations of the eHighway system is related to the extra energy demand and the transformation of the voltage level down to be adequate to the eHighway system, which could cause some extra costs and investments in the grid infrastructure. Certainly, the usage of renewable energy sources (e.g., wind energy along the highway road segments) could decrease the overall energy costs, considering that the electricity grid and the traction substations’ capacity should be good enough to satisfy the traffic demand in the eHighway system. Nevertheless, one of the foremost obstacles of the eHighway system technology is the initial infrastructure cost (e.g., traction substations, overhead wires, grid connection point, maintenance), Siemens Mobility (2019). Despite the high infrastructure costs of the eHighway system, the overhead wires are one of the less expensive solutions for hybrid trucks, considering the high initial cost of HEVs (Akerman, 2019). For example, the report provided by Lehmann (2018) pointed out that the catenary system is more costly acceptable than the fast and overnight chargers for more than 10000 HEVs. Moreover, the catenary system does not influence the road, which ensures the reliability from safety and operative point of view. In this case, any dysfunctionality of the eHighway system doesn't cause the collapse and interruption of traffic flows in the road network. However, the catenary system has a limit related to the maximum number of vehicles to be served in the considered period due to the few constraints such as the length of the electrified segment, the energy demand of traffic flow, the capacity of the station, the resistance of the overhead wires, etc. On the other side, the traffic demand should be enough to justify the implementation of the eHighway system, especially if we take into account that demand uncertainty could be the cause of higher investment costs.

From environmental perspective, the application of OC hybrid trucks in the eHighway system encourages the concept of sustainably mobility and emission mitigation on a long-term period. As future perspective, the eHighway system can be simulated and, thus, improved considering the regenerative braking and energy saving systems. These could give the possibilities for the OC hybrid trucks to return energy to the system in a first way, or in the second way to store extra energy in a battery. The vehicles' regenerative braking and energy saving are crucial for having a lower number of recharging while driving on smaller distances (Jelica et al., 2018). A brief summary of the strengths and weaknesses related to the eHighway system can be found in Table 3.

2.5. Contribution of this study

According to our knowledge, different papers proposed ERS applications in the context of energy demand system modelling and the optimal deployment of charging infrastructure. Most of the highlighted highway network design studies investigated the placement of charging stations/road lane electrification placement in the upper level, considering the users' driving behaviour in the lower-level model. Still, the presence of the eHighway system in the literature was hardly investigated from the transportation network design perspective. Most of the previous works showed the potential of the eHighway system, but they are limited to technical and energy system modelling. Besides the required energy demand and traction substation dimensioning, the travel behaviour modelling is essential for finding the optimal choice set of links to be electrified and, then, estimating vehicles' emissions savings. Consequently, the contribution of this work is given as follows.

- proposing a novel bi-level multi-objective network design model for the eHighway system implementation;
- providing an insight into the assessment of the eHighway system technology in the transportation network design modelling;
- evaluating the environmental benefits of the eHighway system on a real-scale motorway network in terms of CO_2 emissions reduction;
- carrying out a sensitivity analysis for evaluating network design solutions according to different criteria that could serve as a decision support tool for decision-makers in choosing the best alternative.

Table 3
The advantages/disadvantages of the eHighway system.

Characteristics	Strengths	Weaknesses
Environmental	The possibility of the energy generation by using renewable energy sources.	Availability of renewable sources
	The zero-emissions of OC hybrid trucks while travelling on the electrified segments in the eHighway system.	
Vehicle	The application of hybrid technologies has been demonstrated as more fuel consumption efficient compared to ICE trucks.	The eHighway system' demand uncertainty due requirement of hybrid technologies.
	The electrified segment is not reserved only for hybrid vehicle technologies since it has no installation on the road itself.	The eHighway system is not used for passenger cars.
Technical	Relatively easy installation of the catenary system with the possibility of momentaneous overtaking through an active pantograph that allows automatic connection and disconnections of the overhead wires.	The catenary system has a limit related to the maximum number of vehicles to be served in the considered period
	The integration of overhead wires alongside the road does not influence the driveway road.	The integration of overhead wires is not possible on road segments with physical obstacles (e.g., bridges, tunnels, etc.)
Economic	The installation of traction stations could be more cost-efficient compared to the high number of fast-charging stations.	The costs of installing higher number of traction substations due to the limited coverage range of 1–3 km.
	The economic advantages and the higher life cycle performance of the eHighway system in the long-term view.	The hybrid vehicles must be adopted to the eHighway system configuration which requires additional costs.
Energy efficiency	Energy recovery and energy feed back into the system during braking on the electrified segment.	Need for increased power generation.

3. The overview of the eHighway system

The eHighway system is intended to support road freight decarbonisation, energy efficiency and cost saving for freight operators. In the connection between the first and last mile logistics, the eHighways system can be seen as a part of the supply chain, where OC trucks are intended for the long-haul transportation. The integration of the catenary system into existing highway road infrastructure in this system combines both ecological and economic aspects. From a technical perspective, the eHighway implementation requires several points to be managed, from infrastructure to vehicles, from energy (such as the energy demand generation and definition of voltage level) to the maintenance subsystem, as depicted in Fig. 1. The infrastructure of the eHighway system comprises traction substations and a bi-polar catenary system (overhead wires), installed alongside the highway segments, which receives the energy directly from traction substations. Each overhead wire consists of a still rope messenger and contact wire, which are positioned at the beginning and end of the electrified segment (Lehmann, 2018). The height and the design of electric poles are constructed according to the highway network standards, while their position/placement should avoid any contact with surrounding constructions, such as bridges and tunnels.

As might be expected, the integration of the OC hybrid trucks into the catenary system imposes some technical characteristics that slightly differ from hybrid electric vehicles (HEVs), such as the presence of an active pantograph. Specifically, OC hybrid trucks receive the energy while travelling on the electrified segment in the eHighway system only when the active pantograph, positioned at the top of the vehicle, is connected to the overhead wires. For achieving these characteristics, OC hybrid trucks must have a certain height size, and thus, the eHighway system cannot be applied to passenger vehicles. Moreover, the application of active pantograph achieves a better well-to-wheel efficiency of about 80–85%, which is twice higher than ICE trucks (Singh, 2016). In this way, the catenary system integration ensures the smoothness of traffic flow operations and safe overtaking, at any speed range up to 90 km/h. Generally, traction substations are equipped with medium voltage switchgear, power transformers, rectifiers and controlled inverters which are feeding back the electric energy generated through the vehicles' regenerative braking. The purpose of the traction substations is to convert alternating current (AC) from a national grid power supply/renewable energy source to direct current (DC) considering appropriate voltage levels (Sevcik and Prikryl, 2019).

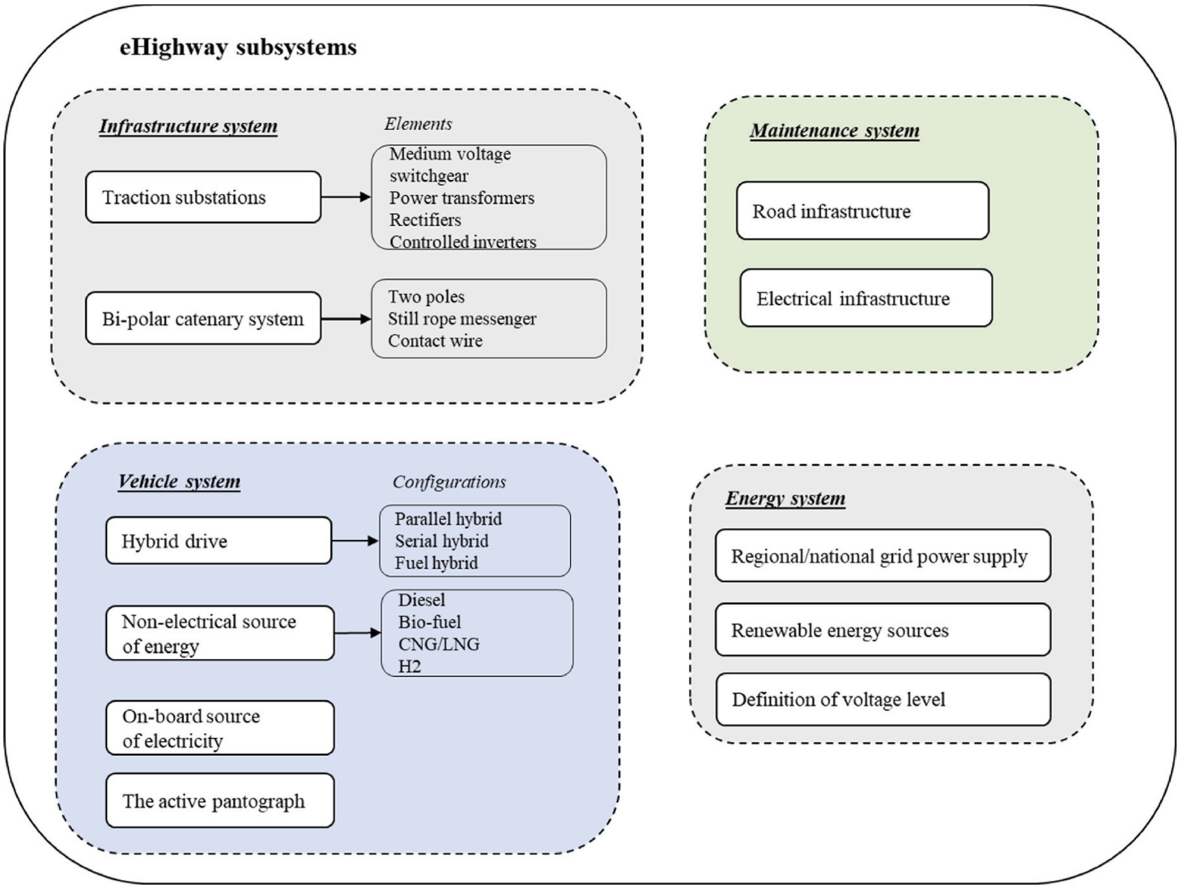


Fig. 1. The main eHighway subsystems.

4. Problem description and modelling

This paper tackles multiple decisions in the eHighway network design related to both economic and ecological aspects through the transportation network optimization formulated as a Bi-level Multi-objective Network Electrification Design Problem (BM-NEDP). The upper level of the bi-level problem merges the interest of both public and transportation authorities concerning transportation system performances and environmental targets; the lower level concerns the welfare of freight operations. These interests are modelled as five criteria of the

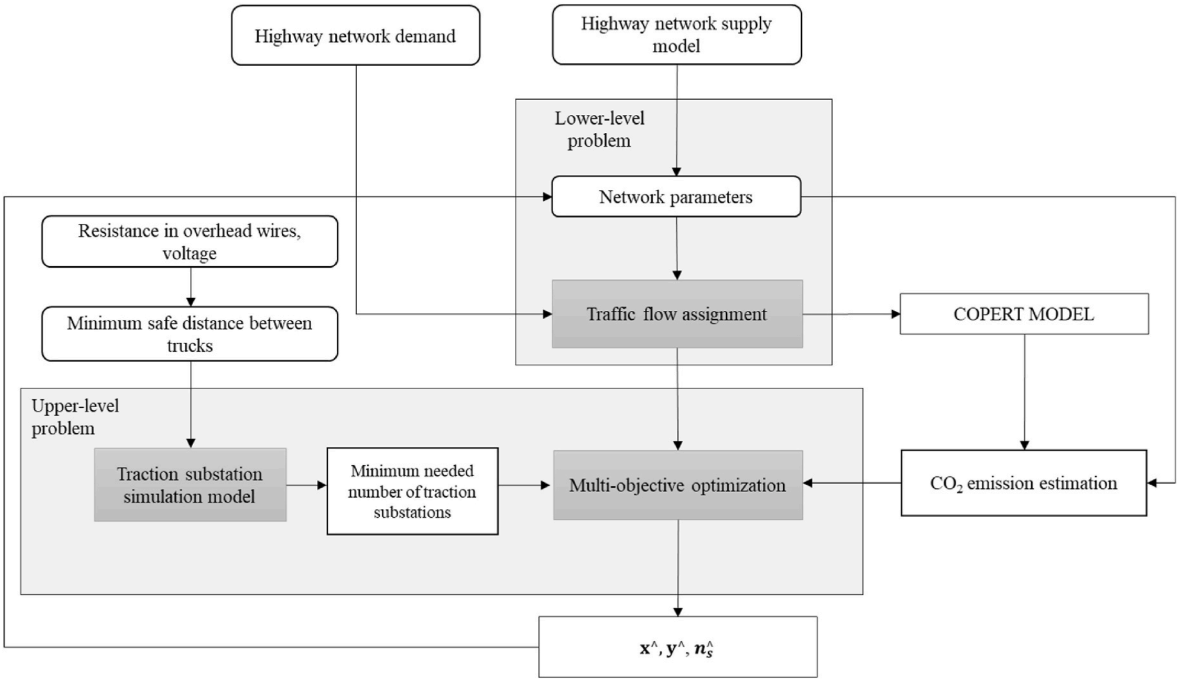


Fig. 2. The methodology of bi-level multi-objective NDM.

multi-objective optimization related to: i) the minimisation of the total travel cost; ii) the minimisation of the total costs needed for capacity expansion of electrified arcs; iii) the minimisation of the infrastructure costs; iv) the minimisation of environmental costs; v) the maximization of the average traffic flows of OC hybrid trucks on the electrified arcs. In addition, the BM-NEDP model deals with finding not only the set of arcs to be electrified but also the capacity expansion of some of the electrified arcs considering the available budget resources. On the one side, capacity expansion of the electrified arcs could increase the network's performance by reducing the needed travelling time, while on the other side, it allows higher operativity and flexibility regarding the demand increment of OC hybrid trucks.

The proposed optimization model considers the previously mentioned features of the eHighway system technology in Section 3. Thus, the methodology of the problem is described as follows (see Fig. 2). First, the energy is transmitted from the power plant generation, assumed using renewable energy sources, to the bulk power supply and, then, to the traction substation. The energy from a traction substation is transmitted to overhead wires and distributed to the OC hybrid trucks when travelling on electrified segments. The capacity of each traction substation must satisfy the total demand for OC hybrid trucks, considering power losses during the energy transmission and the minimum safe distance between trucks. In addition, one traction substation could cover up to 2 km of both lanes on the electrified road segment in each direction, and therefore, the supplementary traction substation must be added in approximately every 2 km of road. We used the simulation model developed by Plougmann et al. (2017) for calculating the minimum required number of traction substations of the eHighway system, described in detail in Appendix A. Also, the used model gives the maximum number of OC hybrid trucks that can be operated by each traction substation.

Second, OC hybrid trucks start their trip from a depot running on fuel propulsion mode, and after approaching the electrified segment of its route, the trucks' active pantograph automatically connects to overhead wires and switches to the electric propulsion mode at any speed from 0 to 90 km/h. Consequently, we assumed that OC hybrid trucks do not produce emissions while driving on electrified segments, not considering emissions from an LCA perspective (e.g., battery and electricity production). The considered emission model (see Section 4.1) calculates CO_2 emissions intended for the assigned fixed traffic flows on the non-electrified segments of the network that are obtained from the lower-level problem. In this way, the electrification of road segments in the eHighway system achieves benefits for both public and private stakeholders.

The main assumptions of the BM-NEDP model are given as follows.

- the study considers a macroscopic model and, therefore, we assumed stationary conditions for OC hybrid trucks (average values of speed and energy consumption);
- the energy recovery during regenerative braking and battery state of charge in macroscopic modelling were not considered;
- the fleet of OC hybrid trucks is homogenous with all vehicles having continuous electricity supply, as well as equal characteristics related to power consumption and minimum safe distance.

4.1. Emission model

The exhaust emissions were estimated by using COPERT 5.4 model according to the TIER 3 approach. Beside different vehicles' categories k, the TIER 3 approach is highly influenced by the average vehicles' speed on roads of type r (i.e., 20 km/h for urban, 60 km/h for extra urban (rural), and 100 km/h for highway roads), Corinair (2021). Thus, we divided the aggregated fleet data, i.e., traffic flows f_a^* [veh/h] obtained by the assignment model, in four categories and grouped by the total number of axes, as well as the maximum payload weight range. Besides category I, referring to passenger cars weighting up to 3.5 t, we focused on the freight categories (heavy-duty vehicles) as the target category of the eHighway technology. These categories are generally powered by diesel, biodiesel and CNG.

The total emissions $E_{urban/rural/highway}$ were calculated considering E_{HOT} emissions during stabilised (hot) engine operations and E_{COLD} emissions during transient thermal engine operations (cold start), as in Eq. (1). Accordingly, the hot emissions $E_{HOT}^{i,k,r}$ of the pollutant i [g], produced by vehicles of category k and driven on roads of type r, were calculated according to the number of vehicles N_k [veh] for the considered period, total distance $M_{k,r}$ [km/veh] driven by each category k on roads type r, and hot emission factor $e_{HOT_{i,k,r}}$ in [g/km] for pollutant i, relevant for the vehicle technology k, operated on roads type r, Eq. (2) (Ntziachristos and Samaras, 2021).

$$E_{urban/rural/highway} = E_{HOT} + E_{COLD} \tag{1}$$

$$E_{HOT}^{i,k,r} = N_k \cdot M_{k,r} \cdot e_{HOT_{i,k,r}} \tag{2}$$

The cold emissions $E_{COLD}^{i,j}$ are considered more often for urban and rural driving conditions and emission factors are more likely available for petrol, diesel, and LPG passenger cars. As reported in Eq. (3), the $E_{COLD}^{i,j}$ depend on the fraction of the distance $\beta_{i,k}$ travelled by cold engine for the pollutants i and produced by vehicle category k, the number of vehicles N_k [veh] for the considered period, total distance $M_{k,r}$ [km/veh] driven by each category k, hot emission factor $e_{HOT_{i,k}}$ in [g/km] for pollutant i, for relevant vehicle technology k, and cold/hot emission quotient for pollutant i and vehicle category k. Generally, factor $\beta_{i,k}$ depends on ambient temperature and average trip length.

$$E_{COLD}^{i,k,r} = \beta_{i,k} \cdot N_k \cdot M_{k,r} \cdot e_{HOT_{i,k}} \cdot \left(\frac{e_{COLD}}{e_{HOT|i,k}} - 1 \right) \tag{3}$$

Consequently, highway emissions estimation $C_e(f_a^*)$ [gCO_2/km] refers to aggregated fleet data $f_{a,k}^*$ [veh/h] considering four vehicle categories k, the CO_2 emission factor $e_{CO_2,k,highway}$ [gCO_2/veh-km] for the period t [h], as reported in Eq. (4).

$$C_e\left(f_a^*\right) = \sum_k f_{a,k}^* \cdot e_{CO_2,k,highway} \cdot t \quad \forall k \in \{1, \ldots 4\} \tag{4}$$

where, $e_{CO_2,k,highway}$ refers to $e_{HOT_{i,k,r}}$ and $e_{COLD}^{i,k}$ for CO_2 pollution factor i, highways road type r, and four vehicle categories k. The methodology of the emission model is represented in Fig. 3.

4.2. Mathematical formulation of the proposed network design problem

The proposed BM-NED problem is defined over a directed graph $G = (N, A)$, where N denotes the set of nodes, $n \in N$, and A denotes the set of arcs, $a \in A$. Additionally, O denotes the set of o origin nodes, $o \in O$, and D denotes the set of d destination nodes, $d \epsilon D$. Each arc a is associated with a traffic flow f_a, length l_a and traffic density k_a. The notations of the problem are reported in Table 4.

4.2.1. Upper-level problem

As previously mentioned, the upper level of the BM-NEDP evaluates the implementation of the eHighway system through the multi-objective network optimization considering costs, traffic, and the environmental point of view. At the same time, it tends to optimise the number of electrified arcs x_a and to increase their capacity by adding new expansion lanes y_a. In this level, each arc $a \in A$ is associated with an equilibrium traffic flow $f_a^*(y_a)$ and a travel time $t_a(f_a, x_a, y_a)$ obtained by the assignment procedure at the lower level. The OC hybrid trucks flow travelling on an electrified segment in the eHighway system is assumed as a percentage λ of the total traffic flow f_a^*.

The objective functions of the upper-level problem are formulated as follows:

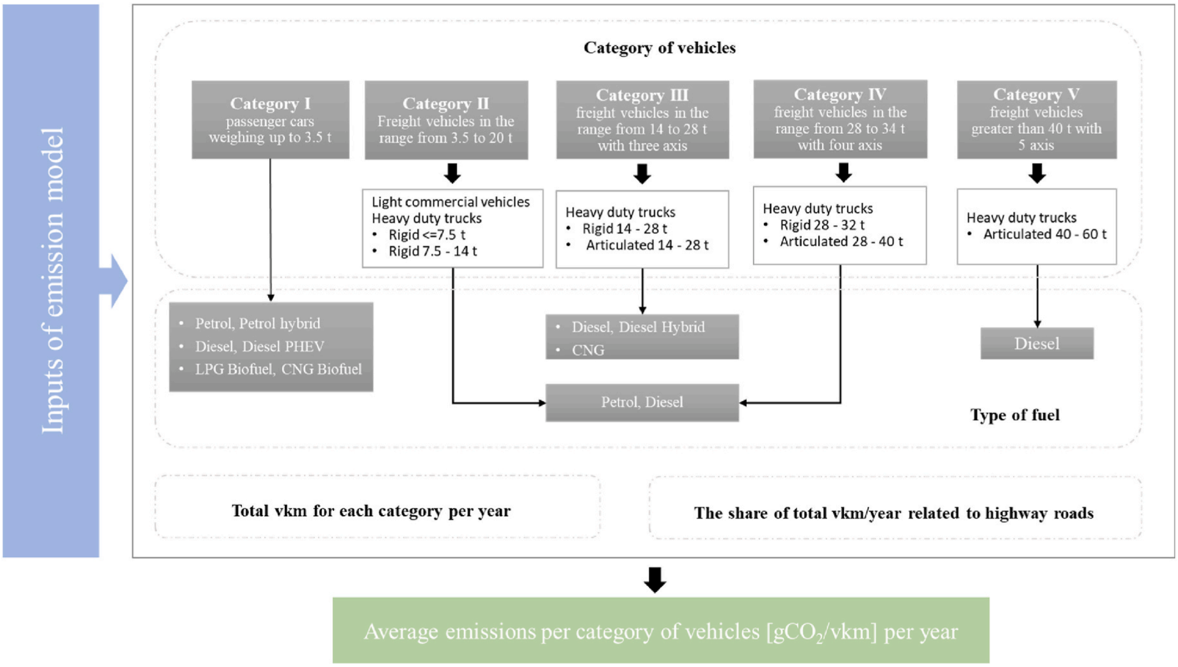


Fig. 3. The methodology of the emission model.

Table 4
Notation of the multi-objective bi-level NDP.

Sets	
N	Set of nodes in the network, $n \in N$
A	Set of arcs in the network, $a \in A$
O	Set of origin centroid nodes, $o \in O$
D	Set of destination centroid nodes, $d \in D$
K_{od}	Set of paths for origin-destination pair (o, d), $k \in K_{od}$
S_f	Set of feasible link flows, $f \in S_f$
Parameters	
t_a	Travel time on link a
h_{od}^k	Path flow for each path $k \in K_{od}$ for each od pair
d_{od}	Travel demand for origin-destination pairs (o, d)
r	Fixed electrification cost of an arc [Mio €/km]
r_s	Cost of a traction substation [Mio €/sub]
r_v	Cost of maintenance in terms of percentage of total costs [%]
r_f	Fixed maintenance costs [€/year]
P_e	Required power per vehicle [kW/veh]
P_s	Power capacity of substation [kW]
P_n	Power consumption of vehicle [kW/km]
k_a	Traffic density on arc a [veh/km]
$n_{min,a}$	Minimum required number of traction substations for arc a
λ	Percentage of OC hybrid trucks
C_b	Battery capacity of a vehicle [kWh/veh]
B_1	Total available budget for the eHighway system [Mio €]
B_2	Total available budget related to the capacity expansion [Mio €]
l_a	Length of arc a [km]
c_{lane}	Cost of lane construction [Mio €/km]
α, β	Parameters of BPR cost function
t_0	Free-flow travel time
u_a	Maximum number of new expansion lanes on arc a
T	Service life time of the eHighway [years]
Variables	
f^*	Vector of equilibrium traffic flows
$\mathbf{x}$	Vector of decision variables x_a, where x_a is equal to 1 if arc $a \in A$ is electrified, 0 otherwise
$\mathbf{y}$	Vector of decision variables y_a, where y_a is the number of expansion lanes on the electrified arcs
$\mathbf{n_s}$	Vector of decision variables $n_{s,a}$, where $n_{s,a}$ is the number of traction substations on electrified arc $a \in A$

$$\mathbf{x}, \mathbf{y} = arg_{\mathbf{x},\mathbf{y}}\ min\ \ z_1(\mathbf{t}(\mathbf{x}, \mathbf{y}); \mathbf{f}^*) = \sum_{a \in A} f_a^* \cdot t_a\left(f_a^*, x_a, y_a\right) \tag{5}$$

$$\mathbf{y} = arg_{\mathbf{y}}\ min\ \ z_2(\mathbf{y}; c_{lane}, \mathbf{l}) = \sum_{a \epsilon A} c_{lane} \cdot l_a \cdot y_a \tag{6}$$

$$\mathbf{x}, \boldsymbol{n}_s = arg_{\mathbf{x},\mathbf{n_s}}\ min\ \ z_3(\mathbf{x}, \mathbf{n_s}; r, 1, r_s, r_v) = \sum_{a \in A} \left(r \cdot l_a \cdot x_a + r_s \cdot n_{s,a}\right) \cdot (1 + r_v) \tag{7}$$

$$\mathbf{x} = arg_{\mathbf{x}}\ min\ \ z_4\left(\mathbf{x}; C_{e,}\mathbf{f}^*, 1, t\right) = \sum_{a \in A} C_e \cdot f_a^* \cdot l_a \cdot (1 - x_a) \cdot T \tag{8}$$

$$\mathbf{x} = arg_{\mathbf{x}}\ max\ \ z_5(\mathbf{x}; \mathrm{K}) = \sum_{a \in A} K_a \cdot x_a \tag{9}$$

The first objective function $z_1(\cdot)$ in Eq. (5) is related to the minimisation of the total travel costs; the second objective function $z_2(\cdot)$ in Eq. (6) is related to the minimisation of the total costs needed for capacity expansion of electrified arcs; the third objective function $z_3(\cdot)$ is related to the minimisation of infrastructure, traction substations and maintenance costs of the electrified arcs (Eq. (7)); the fourth objective function is related to the minimisation of environmental costs of the non-electrified arcs (Eq. (8)), considering emission estimation in Eq. (4). The fifth objective function is related to the maximization of average traffic density of OC hybrid trucks on the electrified arcs, so that $K_a = \lambda \cdot k_a \cdot l_a$ (Eq. (9)). In this way, the objective function z_5 tends to maximize the usage of the eHighway system by giving higher priority to the links with high OC hybrid trucks traffic volume. The constraints of the problem are then formulated as follows:

$$\boldsymbol{f}^* = \Delta \cdot \boldsymbol{P}(\mathbf{t}(\mathbf{f}^*, \mathbf{x}, \mathbf{y}))\boldsymbol{d} \tag{10}$$

$$\mathbf{y} - M \cdot \mathbf{x} \leq 0 \tag{11}$$

$$c_{lane} \cdot \mathbf{l} \cdot \boldsymbol{y}^T \leq B_2 \tag{12}$$

$$P_e \cdot \frac{\mathbf{f}^*}{v} \cdot \mathbf{l} \cdot \mathbf{x}^T \cdot \lambda \leq P_s \cdot \mathbf{n_s} \tag{13}$$

$$\left(r \cdot \mathbf{l} \cdot \boldsymbol{x}^T + r_s \cdot \boldsymbol{n_s}\right) \cdot (1 + r_v) + r_f \cdot t \leq B_1 \tag{14}$$

$$P_n \cdot \mathbf{l} \cdot \mathbf{f}^* \cdot \lambda \cdot \mathbf{x}^T \leq C_b \cdot \lambda \cdot \mathbf{f}^* \tag{15}$$

$$\mathbf{n}_\mathbf{s} \geq \mathbf{n}_\mathbf{min} \cdot \mathbf{x} \tag{16}$$

$$0 \leq \mathbf{y} \leq \mathbf{u} \tag{17}$$

$$\boldsymbol{f}^* \in S_f \tag{18}$$

$$x_a \in [0, 1], \forall a \in A \tag{19}$$

$$n_{s,a} \in \mathbb{Z}^+, \forall a \in A \tag{20}$$

$$y_a \in \mathbb{Z}^+, \forall a \in A \tag{21}$$

where $\widehat{\mathbf{x}}, \widehat{\mathbf{y}}$ and $\mathbf{n}_\mathbf{s}$ are the optimal solution vectors.

Constraints (10) is related to the traffic flow assignment, obtained as the fixed-point solution of the lower-level problem, where $\boldsymbol{f}^*$ is the equilibrium flow vector, Δ denotes the link-path incidence matrix and d is the vector of O-D demand flows of all od pair (Cascetta, 2009). Constraints (11) are related to the capacity expansion of the electrified arcs in terms of the number of new lanes, where M is a big number. The constraint (12) is related to the investment costs for the capacity expansion which must be coherent with the available budget B_2. Constraints (13) are related to substations' capacity, i.e., the energy consumption of OC hybrid trucks using the eHighway system should be lower than the capacity P_s provided by the traction substations n_s, where v is the average vehicle speed and λ is the percentage of OC hybrid trucks within the traffic flow f^*. The detailed description of the procedure to calculate n_s is reported in Appendix A. The constraint (14) ensures that infrastructure, traction substations and maintenance costs of the eHighway system should be lower than the available budget B_1, assuming a life cycle T of 20 years. Constraints (15) refer to the battery capacity of the OC hybrid trucks using the eHighway system. Constraints (16) ensure the consistency of the number of traction substations on electrified arcs, which should be greater than or equal to the number of traction substations n_{min} obtained by the traction substation simulation model. Constraints (17) refer to the lower and upper values of the decision variable related to capacity expansion. Therefore, if there is a capacity expansion on the electrified arc, the decision variable y_a takes the values in the range [0, u_a], and 0 otherwise. Constraints (18) ensure the equilibrium flows belong to a set of feasible link flows S_f defined as follows:

$$S_f = \left\{ f : f = \Delta \cdot h, \forall h \in S_h \left\{ h = [h_{od}]_{od} : h_{od} \geq 0, \forall od \right\} \right\} \tag{22}$$

Constraints (19) refer to the binary nature of variables x_a, where x_a is equal to 1 if the road arc a is electrified and 0 otherwise. Constraints (20) and (21) are related to the discrete nature of variables $n_{s,a}$ and y_a.

4.2.2. Lower-level problem

The subject of the lower-level problem is the traffic assignment in terms of equilibrium flows $\boldsymbol{f}^*$ defined over a set of feasible link flows S_f. The simulation of the supply-demand interaction was obtained by applying Stochastic User Equilibrium (SUE) assignment model. The traffic assignment was formulated as a fixed-point problem and solved using the Method of Successive Flow Averages (MSA-FA) based on the Dial's Algorithm. The latter is based on the implicit path enumeration, and it was chosen as adequate for the level of detail considered in this work. In fact, motorway networks generally present a very limited number of alternatives and, thus, their overlapping can be assumed as negligible. Thus, the resulting traffic flow assignment corresponds to the situation in which, for each origin-destination od pair, the perceived travel time at the equilibrium is less or equal than the perceived cost of every other path (Wardrop's first principle). The lower-level problem was defined on the same graph as described in Section 4.2.1.

The relationship between path and link costs is calculated based on the modified Bureau of Public Roads (BPR) function (Eq. (23)), commonly used for assessing flow-cost interaction in the highways. The travel time function $t_a(f_a, x_a, y_a)$ is calculated based on the traffic flow f_a, free flow traffic time t_0 [h], the capacity of lane cap_l [veh], the capacity of link C_a [veh/h], the decision variable y_a related to the capacity expansion, the decision variable x_a related to the arcs selection for electrification, and the coefficients α and β of the BPR function.

$$t_a(f_a, x_a, y_a) = t_0 \cdot \left(1 + \alpha \cdot \left[\left(\frac{f_a}{C_a} \right) \cdot (1 - x_a) + \left(\frac{f_a}{C_a + cap_l \cdot y_a} \right) \cdot x_a \right]^\beta \right), \forall a \in A \tag{23}$$

The path choice model using Logit, based on the link travel time t_a in Eq. (23), was obtained with implicit path enumeration of Dial's algorithm. Finally, Eq. (24) represents the assignment result as the equilibrium traffic flow vector $\boldsymbol{f}^*$ obtained as solution of the SUE method applied to the fixed-point problem.

$$\boldsymbol{f}^* = \Delta \cdot \boldsymbol{P}\left(-\Delta^T \boldsymbol{t}(\mathbf{f}^*, \boldsymbol{x}, \boldsymbol{y}) \right) \boldsymbol{d} \tag{24}$$

The resulting flows $\boldsymbol{f}^*$ are defined on a set of feasible link flows S_f as defined in Constraint (22) (Cascetta, 2009).

5. Case study of the Veneto motorway

The proposed model has been evaluated on part of a motorway network in the Veneto region in Italy (see Fig. 4) referring to emission indicators of the 2019 year by the Italian Institute for Environmental Protection and Research (ISPRA), i.e., the last national emission inventory before the COVID-19 emergency. The considered network of Veneto's motorways comprises candidate arcs with the highest traffic demand which are suitable for the eHighway system application. Also, arcs' lengths (from 2 to 17 km) are consistent with the current ongoing eHighway test projects (see Section 2.1), and consequently appropriate for the eHighway network design. The road network considered extends for 86 km and was chosen according to data availability provided by motorway operators. Traffic demand was estimated using data provided by CAV (2020) that comprises the publicly available data (links' distances, entrance/exit nodes, and their corresponding traffic flows).

Table 5 reports the values of parameters used for testing the BM-NEDP model, set according to Pilota et al. (2018). The parameter λ was set equal to the share of the heavy-duty trucks categories provided by the ISPRA (2022). Also, the emissions C_e [gCO$_2$/km] associated to the assigned traffic flows on non-electrified links was estimated with regards to the aggregated road transport dataset of Italy during the period of 1990–2021 (ISPRA, 2022). The emission inventory is provided for various vehicle categories and every EURO standard including urban, extra-urban (rural) and highway areas by using COPERT (see Section 4.1).

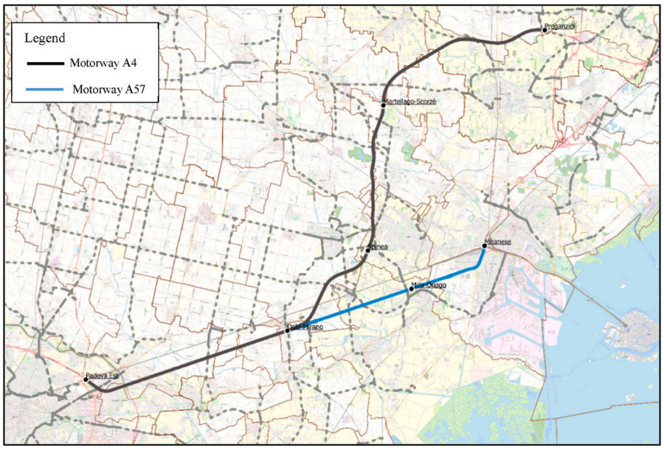


Fig. 4. The motorway network of Veneto's case study.

Table 5
Parameters' values.

Parameter	Value	Parameter	Value	Parameter	Value
r	1	T	20	P_e	150
r_s	2.8	C_b	120	P_s	3000
r_v	0.02	cap_l	2000	B_1	200
r_f	0.5	c_{lane}	10	B_2	250
λ	10.57				

5.1. Solution approach

The BM-NEDP model was developed in Matlab. The SUE model was applied for obtaining traffic assignment in the network, where the parameters α and β of the travel time function $t_a(f_a, x_a, y_a)$ were set using the common values of 0.15 and 4, respectively. Since the BM-NEDP is a non-convex optimization problem, it requires advanced approaches for finding good-quality solutions. In this work, we used the Elitist Multi-Objective Genetic Algorithms (MOGAs) as they can deal with multiple objectives using a mature population-based metaheuristic. The algorithm is based on the process of natural selection of GA in which the strongest individuals in the population have the biggest chance of surviving and creating new offsprings. Elitist MOGA generates the set of Pareto-optimal solutions in order to assign the fitness function to members of the population based on the non-dominated solutions The multi-objective optimization ensures the convergence of the Pareto-optimal set by maintaining the diversity and uniqueness in solutions of the Pareto-optimal set (Deb et al., 2002). The presence of objective functions of different natures makes it difficult to estimate their influence and to compare them. Thus, a sensitivity analysis was carried out using the weighted sum method in which objectives functions were normalized in order to: i) carry out a proper comparison among objective functions of different nature; ii) investigate the impact/priority of each objective function by assigning different weights.

5.2. Application and results

Pareto-optimal solutions of the multi-objective optimization comprises the set of non-dominated solution, as represented in Fig. 5. For instance, Fig. 5a shows the Pareto front of non-dominated solutions among the objective functions z_2, z_3, and z_5. Accordingly, Fig. 6a shows the shares of electrification and traction substation costs, and, correspondingly, Fig. 6b represents the obtained potential CO_2 savings for $T = 20$. On average, the electrification and traction substations costs represent 68% and 32%, respectively, within the total infrastructure costs. Also, the average percentage of electrification resulted as about 54% and the potential CO_2 emissions reduction level resulted as about 67%, corresponding to 937.2 $ktCO_2$ saved on average of all Pareto-optimal solutions. Correspondingly, the total average cost for emissions reduction resulted to be 185 €/tCO_2 (amount for saving 1 ton of CO_2) by considering both electrification and capacity expansion costs. As part of these costs, the amount of 73 €/tCO_2 refers only to electrification costs, corresponding to a share of about 40% of total infrastructure costs. The maximum percentage of the electrification of the overall Pareto optimum solutions resulted as about 92%. Specifically, the correlation between the infrastructure costs in objective function z3 and the obtained percentage of electrification is represented in Fig. 7a. For instance, the electrification costs of around 140 Mio € can lead to about 92% of electrification. The relationship between the eHighways' emissions reduction in tCO_2, z_4, and the percentage of electrification is reported in Fig. 7b. As expected, the increase in electrification leads to a reduction in emissions in the network under consideration, by reducing CO_2 emissions by an average of about 34% for $T = 20$.

Table 6 reports the descriptive statistics of the results for different scenarios based on assumed budget resources that might vary among countries according to the different interest, goals, and expectations of decision makers (Deshpande et al., 2023). Through these scenarios, decision makers can have insights into road electrification and capacity expansion. For instance, the electrification budget of 150 Mio € can lead to the average percentage of electrification of about 29% considering all Pareto-optimum solutions. In addition, the increase of the budget resources leads to the increase of road network electrification and capacity expansion percentage; the available budget resources in the fourth scenario allow the network electrification of about 63%, and capacity expansion in 3 lanes on average in the overall network. For Scenario 2 we obtained higher average number of lanes with capacity expansion compared to Scenario 1, although with a lower budget B_2. We can conclude that number of lanes with capacity expansion is determined not only by its budget resources B_2, but also by the available budget B_1 for road eHighway electrification. This is due to the fact that capacity expansion is intended only for electrified links with eHighway system.

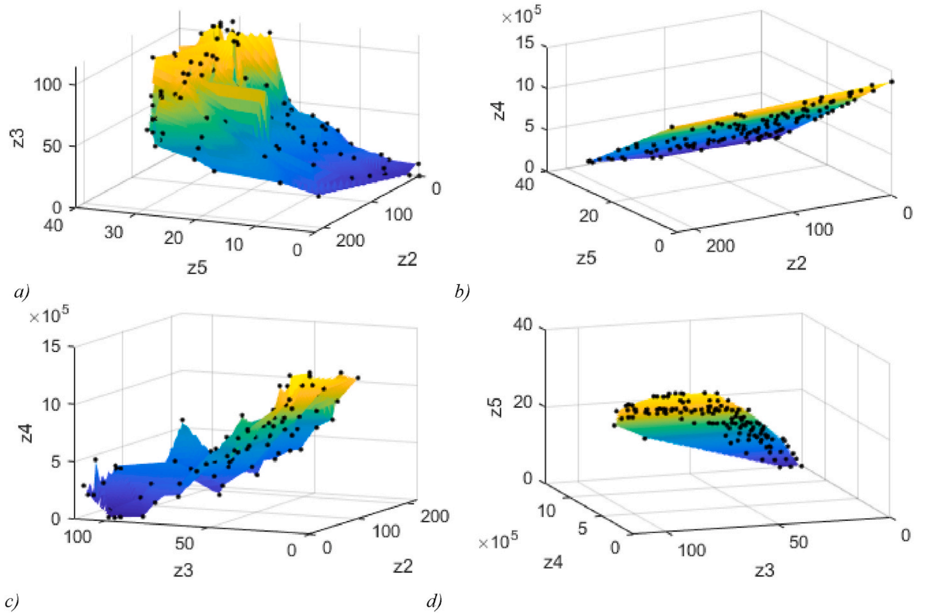
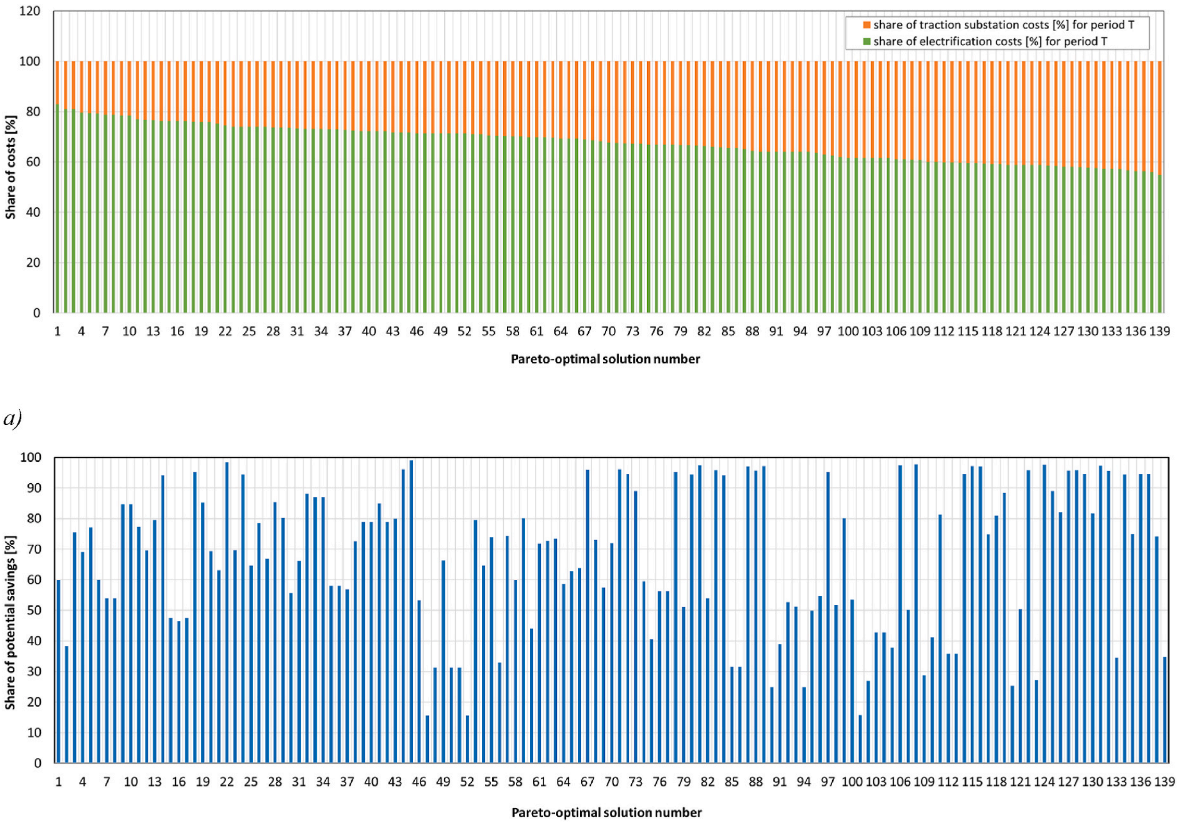
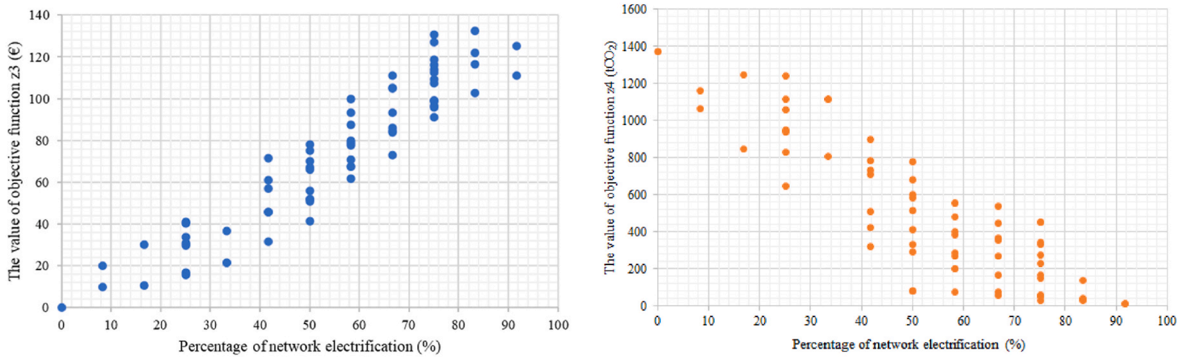


Fig. 5. Pareto front of the bi-level multi-objective optimization model among: a) obj. functions z_3 [Mio €], z_2 [Mio €], and z_5 [veh]; b) obj. functions z_4 [tCo_2], z_2 [Mio €], z_5 [veh]; c) obj. functions z_4 [tCo_2], z_2 [Mio €], z_3 [Mio €]; d) obj. functions z_3 [Mio €], z_4 [tCo_2], z_5 [veh].



a)

Fig. 6. The share [%] of: a) electrification and traction substation costs; b) potential environmental savings for $T = 20$.



a) b)

Fig. 7. The relationship between: a) the percentage of the network electrification and the eHighway electrification costs (z_3); b) the percentage of the electrification and the potential CO_2 emissions (z_4).

Table 6
The results of the multi-objective optimization for different budget availability.

Scenario No.	B_1	B_2	Perc. of electrification (%)			Perc. of emissions reduction (%)			Average capacity expansion [no. lanes]
			average	max	mode	average	max	mode	
1	150	200	28.69	50.00	25.00	30.22	51.84	25.39	1.98
2	170	150	39.88	66.67	41.67	44.48	78.72	57.31	2.16
3	190	220	45.71	75.00	58.33	57.87	97.53	72.84	2.21
4	250	300	62.86	100.00	66.67	72.54	100.00	100.00	3.07

5.3. *Sensitivity analysis*

A sensitivity analysis was conducted to gain insight into the impact of the eHighway road network design by assigning different weights to the objective functions. The analysis was carried out by applying the weighted sum method in which different weight coefficients w_i are assigned to the objective functions so that their sum equal to 1, i.e., $\sum_i w_i = 1$. To make the objective functions comparable, each of them was normalized by dividing it by the corresponding maximum value as follows:

$$\overline{z_1}(\mathbf{t}(\mathbf{x},\mathbf{y});\mathbf{f}^*) = \frac{\sum_{a\in A} f_a^*\cdot t_a\left(f_a^*, x_a, y_a\right)}{\sum_{a\in A} f_a^*\cdot t_a\left(f_a^*\right)} \tag{25}$$

$$\overline{z_2}(\mathbf{y}; c_{lane}, \mathbf{l}) = \frac{\sum_{a\epsilon A} c_{lane}\cdot l_a\cdot y_a}{\sum_{a\epsilon A} c_{lane}\cdot l_a} \tag{26}$$

$$\overline{z_3}(\mathbf{x},\mathbf{n_s}; r, 1, r_s, r_v) = \frac{\sum_{a\in A}\left(r\cdot l_a\cdot x_a + r_s\cdot n_{s,a}\right)\cdot(1+r_v)}{\sum_{a\in A}\left(r\cdot l_a + r_s\cdot n_{min,a}\right)\cdot(1+r_v)} \tag{27}$$

$$\overline{z_4}\left(\mathbf{x}; C_e, \mathbf{f}^*, 1, t\right) = \frac{\sum_{a\in A} C_e\cdot f_a^*\cdot l_a\cdot(1-x_a)\cdot t}{\sum_{a\in A} C_e\cdot f_a^*\cdot l_a\cdot t} \tag{28}$$

$$\overline{z_5}(\mathbf{x}; \mathrm{K}) = \frac{\sum_{a\in A} K_a\cdot x_a}{\sum_{a\in A} K_a} \tag{29}$$

Therefore, the corresponding problem is constructed as follows:

$$Z(\mathbf{x},\mathbf{n_s},\mathbf{y}) = w_1\overline{\overline{z_1}}(\mathbf{x},\mathbf{y}) + w_2\overline{z_2}(\mathbf{y}) + w_3\overline{z_3}(\mathbf{x},\mathbf{n_s}) + w_4\overline{z_4}(\mathbf{x}) + w_5\overline{z_5}(\mathbf{x}) \tag{30}$$

$$\left[\hat{\mathbf{x}}, \hat{\mathbf{n_s}}, \mathbf{y}\right] = Arg_{\mathbf{x},\mathbf{n_s},\mathbf{y}}\ min\ Z(\mathbf{x}, \boldsymbol{n}_s, \mathbf{y}) \tag{31}$$

s.t.

Eq. (10)–(22)

The analysis was carried out solving the BM-NEDP by using the GA in which weight w_i were set as to construct four significant scenarios and budgets B_1 and B_2 set equal to 200 Mio € and 250 Mio €, respectively. The results obtained after 10 runs are reported in Table 7. According to Scenario I, the equal priority to the objective functions z_3 and z_4 leads to the average electrification and emissions reduction of about 47% and 72%, respectively. Otherwise, by giving the highest priority to the objective functions z_3 and z_4 we obtained the highest percentage of electrification (61% on average) and the highest emissions reduction (88% on average), as depicted in Scenario II. These results have been confirmed in Scenario III in which the lowest priority to electrification ($w_3 = 0.65$) leads to lowest average emissions reduction of about 39% on average. By giving the highest priority to the objective functions z_1 and z_5 in Scenario IV, the average percentage of electrification is slightly lower compared to Scenario III, resulting in about 53% on average.

Furthermore, the results of the capacity expansion obtained after three runs are quite similar for Scenario I and Scenario II, resulting in about 22% and 17% on average, respectively. However, Scenario I resulted in slightly higher average percentage of capacity expansion due to lower criteria weight of the objective function z_4, compared to Scenario II. The highest capacity expansion percentage (about 32% on average considering all three runs) was obtained for Scenario IV by giving the highest priority to the objective functions z_3 and z_4, as well as the maximization the average traffic density of OC hybrid trucks in z_5. For example, the first run of Scenario IV resulted in the total of 3 links with the capacity expansion; the total number of lanes with the capacity expansion for second and third run in Scenario IV was 2. Differently, by giving the highest weight to the objective function z_3 in Scenario III, we obtained lowest environmental improvement and zero lanes with the capacity expansion.

5.4. Discussion and policy implications

The attention on climate-focused policies to support the decarbonisation of road freight transport and CO_2 emissions from heavy trucks is still necessary. In this context, there is still an open space for new proposals in the regulation of ERS deployment, and especially eHighways, considering that most practical applications are still experimental. For this reason, this work is aimed at creating opportunities for collaboration between public authorities/government and the private sector. Therefore, the proposed model assesses the environmental benefits and opportunities of implementing eHighways through multiple objectives

Table 7

The best results of GA obtained after 10 runs considering four different scenarios ($B_1 = 200, B_2 = 250$).

Scenario I

No.	$\bar{Z}$	$w_1 = 0.05$	$w_2 = 0.05$	$w_3 = 0.4$	$w_4 = 0.4$	$w_5 = 0.1$	Electrification (%)	Capacity expansion (%)	Potential CO_2 reduction (%)
		$z_1^*(\mathbf{x},\mathbf{y})$	$z_2^*(\mathbf{y})$	$z_3^*(\boldsymbol{x},\boldsymbol{n}_s)$	$z_4^*(\boldsymbol{x})$	$z_5^*(\boldsymbol{x})$			
1	0.2416	0.0500	0.0081	0.1512	0.1091	0.0727	50.00	16.67	72.73
2	0.2312	0.0500	0.0058	0.1382	0.1098	0.0726	41.67	33.33	72.56
3	0.2466	0.0500	0.0081	0.1512	0.1130	0.0717	50.00	16.67	71.75

Scenario II

No.	$\bar{Z}$	$w_1 = 0.05$	$w_2 = 0.05$	$w_3 = 0.15$	$w_4 = 0.7$	$w_5 = 0.05$	Electrification (%)	Capacity expansion (%)	Potential CO_2 reduction (%)
		$z_1^*(\mathbf{x},\mathbf{y})$	$z_2^*(\mathbf{y})$	$z_3^*(\boldsymbol{x},\boldsymbol{n}_s)$	$z_4^*(\boldsymbol{x})$	$z_5^*(\boldsymbol{x})$			
1	0.1209	0.0500	0.0029	0.0768	0.0398	0.0472	58.33	16.67	94.32
2	0.1141	0.0500	0.0035	0.0809	0.0294	0.0479	58.33	16.67	95.80
3	0.2636	0.0500	0.0035	0.0705	0.1786	0.0372	66.67	16.67	74.49

Scenario III

No.	$\bar{Z}$	$w_1 = 0.05$	$w_2 = 0.05$	$w_3 = 0.65$	$w_4 = 0.05$	$w_5 = 0.2$	Electrification (%)	Capacity expansion (%)	Potential CO_2 reduction (%)
		$z_1^*(\mathbf{x},\mathbf{y})$	$z_2^*(\mathbf{y})$	$z_3^*(\boldsymbol{x},\boldsymbol{n}_s)$	$z_4^*(\boldsymbol{x})$	$z_5^*(\boldsymbol{x})$			
1	0.1000	0.0500	0.0000	0.0863	0.0343	0.0784	16.67	–	31.35
2	0.0912	0.0500	0.0000	0.0942	0.0328	0,0859	25.00	–	34.36
3	0.0874	0.0500	0.0000	0.1374	0.0250	0,1250	33.33	–	49.99

Scenario IV

.	$\bar{Z}$	$w_1 = 0.65$	$w_2 = 0.05$	$w_3 = 0.05$	$w_4 = 0.05$	$w_5 = 0.2$	Electrification (%)	Capacity expansion (%)	Potential CO_2 reduction (%)
		$z_1^*(\mathbf{x},\mathbf{y})$	$z_2^*(\mathbf{y})$	$z_3^*(\boldsymbol{x},\boldsymbol{n}_s)$	$z_4^*(\boldsymbol{x})$	$z_5^*(\boldsymbol{x})$			
1	0.4904	0.6500	0.0099	0.0262	0.0099	0.2006	58.33	33.33	80.25
2	0.4749	0.6500	0.0058	0.0265	0.0076	0.2121	50.00	33.33	84.85
3	0.5133	0.6500	0.0052	0.0236	0.0074	0.1704	50.00	25.00	85.18

that can be all or separately embedded according on different expectations and goals of policy makers.

Similar to existing policies on eco-friendly LDV deliveries in urban areas, the eHighway regulation should benefit from incentivizing hybrid trucks' market share. For this reason, when making long-term decisions, the environmental benefits of an eHighway system are influenced by investments on infrastructure, OC trucks, catenary and traction substations, as observed from scenarios in Table 6. These aspects, modelled in objective functions $z_3^*(\boldsymbol{x}, \boldsymbol{n}_s)$ and $z_4^*(\boldsymbol{x}),$ can be seen as general criteria for decision makers to evaluate the eHighway system according to the specific infrastructure parameters.

In the policy context, the efforts of public authority/government in accelerating electrification and installation of road charging infrastructure can push the development of eHighway on the one hand, and on the other hand can strengthen the connection between light- and heavy-duty vehicle emission targets. At the same time, government initiatives should focus on promoting sustainable technologies and imposing incentives on the private sector (e.g. logistics companies) to switch from ICE trucks to OC hybrids, thus providing a reliable demand for vehicle manufacturers. Consequently, the public sector/government/highway operator would be interested in maximizing the use of the eHighway system and imposing certain rules for the market penetration of these vehicles. For this reason, the objective function $z_5^*(\boldsymbol{x})$ is intended to maximize the average traffic density of OC hybrid trucks served on electrified arcs. In addition, capacity expansion is introduced into the BM-NED problem to address the possibility of improving traffic flow conditions and handling the future increase in demand for OC trucks. Nevertheless, the presence of the objective function $z_1^*(\boldsymbol{x}, \boldsymbol{y})$ should ensure the operability of the transport system and the minimisation of total travel costs for freight operators.

Nonetheless, the proposed study has some limitations regarding assumptions and uncertainties related to the hybrid truck market share. In this context, detailed analysis on market competition with battery electric trucks could be carried out to highlight strengths and weaknesses of these technologies, as summarized in Table 3. Currently, this work is in line with the literature, as most of the research concerns hybrid technology. However, eHighways can be seen as an opportunity for both hybrid and full electric trucks since the electrified roads can serve both technologies, i.e., full electric trucks equipped with pantograph can exploit eHighways infrastructure to charge their batteries.

6. Conclusions

The technological innovations of heavy-duty trucks play an essential role for novel freight transportation solutions. The electrification of transportation and the introduction of the eHighway system enable the use of various alternative fuels, making it environmentally appropriate, as freight transport is a significant contributor to increased emissions and pollution. The eHighway system uses OC hybrid trucks that allow the usage of electric mode while driving on electrified road segments, without any interruptions, and therefore enhance the long-term decision-making questions regarding the mitigation of environmental impact. To this point, a Bi-level Multi-objective Network Electrification Design (BM-NED) model has been proposed, in which the output of the upper level related to the set of links to be electrified, as well as capacity expansion of some electrified links, was achieved through the multi-objective optimization, while the lower level is the traffic assignment problem. The capacity expansion was introduced to minimize the travel time on the electrified arcs on the one side, but on the other side the increase of links' capacity allows the demand flexibility due to the future increase of the OC hybrid trucks demand. The multi-objective optimization considered five criteria related to the minimisation of the total travel cost, the total infrastructure electrification and capacity expansion costs, environmental costs, and the maximization of the average traffic flows of OC hybrid trucks on the electrified arcs. The constraints are related to the capacity of substations, the number of traction substations on the electrified arcs, the budget limitations regarding the eHighway system costs and available budget for the capacity expansion, perceived as the number on lanes to be added on the electrified arcs, etc. Also, the proposed model is based on a traction substation simulation model for determining the minimum number of the traction substations required according to the OC hybrid trucks' flow for each road segments. The model was tested on part of the motorway network in the Veneto region in Italy, while a sensitivity analysis was carried out through the weighted sum method considering different criteria weights in the upper level. The results of the model showed good performances regarding the emissions reduction and the number of the electrified arcs, considering an electrification budget of 200 Mio € for a 17 km of motorway network. Moreover, the model application obtained an average percentage of the electrification and emissions reduction as about 54% and 66%, respectively. The performance and results of the developed model could help decision-makers to decide whether to adopt this technology or not, according to the limited budget resources. Also, the developed model could benefit authorities who are making long-term decisions since the advantages could be achieved for a long period (e.g., we assumed a service time of 20 years). For that purpose, we reported the descriptive statistics of multi-objective optimization considering different budget resources in the terms of the percentage of network electrification, emission reduction, and capacity expansion.

Currently, this paper provides insights into eHighway technology from the perspective of transportation network design and at a strategic planning level. In this respect, further works could deal with the operational level of planning, e.g., finding the optimal routing of OC hybrid trucks from an operating cost minimisation perspective. Also, this work can give insights to researchers and practitioners for developing extensions of this model, e.g., considering route choice models. Finally, future developments might: i) consider energy recovery during regenerative braking and energy consumption of OC trucks depending on acceleration/deceleration; ii) consider a traffic demand forecasting model for OC hybrid trucks.

CRediT authorship contribution statement

Aleksandra Colovic: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Mario Marinelli:** Writing – review & editing, Software, Methodology, Conceptualization. **Michele Ottomanelli:** Writing – review & editing, Supervision, Funding acquisition.

Data availability

The authors do not have permission to share data.

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Appendix A

In the proposed model, traction substations are perceived as one of the crucial points in the eHighway system since the optimal configuration (position and capacity of traction substations) are essential for smooth and continuous traffic flow operations. To deal with that, we embedded the traction substation model developed by Plougmann et al. (2017) which simulates OC hybrid trucks and traction substation behaviour, to obtain the minimum required number of traction substations n_s (Eq. (13)) for each electrified segment. Each segment of the electrified road is controlled by a "power box" with a voltage range of 670–740 V DC (Suul and Guidi, 2018). Thus, the simulation model considers the single-feeder solution with a voltage of 660/600 V. The output voltage of traction substations is designed to transmit the required 600 V for OC hybrid trucks plus the additional 10% to ensure that the eHighway system can operate without any break (i.e., 660 V is set to be the upper voltage level U_{upper}, while the bottom voltage level U_{lim} is equal to 500 V). OC hybrid trucks are not able to operate under the bottom voltage level. Based on the voltage drops, each traction substation has a limit on the total number of OC hybrid trucks n_{veh} that could operate without any failures. Since OC hybrid trucks are driving with constant speed V and minimum safe distance l_{min} when approaching the electrified arc, voltage drop depends on the resistance in overhead wires, the resistance of the truck R_t, the resistance between vehicles R_d, the resistance between vehicle and connection point R_v, and the number of vehicles n_{veh} connected to the overhead wires for each traversed distance l, during the fixed time. When approaching an electrified arc and connection point of traction substation, if no other trucks are connected to overhead wires, the resistance is fixed, and the truck can receive the maximal input voltage of 600 V (Plougmann et al., 2017). As moving further from the connection point of the traction substation, the resistance in overhead wires increases and, therefore, the next truck can receive lower input voltage. The model calculates the voltage drop until the traversed distance is equal to $lmin$, and another truck can approach the electrified arc in the eHighway system. When the voltage drop is lower than U_{lim}, the system is not able to receive more trucks for a defined period. At the end, the model calculates the maximum distance l for which the voltage level doesn't drop down to lower than U_{lim} and gives the maximal number of trucks n_{veh} that could be operated on an electrified arc. The eHighway system configuration considering traction substations is presented in Fig. 8.

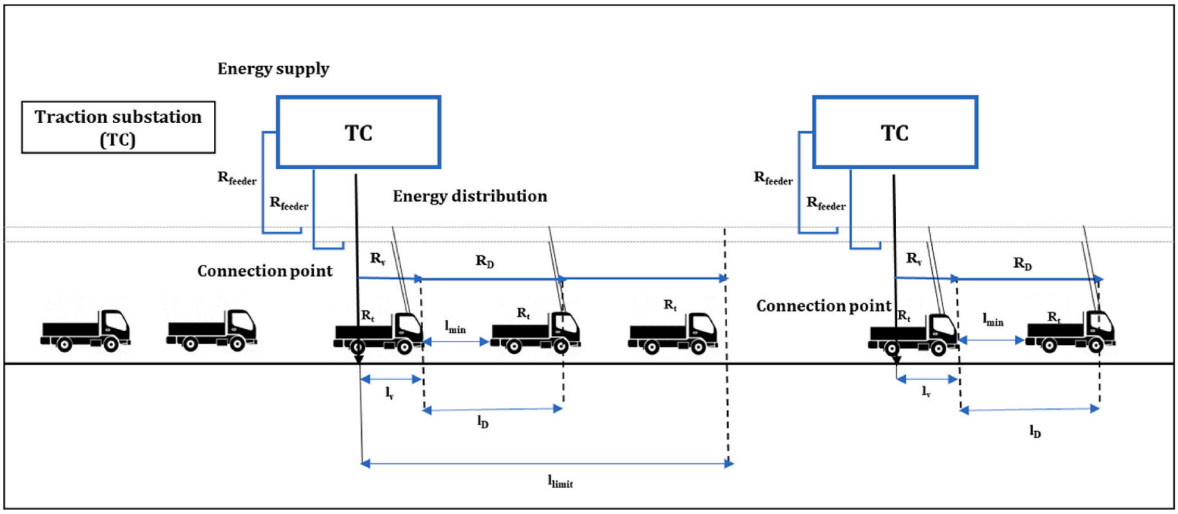

Fig. 8. Traction substation simulation model.

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