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New freight transport incentive to achieve modal shift targets: Methodology and application to Italy

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ABSTRACT

This study illustrates a new freight transport incentive for achieving modal shift targets. The proposed incentives are jointly designed for all non-road modes within an optimization framework, varying by origin–destination pair to maximize effectiveness while adhering to budget constraints and market competition regulations. This approach addresses the limitations and side effects of existing incentive schemes. Methodological issues related to the formulation and solution of the optimization problem are discussed, and a specific heuristic algorithm is presented to apply the proposed approach to large-scale instances. The viability of the proposed approach is demonstrated with an example of a multimodal freight system in Italy, considering various assumptions on freight mode choice and cargo values of time. The results show that the proposed approach outperforms nationwide incentive schemes.

Motivation and background

Transport accounted for 29 % of total economy-wide greenhouse gas (GHG) emissions in the European Union (EU) in 2018 (Buysse and Miller, 2021), with approximately one-third of transport-related emissions originating from fuel combustion in road freight transport (Yan et al., 2021). For freight-related transport, more than 72 % of GHG emissions are due to road transport, followed by aviation (13.3 %), maritime transport (12.8 %), and rail transport (0.5 %) (Beatrice et al., 2023). The World Economic Forum (2021) indicates that road freight generates 15 % of CO_2 emissions in Europe, with 70 % of these emissions coming from medium- and heavy-duty trucks.

Reducing emissions from road freight transport is a key step towards climate change mitigation, achievable through various policies consistent with the “avoid-shift-improve” approach (Wilson et al., 2020). Unfortunately, as reported by Beatrice et al. (2023) and Marzano et al. (2022), road freight transport emissions are difficult to abate, especially in Italy and similar markets, because almost 90 % of truck vehicle kilometres on Italian motorways involve trips shorter than 300 km (Ministero delle Infrastrutture e dei Trasporti, 2022), a distance where other freight transport alternatives are not competitive. This necessitates policies focusing on avoiding (e.g., improving truck load factors) and improving (e.g., incentives for transitioning to less polluting fuels and/or electric trucks). Zis et al. (2020) and Psaraftis et al. (2021) demonstrated that the ecological footprint of other freight modes can also be improved.

At medium-to-long distances, the competition among freight modes becomes significant, increasing the need for effective modal shifting policies, a long-pursued goal for achieving climate and environmental targets. As widely acknowledged in the literature (Aminzadegan et al., 2022), non-road freight modes are generally cleaner and more efficient for long-distance shipments. Thus, freight modal shift can be seen as both a political tool to achieve overarching policy objectives (e.g., environmental targets) and a policy objective in itself (Björk and Vierth, 2021).

Unfortunately, non-road freight modes are less flexible than road transport, owing to spatial discontinuities (i.e., accessibility only at dedicated loading/unloading terminals) and time constraints (i.e., scheduled services). This generally results in higher transport costs, which need to be compensated to make non-road modes more attractive, usually by internalizing environmental costs in road transport and/or incentivizing non-road modes (Kaack et al., 2018). Incentives can be granted to freight demand (shippers) and/or freight supply (carriers) to align transport costs across competing modes. In many countries, such as those in the EU, incentives must comply with regulatory frameworks to ensure fair market competition (Crozet, 2017; Laroche et al., 2017).

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Additionally, other policies can be implemented, such as the optimal intermodal routing problem addressed by Heinold and Meisel (2020), where shippers define a cap on their GHG emissions for an intermodal rail/road network in Europe.

This problem also arises in last-mile logistics and urban freight transport, compounded by the usual unavailability of non-road alternatives. In this context, incentives can be crucial; for instance, they can be granted to freight receivers (e.g., business establishments) to accept off-peak deliveries (Silas et al., 2012).

As noted in the literature review (Section 2), incentives are typically dispensed separately for each non-road mode, often at a constant amount nationwide, ignoring the heterogeneity of freight mode competition across origin–destination pairs. This approach leads to negative side effects, including nonoptimal budget spending and unnecessary competition among non-road freight modes, contrary to basic eco-rationality principles.

This study addresses these issues by presenting a novel incentive scheme for non-road freight modes aimed at achieving modal shift targets. These coordinated incentives are designed for all non-road modes within an optimization framework, varying by origin–destination pair to maximize effectiveness while adhering to budget constraints and market competition regulations. To the best of our knowledge, no similar incentive schemes exist in the literature. The main research challenge lies in solving the complex underlying optimization problem, whose properties and solutions are analysed. The viability and applicability of the proposed approach to large-scale instances are demonstrated using a multimodal freight system in Italy.

The remainder of this paper is organized as follows: Section 2 reviews the existing literature and relevant incentive schemes in EU and Italy. Section 3 presents the proposed methodology and practical solutions. Sections 4 and 5 describe the application to a multimodal freight system in Italy. Finally, Section 6 presents the conclusions and research prospects.

2. Literature review

This section highlights benchmark policies for incentive implementation in EU (Section 2.1) and Italy (Section 2.2) and reviews relevant aspects of the scientific literature on the design of incentives for freight modal shift (Section 2.3).

2.1. Incentives towards freight modal shifts in EU

EU has been promoting freight modal shifts for more than 30 years (Baird, 2007). The Marco Polo program, launched in 2003, incentivized freight transport service operators to shift from road to environmentally friendly modes, consistent with the EU White Paper on Transport (European Commission, 2011). The second edition of the Marco Polo program, from 2007 to 2013, was even more ambitious, with a larger budget and wider scope for both geographical coverage and actions. According to Horn and Nemoto (2005) and Kaack et al. (2018), the Marco Polo program compensated projects with 1–2 € per 500 tons·km shifted, corresponding to an equivalent saving of 25–50 € of CO_2 emissions per ton transported. Tsamboulas et al. (2007) analysed the context of a model-based analysis of modal freight competition in Europe, focusing on the role of internalizing CO_2 in freight mode costs. Although the overall efficacy of the program is disputed, especially in achieving modal shift targets (European Commission, 2018), the effectiveness of incentives is unanimously acknowledged (Santos et al., 2015).

The EU has also set a regulatory framework to incentivize freight transport by rail through the communication 2008/C 184/07 “Community guidelines on State aid for railway undertakings,” and by sea, as detailed by Bilbao-Ubillos et al. (2021). These regulations have paved the way for many national-based incentive initiatives.

In the railway sector, incentives can be granted to railway undertakings and/or rail network infrastructure managers (Boston Consulting Group, 2015). Steer (2015) highlighted that approximately 30 % of the total railway costs were covered by incentives in Europe in 2012. Matthews et al. (2009) and Finger and Messulam (2015) analysed the impact of incentives on the rail freight market in Europe, while Reis (2014) and Islam and Zunder (2014) explored the effectiveness of rail incentives as a prominent policy measure. Non-EU best practices are also available, such as case studies in the UK (ORR, 2016a; ORR, 2016b; UK Department of Transport, 2017a; UK Department of Transport, 2017b) and Switzerland (Finger and Holterman, 2013). Further details on the incentives for freight transport by rail are reported in the literature review by Marzano et al. (2018). Marzano et al. (2018) and Pittman et al. (2020) emphasize the importance of incentives as short-term policy measures that can be combined with long-term infrastructural investments.

In the maritime sector, EU regulations allow incentives to be granted only to shipping companies. Douet and Cappuccilli (2011) identified some shortcomings in the EU policies towards the promotion of Short-Sea Shipping (SSS) and proved that the competitiveness of maritime transport in EU, compared to all-road transport, depends highly on incentives. Similarly, Suárez-Alemán et al. (2014) analysed key drivers to foster fair and efficient intermodal competition between freight transport modes in EU, highlighting the importance of direct incentives to maritime transport. Merkel and Lindgren (2022) observed significant variations in freight demand elasticities to transport costs and, thus, to incentives, with relevant policy implications.

2.2. Incentives to freight transport in Italy

For this study, we recall the patterns of incentives for rail and maritime freight transport in Italy.

In the railway sector, the Italian government incentivizes both shippers/multimodal transport operators (the *Ferrobonus*) and railway undertakings (the *Norma Merci*). The shipper-based incentive *Ferrobonus*, established in Italian Decree 125/2017 by the Ministry for Transport and Infrastructure, aims to internalize the lower social and environmental costs of freight transport by railway compared to road transport. Beneficiaries must achieve predefined rail freight traffic targets and maintain them after the incentive to avoid market distortion. *Norma Merci* discounts the network toll that railway undertakings must pay to the rail network infrastructure manager, with a further grant to railway undertakings operating trains to/from Southern Italy and Sicily–the most penalized regions in terms of the infrastructural performance of the freight rail network. A recent study by Rete Autostrade Mediterranée (2021) estimated that *Ferrobonus* shifts between 0.5 % and 0.8 % of freight traffic from roads with significant environmental savings, consistent with the European Commission (2014) calculation guidelines. Considering other incentives for the renewal of rolling stock and upgrade of existing rolling stock to new safety regulations, the overall average yearly budget of incentives for freight railway transport in Italy in recent years can be estimated at 130 M€, of which approximately 100 M€ is for *Norma Merci* and 30 M€ for *Ferrobonus*.

In the maritime sector, the pioneering *Ecobonus* initiative was launched between 2007 and 2009, with an overall budget of 168.5 M€ to incentivize truck drivers to shift towards the Motorways of the Sea (Marzano et al., 2020). Tsamboulas et al. (2015) established a methodological framework to assess the effectiveness of *Ecobonus*. Leveraging *Ecobonus*, EU funded a Connecting Europe Facility project in 2015 to develop a smarter incentive scheme for maritime freight transport, called *Med Atlantic Ecobonus*. Soon after 2015, Italian National Law 208/2015 established a new incentive called *Marebonus* to support investments by maritime companies operating Ro-Ro services in proportion to the number of trucks·km diverted from roads. Maritime companies must, in turn, pass a share of 70 % or 80 %, depending on the number of trucks embarked per year of the received incentive to their customers, i.e., the embarked truck operators, to support the modal shift. The *Marebonus*, active between 2017 and 2019, with an overall budget of 118 M€, increased the weekly capacity of incentivized Ro-Ro services by 104,800 linear meters (+7.5 % compared to the period preceding the *Marebonus*), with around 190,000 trucks diverted from road (Rete Autostrade Mediterranée, 2021).

Despite modal shift incentives, freight transport by road is by far the most subsidized mode in Italy, with an average budget of 240 M€/year to compensate for lump sum reimbursements, operational expenditures (including discounts on motorway tolls), and support truck fleet renewal. Freight transport by road in Italy also benefits from a discount on fuel excesses for a total average amount of more than 200 million per year.

Overall, incentives in Italy do not appear to be coordinated or fully eco-rational in their objectives. Incentives are granted on a watering-can principle without accounting for the heterogeneity of freight transport supply and demand across the country, i.e., they do not consider the actual transport costs for different origin–destination pairs. This might lead to undesirable effects, such as providing incentives to origin–destination pairs with an already acceptable modal split towards non-road modes or to origin–destination pairs and/or commodities already substantially captive (thus not responsive to any incentives) on specific modes. Additionally, a lack of coordination might yield ineffective incentive-based competition among simultaneously subsidized non-road modes. Furthermore, current incentives are *de facto* subsidies to all modes of transport and, thus, to the economic system in general, rather than being clearly oriented towards modal rebalancing. Additionally, the practical implementation of current incentives primarily involves carriers with limited and not fully transparent perception of shippers.

This motivates the research presented in this paper, which aims to improve the current incentive schemes in two directions: first, to develop a holistic formulation of an overall incentive scheme pursuing modal shift and/or environmental targets; second, to account for the inherent heterogeneity of freight mode performance across origin–destination pairs by allowing incentives to vary geographically within a country. Such incentives may also foster freight digitalization and better data collection to overcome well-known issues.

2.3. *Review of scientific papers dealing with incentives for modal shift*

Despite the prominence of incentives as effective policy measures for modal shifts worldwide, only a few studies have addressed the issue of designing effective incentives. Instead, researchers mainly focussed on ex-post analyses and/or monitoring the impacts of incentives, as per the literature cited in the previous subsections.

Tao (2013) estimated two discrete choice models to quantify the potential incentives for intermodal freight transport between Ningbo Port and East Jiangxi Province in China. Chen et al. (2014) introduced state incentives for coastal shipping operators in a coastal intermodal network design problem aimed at minimizing the public budget, presenting a case study on Bohai Bay in China. Marzano et al. (2018) proposed an innovative concept of incentives for railway undertakings to compensate for the infrastructure gap they encountered on the Italian rail network, relative to the EU's optimal performance targets. This incentive, dispensed on a region-to-region basis, has proven to be fairer than the current *Ferrobonus* and *Norma Merci* principles (see Section 2.2). Yang et al. (2020) designed an incentive scheme to support container transport by rail, coordinating incentives provided by various public bodies, with application to containerized trade between Northeast Asia and Europe and within Northern Chinese inland cities. They demonstrated that coordinated optimization yields better total social welfare with a lower budget. Yin et al. (2021) developed a rail freight incentive accounting for various influencing factors, proposing a bi-level programming model with the upper level maximizing rail freight flows and lower level minimizing o-d freight transport costs, applied to a case study in the Yangtze River Delta in China.

Raza et al. (2020) reviewed the existing literature and identified innovative incentives to promote SSS in conjunction with taxes on road haulage as an opportunity for future research. Li and Zhang (2020) optimized freight pricing, backlog control, and flexible dispatching to push the modal shift from road to rail, applying their methods to a case study encompassing five central cities in China. Gong and Li (2022) analysed the joint effect of incentives on rail freight and sulphur emission control schemes on maritime transport between China and Europe along the Silk Road corridors, proposing welfare maximization models to optimize incentives and sulphur emission control. They found that promoting intermodal competition was more effective than promoting intermodal cooperation. Hu et al. (2022) proposed a linear incentive scheme for waterborne transport consisting of fixed-rate and variable components proportional to the sailing distance. They developed a bi-level programming formulation with diverse objective functions and solution algorithms, applied to a case study of the Pearl River Delta in China, and found similarities in the results either by maximizing the modal shift from the road or minimizing the GHG emissions.

3. Methodology

Notation and problem formulation

In this study, we propose an optimal design of incentives to shift freight transport from harmful modes to more eco-friendly modes, overcoming the inherent inefficiencies and ineffectiveness of the current incentive schemes discussed in Section 2. To illustrate the proposed approach given in the study area, let:

- Z be a set of Traffic Analysis Zones (TAZs); therefore, so that $ZxZ \equiv Z^2$ is the set of origin–destination pairs;
- R be a set of regions within the study area, typically with $|R| \ll |Z|$, so that $R \times R \equiv R^2$ is the set of region-to-region pairs;
- Z_r^2 be the set of origin–destination pairs of TAZs such that the origin and destination TAZs for any $j \in Z_r^2$ belong respectively to the origin and destination regions identified by $r \in R^2$;
- $r(j)$ be an index that identifies the pair of regions $r \in R^2$ corresponding to the pair of zones $j \in Z^2$;
- M be the set of available transport modes in the study area, partitioned into two subsets E and H, with $E \cap H = \varnothing$ and $E \cup H = M$, containing eco-friendly and harmful modes respectively. Let $H \equiv \{road\}$;
- dr_j be the total distance by road between the o-d pair $j \in Z^2$;
- dr_j^m be the length of the feeder legs by road needed to reach the loading terminal of mode $m \in E$ from the origin and destination from the unloading terminal of mode $m \in E$;
- d_j^m be the road distance saved using mode $m \in E$ for the o-d pair $j \in Z^2$, i.e., $d_j^m = dr_j - dr_j^m$;
- v_j be the freight transport volume related to $j \in Z^2$, expressed for instance in vehicles/year or tons/year;
- v_j^m be the freight transport volume on mode $m \in M$ related to $j \in Z^2$, such that $\Sigma_m v_j^m = v_j \ \forall j \in Z^2$;
- c_j^m be the transport costs of a freight unit on mode $m \in M$ for the o-d pair $j \in Z^2$;
- B_{max} be the maximum budget available for incentives.

The rationale of the proposed approach is to grant geographically differentiated incentives for eco-friendly modes in the study area to account for the inherent geographical heterogeneity of freight transport supply and market conditions within a country. Two contrasting needs should be addressed: on one hand, an o-d-based incentive is practically implementable only with a limited number of origins/destinations, while on the other hand, origins/destinations should be abundant enough to precisely estimate freight transport costs. The proposed incentive solves this dichotomy by following the geographical granularity of R; in other words, given $r \in R^2$, the same incentive is granted to all o-d pairs belonging to Z_r^2, while possibly different incentives are enabled across pairs of regions within R^2. The freight transport costs were calculated for each o-d pair belonging to Z^2.

Hence, the objective of the proposed incentive is to maximise the overall amount of freight·km saved from the road (harmful mode), expressed by the following function:

$$\sum_{j\in Z^2, m\in E} d_j^m \bullet v_j^m = \sum_{j\in Z^2, m\in E} \left(dr_j - dr_j^m\right) \bullet v_j^m \tag{1}$$

The freight volume v_j^m depends upon the unit transport costs c_j^m of all modes $m \in M$, which in turn can be modified by means of the incentive.

Without loss of generality, the incentive is expressed as a percentage s_r^m of the full (i.e., not incentivised) unit cost c_j^m for each incentivised mode $m \in E$ and for each origin–destination pair of regions $r \in R^2$, yielding the incentivised unit cost sc_j^m for each origin–destination pair $j \in Z^2$:

$$sc_j^m = c_j^m \bullet \left(1 - s_{r(j)}^m\right) \forall m \in E, \forall j \in Z^2 \tag{2}$$

An appropriate upper bound s_{max} of the incentive percentage s_r^m can be conveniently set to model possible regulations on State aid, as recalled in Section 2. Letting $\mathbf{sc_j}$ be the vector of possible[1] incentivised costs for all modes available for the o-d pair *j,* a mode choice model (usually nonlinear with respect to incentives) can be applied to calculate the probability $\rho_j^m(\mathbf{sc_j})$ of choosing mode *m* for *j*. This allows the calculation of freight volumes in each mode, and thus, the total incentive granted to mode *m* on the o-d pair *j*:

$$S_j^m = s_{r(j)}^m \bullet c_j^m \bullet v_j \bullet \rho_j^m(\mathbf{sc_j}) \forall m \in E, \forall j \in Z^2 \tag{3}$$

The summation of (3) over the modes and o-d pairs yields the total budget requested for the incentive:

$$B = \sum_{m\in E, j\in Z^2} s_{r(j)}^m \bullet c_j^m \bullet v_j \bullet \rho_j^m(\mathbf{sc_j}) \tag{4}$$

to be compared with the maximum available budget B_{max}.

Overall, the following optimization problem can be set to find the best incentive:

$$\max \sum_{j\in Z^2, m\in E} d_j^m \bullet v_j \bullet \rho_j^m(\mathbf{sc_j}) \tag{5}$$

s.t.

$$\sum\nolimits_{j\in Z^2} B_j \le B_{max} \tag{6}$$

$$B_j = \sum_{m\in E} s_{r(j)}^m \bullet c_j^m \bullet v_j \bullet \rho_j^m(\mathbf{sc_j}) \tag{7}$$

$$sc_j^m = c_j^m \bullet \left(1 - s_{r(j)}^m\right) \forall m \in E, \forall j \in Z^2 \tag{8}$$

$$B_j \ge 0 \forall j \in Z^2 \tag{9}$$

$$sc_j^m \ge 0 \forall m \in M, \forall j \in Z^2 \tag{10}$$

$$0 \le s_r^m \le s_{max} \forall m \in E, \forall r \in R^2 \tag{11}$$

The variables of the optimisation problem are the incentive percentages[2] s_r^m $\forall m \in E$, $\forall r \in R^2$. Objective function (5) maximizes vehicles·km in eco-friendly freight modes in accordance with Eq. (1). Constraint (6) sets the overall budget constraint, consistent with constraint (7), which sets the total incentive budget for each o-d pair. Constraint (8) is given by Eq. (2), which computes the incentivized cost as a percentage of the actual unit cost for eco-friendly modes. Finally, constraints (9), (10), and (11) set the relevant upper and lower bounds.

Problem (5) is nonlinear due to constraint (7), making its solution nontrivial. Generally, the proposed formulation resembles other types of optimization problems, such as location problems (Freire et al., 2016), resource allocation problems (Patriksson, 2008), and choice-based problems (Pacheco et al., 2022). Several methods have been proposed for addressing these problems; however, their effective transferability to the problem under investigation is cumbersome, owing to their specific features. Therefore, an ad-hoc heuristic is proposed to solve large real-world instances of the problem, as described in the next section.

Problem solution: region-based sequential heuristic

The heuristic is based on the region-based decomposition of the full problem in (5)–(11). Given an origin–destination pair of regions $r \in R^2$, the effect of a given set $\mathbf{s_r} = \left\{s_r^m \in [0, s_{max}] \forall m \in E\right\}$ of incentive percentages on the objective function can be calculated by applying Eq. (8) first, then the mode choice model that yields the choice probabilities $\rho_j^m(\mathbf{sc_j})$ for each mode *m*, and finally:

$$\sum_{j\in Z_r^2} \sum\nolimits_{m\in E} d_j^m \bullet v_j \bullet \rho_j^m(\mathbf{sc_j}) \tag{12}$$

which represents the contribution of *r* (through $\mathbf{s_r}$) to the objective function (5). Similarly, the budget corresponding to $\mathbf{s_r}$ is is given by:

$$\sum\nolimits_{j\in Z_r^2} \sum\nolimits_{m\in E} s_{r(j)}^m \bullet c_j^m \bullet v_j \bullet \rho_j^m(\mathbf{sc_j}) \tag{13}$$

which is the summation of (7), calculated on $\mathbf{s_r}$, over all o-d pairs of zones within Z_r^2.

Eqs. (12) and (13) enable a simple sequential heuristic to reduce the complexity of the problem in three steps:

At a glance, the first step is a grid-based exploration of the space of incentive percentages for each pair of regions $r \in R^2$, based on (12) and (13), aimed at reducing the feasibility domain of the problem by discarding dominated solutions. The second step operates separately on each origin region $o \in R$: thanks to the outcomes of the first step, the maximisation of vehicle·km subtracted to road from *o* towards all destination regions is formulated as a linear optimisation problem, solved for various values of budget. The third step leverages the outcomes of the second step and consists of applying another linear optimisation problem, similar to step #2, to allocate the overall budget B_{max} across the origin regions, obtaining a suboptimal solution. In principle, small problem instances might allow optimising all pair of regions $r \in R^2$ together, without running in sequence the second and the third steps.

In detail, each step of the proposed sequential approach is illustrated below:

1 for each pair of regions $r \in R^2$, a grid calculation of (12) and (13) is performed on the entire feasibility set of incentive percentages. Formally, letting γ_c be the number of points where to calculate each s_r^m between 0 and s_{max}, Eqs. (12) and (13) are calculated for each set of incentive percentages $\mathbf{s_r} = \left\{s_r^m = \frac{\gamma_m}{\gamma_c - 1} s_{max} \forall m \in E\right\}$ with each integer γ_m varying between 0 and γ_c-1. Overall, ${\gamma_c}^{|E|}$ combinations of contributions to the objective function (12) and the corresponding budgets (13) are obtained. Some of them are dominant and are thus removed from the entire set of combinations, specifically those such that other combinations exist with the same contribution to the objective function (12) and with a higher budget (13). Let $\mathbf{C}_r$ be the set of all incentive percentages $\mathbf{s_r}$ corresponding to non-dominated combinations, likely with $|\mathbf{C}_r| \ll {\gamma_c}^{|E|}$. The values of objective function (12) and budget (13) corresponding to each $\mathbf{s_r} \in \mathbf{C}_r$ can be collected in two column vectors, respectively denoted as $\mathbf{f}_r$ and $\mathbf{b}_r$, with the number of rows equal to $|\mathbf{C}_r|$. The maximum of $\mathbf{b}_r$ represents intuitively the maximum budget B_{max}^r, making it logical to allocate to the pair of regions $r \in R^2$.

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[1] Clearly, $\mathbf{sc_j}$ includes the incentivised cost for eco-friendly modes and the current cost for harmful modes.

[2] The condition $|E| < |M|$, implying that at least one harmful mode exists, ensures the problem to be well-posed in case of additive mode choice models, wherein only differences in (dis)utilities matter.

As a result, each region $o \in \mathrm{R}$ is associated with:

- a maximum budget $B^{o}_{max} = \sum_{d \in R} B^{r=\{o,d\}}_{max}$;
- a column vector of objective function (12) values $\mathbf{f_o}$, obtained by appending by column all vectors $\mathbf{f}_{\boldsymbol{r}}$ with $r = \{o,d\}\forall d$, i.e., with a number of rows equal to $\sum_{d \in \mathrm{R}} |\mathbf{f}_{\boldsymbol{r}=\{\boldsymbol{o},\boldsymbol{d}\}}|$;
- a column vector of budget values $\mathbf{b_o}$, obtained as the previous by appending by column all vectors $\mathbf{b}_{\boldsymbol{r}}$ with $r = \{o,d\}\forall d$. By definition, $\mathbf{b_o}$ has the same dimension as $\mathbf{f_o}$;
- a region-destination region incidence matrix $\mathbf{A_o}$, with dimension $|\mathrm{R}| \cdot \sum_{d \in \mathrm{R}} |\mathbf{f}_{\boldsymbol{r}=\{\boldsymbol{o},\boldsymbol{d}\}}|$, whose generic element a_{ij} equals 1 if region i is the destination region of the j-th element of the vector $\mathbf{f_o}$, and zero otherwise. $\mathbf{A_o}$ is required to specify the optimisation variables of problem (14) through constraint (16) in the following step:

Sequentially, for each origin region $o \in \mathrm{R}$, let γ_{bo} be the number of points to explore between 0 and B^{o}_{max}. For each $\gamma \in [0, \gamma_{bo}\text{-}1]$ let $B^{o}_{\gamma} = \frac{\gamma}{\gamma_{bo}-1} B^{o}_{max}$, yielding the following binary integer linear optimisation problem:

$$max \boldsymbol{f_o} \times \boldsymbol{x_g} \tag{14}$$

s.t.

$$\boldsymbol{b_o x_\gamma} \leqslant B^{o}_{\gamma} \tag{15}$$

$$\boldsymbol{A_o x_\gamma} = 1 \tag{16}$$

where the objective function (14) mimics the optimisation problem (5) and is consistent with the budget constraint (15). Constraint (16) ensures that only one combination of incentives is selected for each destination region, together with the related values of the objective function and budget. Evidently, γ_{bo} instances of problems (14)–(16) should be solved for each region, however, with a very limited computational burden, owing to their simplicity. The solution of the optimisation problem identifies the optimal sets of incentive percentages$\mathbf{s}_{\mathbf{r}\gamma} \in \mathbf{C}_{\boldsymbol{r}}$ for each pair of regions $r \in \mathrm{R}^2$ such that the origin region of r is o, consistent with the given budget constraint B^{o}_{γ}, yielding also the corresponding optimal values of the objective function (12) and their associated budget.

The optimisation problems in step #2 quantify the maximum of the objective function (12), i.e., the vehicle·km subtracted from road, for all pair of regions with origin o and γ_{bo} budget values B^{o}_{γ} variable between 0 and B^{o}_{max}. Indeed, based on the outcomes of step #2, the overall national budget can be optimised across origin regions with a linear allocation problem analogous to (12)–(14), with the explicit constraint that the sum of the regional budgets should not exceed the overall national budget. The formulation of this optimisation problem is not reported for brevity because it is formally equal to (12)–(14). Further budget constraints might be introduced to account for further policy considerations, for instance, by imposing a minimum and/or maximum budget per region; these are not considered in this study for the sake of simplicity.

At the end of step #3, nationwide optimised results by origin region, in terms of budget and incentive percentages for each destination region, are available together with the corresponding optimised values of the objective function, i.e., vehicle-km subtracted from the road originating in each region.

3.3. Nation-based optimised approach as term of comparison

A nation-based instance of problems (5)–(11) can be formulated by assuming R as a singleton; i.e., the entire nation is considered as a single region. This yields $\mathrm{Z}^2_{\mathrm{r}} = \mathrm{Z}^2$ and the variables to optimise shrinkage to $|\mathrm{E}|$, which is a unique national-based incentive percentage s^m for each non-road eco-friendly mode. In other words, the incentive is still o-d based, being a percentage of the total cost, yet with a very limited number of variables (two in the practical example proposed in this paper), which substantially reduces the computational burden of the problem and makes the heuristics illustrated in Section 3.2 unnecessary.

Importantly, the solution of the national-based optimised approach is better than the current situation described in Section 2.2, i.e., with non-optimised incentives provided on a watering-can principle. It represents the baseline for the region-based incentive proposed in Section 3.1, to showcase the superiority of a region-based incentive with respect to nation-based optimisation.

3.4. Mode choice model

As mentioned, the design of an incentive requires modelling freight mode choice, a classic topic in freight transport research. Data availability is a major concern, often preventing proper development of freight mode choice models (Ben-Akiva et al., 2016). This is the case in Italy and, in fact, many countries worldwide, where only the aggregate market shares of freight modes can be easily observed.

Thus, researchers and practitioners must compromise between effectiveness and real-world development. Following de Jong et al. (2014), Holguín-Veras et al. (2021), and Kalahasthi et al. (2022), a simplified yet robust approach to modelling nationwide freight mode choice in such situations is to resort to a Multinomial Logit (MNL) model with cost, time, and possibly time reliability attributes. In such models, the value of time (VOT), that is, the time-to-cost substitution ratio, plays a major role, and its estimation is another classic issue in transport engineering (de Jong et al., 2004; de Jong, 2008; de Jong et al., 2014; Jensen et al., 2019).

In general, freight VOT can be split into two major components (de Jong et al., 2014): the transport component VOT_t, which refers to carrier-related transport costs, and the cargo component VOT_c, which refers to the holding cost of the carried freight faced by the shipper. Usually, the transport component accounts for the majority of the total VOT—roughly 80 % according to Jensen et al. (2019)—with the cargo component being negligible for most commodities (Holguín-Veras et al., 2021). According to in-depth reviews by de Jong et al. (2014) and Jensen et al. (2019), the entire VOT usually falls between 4 and 6 €/ton/h, with the sole cargo component averaged across commodities not greater than 0.5 €/ton/h (Jensen et al., 2019).

Recently, Marzano et al. (2022) applied a threshold-based freight mode choice model to analyse the policy implications of truck platooning in Italy. These positive outcomes also suggest testing the Multinomial Weibit model (MNW, for a comprehensive interurban mode choice application of MNW-based models see Tinessa, 2021), which can be interpreted as a continuous formulation of a threshold-based freight mode choice model. The MNW model differs from the MNL model in its assumption of the distribution of random error terms (Weibull vs. Gumbel), yielding a multiplicative disutility function and consistent closed-form probability statement based on the ratios between systematic disutilities (see Section 3.4 for details). Interestingly, to the best of our knowledge, there are no examples of applications of the MNW model to nationwide freight mode choice modelling.

As a result, various practical instances of the problem (5)-(11) can be set, depending upon the specification of the functional form of the mode choice model underlying calculation of probabilities $\rho^{m}_{j}(\mathbf{sc}_{\mathrm{j}}) \ \forall m \in \mathrm{M}$. Consistent with the above, the MNL and MNW models were considered, which are specified as follows:

Multinomial Logit model. Freight mode choice probabilities can be calculated with the MNL model by associating each mode $m \in \mathrm{M}$ for each o-d pair $j \in \mathrm{Z}^2$ with a systematic utility V^{m}_{j}, yielding the well-known probability statement:

$$\rho^{m}_{j}(\mathbf{sc}_{\mathrm{j}}) = \frac{\exp(V^{m}_{j}/\theta)}{\sum_{m'} \exp(V^{m'}_{j}/\theta)} \tag{17}$$

θ being the variance parameter of the MNL model. The role of the MNL model (17) in the optimisation problem (5) is to split the overall freight volume v_j across modes for each o-d pair $j \in Z^2$, thus with an aggregated approach, a natural choice when only aggregated data (i.e., observed freight mode shares) are available for model estimation and validation. Systematic utility is specified as follows:

$$V_j^m = -(c_j^m + VOT_c \bullet t_j^m) = -(c_{j_{nt}}^m + VOT_t \bullet t_j^m + VOT_c \bullet t_j^m) \tag{18}$$

wherein c_j^m and t_j^m are respectively the carrier-based freight transport costs (including time-related costs) and times for the o-d pair $j \in Z^2$. The total cost c_j^m can in turn be split into a time-independent component $c_{j\_nt}^m$ and time-dependent component $VOT_t \bullet t_j^m$ linked to the transport component of the value of time. The practical specifications of (18) for each mode are listed in Table 1 of Section 4.1. A time reliability attribute was not included in (18), as the reliability of nationwide shipments in Italy is relatively high and thus not perceived as a discriminating choice attribute. Furthermore, the time value is assumed to be independent of the mode because, consistent with the above, it represents the cargo component of the time value.

Multinomial Weibit model. The choice probabilities of the Multinomial Weibit (MNW) model were calculated using the following formulae:

$$\rho_j^m(\mathbf{sc_j}) = \frac{1}{\sum_{m'}\left(\frac{V_j^{m'}}{V_j^m}\right)^{-\lambda}} \tag{19}$$

where λ is a variance parameter to estimate $V_j^m < 0 \forall j$, and all remaining values are equal to those of the MNL model, including (18).

4. Application to Italy: Setup

4.1. Study area and freight supply models

The proposed methodology was applied to Italy based on the supply model introduced by Marzano et al. (2022) and Buonocore et al. (2023). The study area (Fig. 1, top left) includes 20 regions, whose combinations yield set R, and 611 Local Labour Systems (LLSs),[3] whose combinations yield set J. For simplicity, only national shipments are considered; i.e., the effect of incentives on international freight transport is not considered.

Three freight modes were modelled: on the harmful side, road (set H); on the eco-friendly side, rail, and maritime transport (set E). Costs c_j^m for each mode m and each origin–destination pairs $j \in J$ are calculated with mode-specific freight supply models; supply models for non-road modes also include costs of road feeder legs (see Section 3.1). Without loss of generality, costs are calculated in the light of freight carriers, i.e., they should be interpreted as freight transport production costs with reference to a shipment size equivalent to a full truck load to ensure fair comparison of costs across modes.

The topological models developed by Marzano et al. (2022) are illustrated in Fig. 1 with reference to road (top right), rail (bottom right), and maritime transport (bottom left). Maritime links represent nationwide regular Ro-Ro/Ro-Pax liner maritime services.

The cost components of the analytical model for each mode are reported in Table 1, with a breakdown of all the time-dependent components leading to the transport value-of-time VOT_t and time-independent $c_{j\_nt}^m$ costs in Eq. (18).

In particular:

- For the road mode, data were taken from Marzano et al. (2020) and Marzano et al. (2022), considering the stop/rest times of sub-additive truck drivers as per the European Commission Regulation 2020/1054. Two options have been introduced for road fuel costs, depending on whether subsidies are granted to freight transport by road to reduce operational costs and support economic growth. The policy implications of these options are discussed in Section 4.3. Fuel consumption for each link was calculated as a function of slope and speed.
- For the rail mode, costs were computed using the model proposed by Marzano et al. (2018), which accounts for track gauge, slope, maximum train length, *gabarit*, weight, and maximum speed differentiated by train type. Train costs were converted into unit shipment costs per truck equivalent load, considering a 90 % average load factor per train.
- For the maritime mode, travel times were retrieved from official timetables, and freight costs for accompanied (considering both trailer and tractor embarked) and unaccompanied (considering only the trailer embarked, without driver and tractor) options were computed according to Sambracos and Maniati (2020) and Marzano et al. (2022).

4.2. Freight transport volumes

Consistent with Section 4.1, o-d freight flow volumes should be estimated between o-d pairs in set Z^2 for the study area, as illustrated in Fig. 1. This study uses the o-d flow estimates provided by Marzano et al. (2022), updated with input data from the Italian National Statistics Institute and the Italian Ministry for Infrastructures and Transport. Captive shipments in specific modes (e.g., iron or coils, usually transported only by sea/rail) are excluded, along with air freight, inland waterways, and pipelines, all of which are negligible for domestic shipments in Italy. Summary statistics of domestic o-d freight flows by type of o-d pair can be found in Marzano et al. (2022).

Notably, based on the data considered, the total freight demand was 183 billion ton-km, with 70.8 % of the total tons referring to travel distances of less than 200 km. In this latter group of o.-d pairs, road transport can be considered a captive mode. Thus, these pairs can be considered insensitive to potential rail/maritime incentives.

4.3. Mode choice model parameters

As only aggregated freight mode market shares were available, to prevent the estimation of VOT for the case study, two reasonably extreme VOT_c bounds were considered. The former is 0, i.e., there is no cargo component for VOT; the latter is 1, which represents an upper bound consistent with the literature (see Section 3.4). Thus, given VOT_c, the variance parameters θ and λ of the MNL and MNW models can be estimated, consistent with Section 3.4, using a nonlinear least squares approach, yielding the estimated values reported in Table 2.

5. Application to Italy: results

The approaches proposed in Section 3 are applied to the case study presented in Section 4, maintaining the current fuel price discount for road freight. As discussed in Section 2.2, all freight modes are incentivized or subsidized in Italy, including a fuel price discount for road freight. In principle, one might reduce or even eliminate any incentives/subsidies to harmful modes (i.e., road), which is a push policy in favour of a modal shift towards eco-friendly modes. However, this would increase transport costs, especially for o-d pairs with mostly road-captive shipments, negatively impacting the overall economic and social systems.

Thus, maintaining fuel price discounts for road freight is more politically acceptable, despite reducing the effectiveness of the budget for incentivizing eco-friendly modes. Nonetheless, the modal shift from

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[3] The LLSs represent homogenous clusters of Italian municipalities, as defined by the Italian National Statistics Institute.

Table 1
Cost components: breakdown by mode and type of cost (.

Mode	Cost Component		Unit	Value/Function
Road	time dependent (VOT_t)	driver cost (driving, calculated on t_{driv})	€/h	24.48
		driver cost (resting, calculated on t_{rest})	€/h	0
		tractor + trailer (truck) holding cost (calculated on $t_{driv} + t_{rest}$)	€/h	7.03 + 1.64 = 8.67
	time independent ($c^m_{j\_nt}$)	fuel cost not including discounts/subsidies	€/l	1.380
		fuel cost with discounts/subsidies		1.130 (0.250 discount)
		motorway tolls (per kilometre or per stretch)	€	2022 official figures
		other expenditures (insurance, taxes, maintenance)	€/km	0.18
Rail	time dependent (VOT_t)	drivers (2 drivers onboard)	€/h	57.29
		locomotive holding cost (incl. maintenance)	€/h	296.88
		rolling stock holding cost (incl. maintenance)	€/h	83.33
	time independent ($c^m_{j\_nt}$)	energy and network toll	€/train·km	3.00
		total (origin and destination) shunting costs and other terminal-related costs (e.g., train control)	€/train	1300
		general expenditures (insurance included)	€/train	475
		terminal costs	€	30 € per rail terminal
		road feeder legs costs	€	by road supply model
Maritime	time dependent (VOT_t)	tractor holding cost	€/h	7.03 (accompanied) 0 (unaccompanied)
		trailer holding cost	€/h	1.64
	time-independent ($c^m_{j\_nt}$)	maritime fare (accompanied)	€/km	≤300 nm: 0.85 >300 nm: 1.10
		maritime fare (unaccompanied)	€/km	≤300 nm: 0.68 >300 nm: 0.88
		terminal costs (accompanied)	€	21.68 € overall *
		terminal costs (unaccompanied)	€	48.67 € for each port **
		road feeder legs costs	€	by road supply model

* *It* comes by considering the holding cost corresponding to waiting time at departure/arrival ports, assumed equal to 2 h and 0.5 h respectively to mimic typical embarking/disembarking conditions. No further handling cost should be considered.

** It comes by recognizing that the holding cost of a trailer is very low (1.64 €/h vs. 7.03 €/h), making it negligible with respect to the fare for embarking/disembarking operations by a Ro-Ro terminal operator, set equal to 40 € for each port. In addition, the holding costs during the waiting time for pickup/delivery of unaccompanied trailers should be considered, by assuming a waiting time of 1 h per port.

adapted from Marzano et al., 2022)

road transport, triggered by incentives for eco-friendly modes, reduces road fuel demand and, consequently, the budget required for its discount. In other words, the budget to incentivize eco-friendly modes is partially cross-funded by such a reduction. Thus, B_{max} should be the net resulting budget.

The following setup of parameters has been considered for the application to Italy: $\gamma_c = 40$ (granularity of grids in step #1 in Section 3.3), $\gamma_{bo} = 40$ (granularity of grids in step #2 in Section 3.3), $s_{max} = 0.30$ (maximum incentive percentage). Furthermore, Sardinia has been excluded because its intra-regional freight shipments are captive by road and inter-regional freight shipments are captive by maritime mode.

The upper bound $B_{max,upper}$ of the maximum budget B_{max} to allocate to the incentive policy is given by the sum of the maximum regional budgets B^o_{max} for each $o \in$ R, calculated in the context of step #1 in Section 3.3. Results are presented by setting B_{max} considering γ_{bn} points to explore between 0 and $B_{max,upper}$, i.e., for each $\gamma \in [0, \gamma_{bn}\text{-}1]$ let $B_{max} = \frac{\gamma}{\gamma_{bn}-1} B_{max,upper}$. where $\gamma_{bn} = 40$.

It is worth first looking at how different VOT$_c$ (0 vs. 1 €/ton/h) and mode choice models (Logit vs. Weibit) affect the solution of the region-based optimisation problem. To this end, Fig. 2 illustrates the amount of vehicle•km saved from road (harmful mode) countrywide for various budget values B_{max} for the Logit (blue lines) and Weibit (red lines) model, and for VOT$_c = 0$ (full lines) vs. VOT$_c = 1$ €/ton/h (dashed lines). All curves exhibit a convex shape and similar trend, with a budget threshold beyond which there is no appreciable reduction in vehicle·km by road. Furthermore, the larger the VOT, the lower the impact of the incentive on the number of vehicle σ·km saved by the road.

The superiority of the region-based incentive with respect to the nation-based incentive is illustrated in Fig. 3, that compares, again for each combination of mode choice model and VOT$_c$, the amount of vehicle•km saved from road countrywide for various budget values B_{max}. Interestingly, the region-based optimisation always yields larger savings compared to the nation-based optimisation, especially in the range of currently provided budgets for incentives in Italy (in between 0.3 and 0.6B€/year).

It is also worth looking at the graphical representation, for each region, of the solutions of the optimisation problems (14)–(16) in step #2 in Section 3.3. To this end, each diagram in Fig. 4 illustrates, for each origin region, the relationship between the incentive budget (x-axis) and the corresponding amount of vehicle•km saved from road countrywide for various regional budget values (y-axis). The results show noticeable heterogeneity across regions, highlighting the need to account for region-based market conditions when designing incentives.

Interestingly, the effect of VOT$_c$ on the number of vehicles saved from roads varies across regions. For some regions, the effect of a nonzero VOT$_c$ is the opposite of the national trend displayed in Fig. 2; i.e., the larger the VOT$_c$ the higher the effect of the incentive. This happens mainly for regions such as Calabria and Sicilia, where considerable freight demand occurs to/from regions far enough away to activate drivers' 9-h resting by road. In this case, non-zero VOT$_c$ values in systematic utility (18) yield a higher penalty for roads than for other (faster) modes.

Finally, to showcase the importance of geographical differentiation of subsidies, Fig. 5 reports the heat map of such incentive percentages for rail (top) and maritime (bottom) freight for the Lombardia region, the first in Italy by generated/attracted freight shipments resulting from the optimisation at the end of step #2 in Section 3.3 for the Weibit model, and for VOT$_c = 0$.

6. Conclusions and research prospects

This study explored the viability of a region-based incentive to foster a freight modal shift from road to other modes. The proposed methodology adopts two different geographical granularities: incentives are

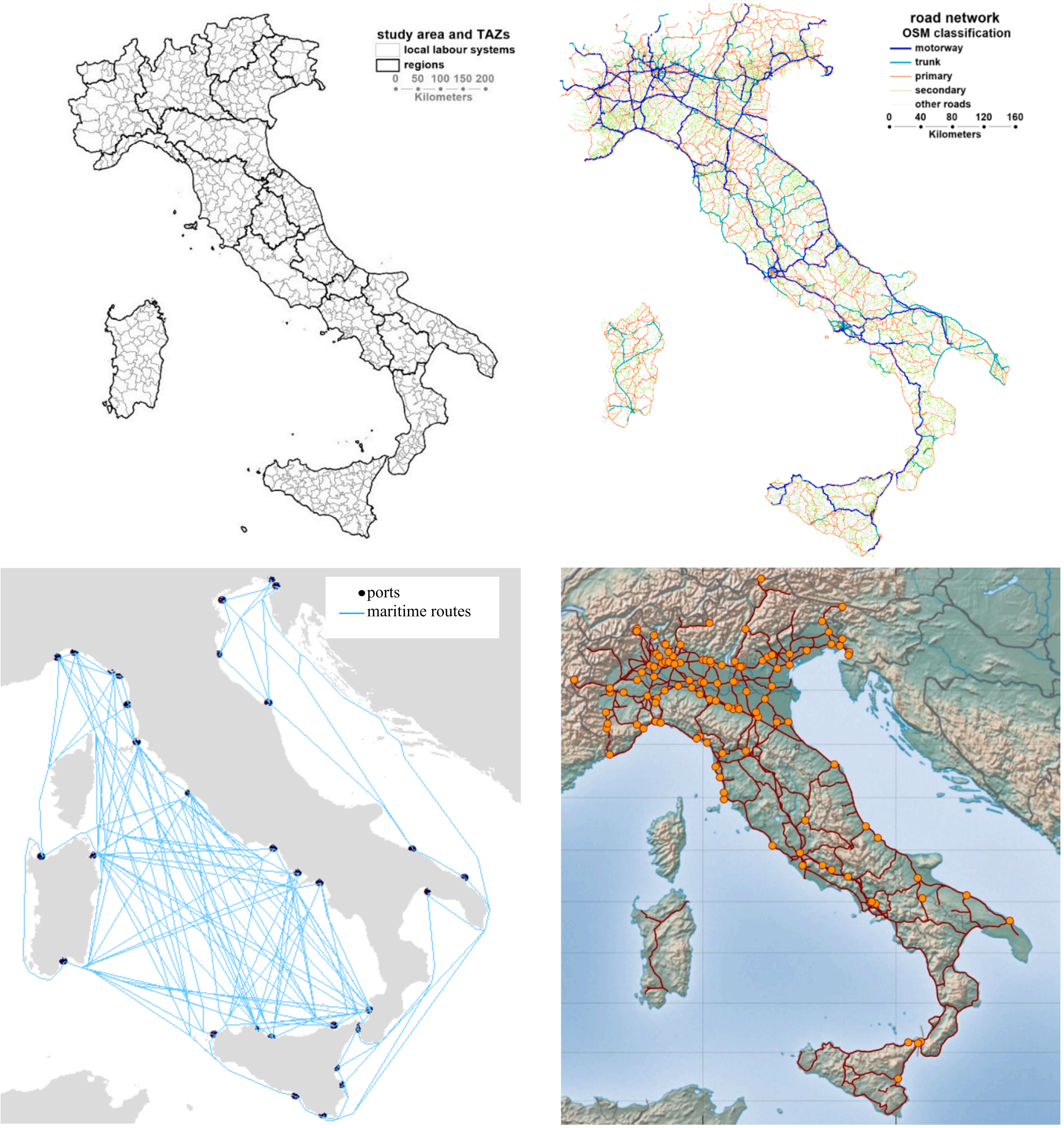


Fig. 1. Top left: study area and traffic analysis zones (TAZs). Top right: road topological model. Bottom left: maritime topological model. Bottom right: rail topological model and rail terminals. ().
Source: Marzano et al., 2022

Table 2
Estimated parameters of mode choice model.

	Parameter (mode choice model)	
VOT_c	θ (MNL)	λ (MNW)
0	65.02	13.04
1	21.96	8.97

granted between pairs of regions, defined in limited numbers in the study area to enable practical operationalization of region-based incentives, whereas freight transport costs, needed to quantify the incentives and their effect on modal splits, are calculated on a much more detailed layer of traffic analysis zones.

The optimization problem for the calculation of region-based incentives, expressed as discount percentages relative to the full transport cost of non-road freight modes, was presented and tested with two different freight mode choice models (Logit and Weibit) and two

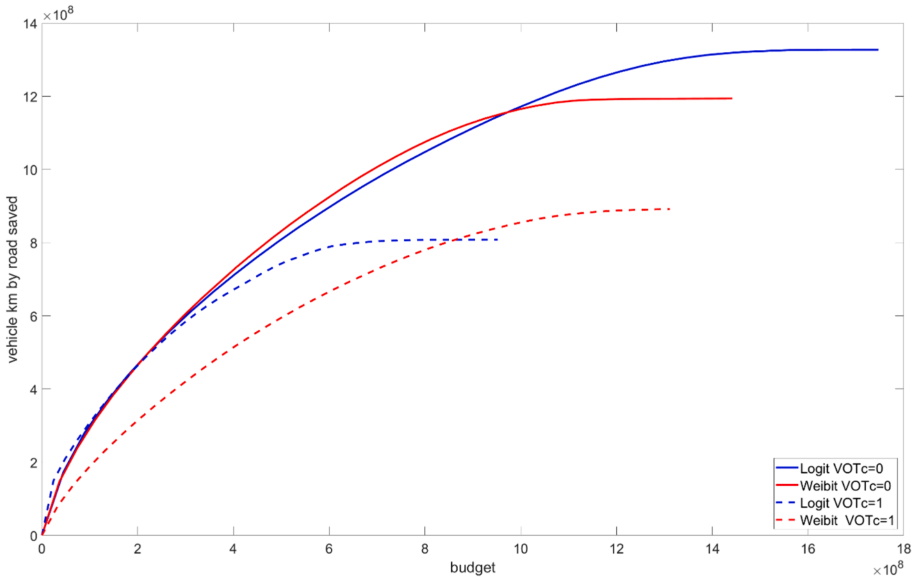


Fig. 2. Freight vehicle·km by road saved from road (harmful mode) countrywide for various budget values B_{max} for Logit (blue lines) and Weibit (red lines) models, and $VOT_c = 0$ (full lines) vs. $VOT_c = 1$ €/ton/h (dashed lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

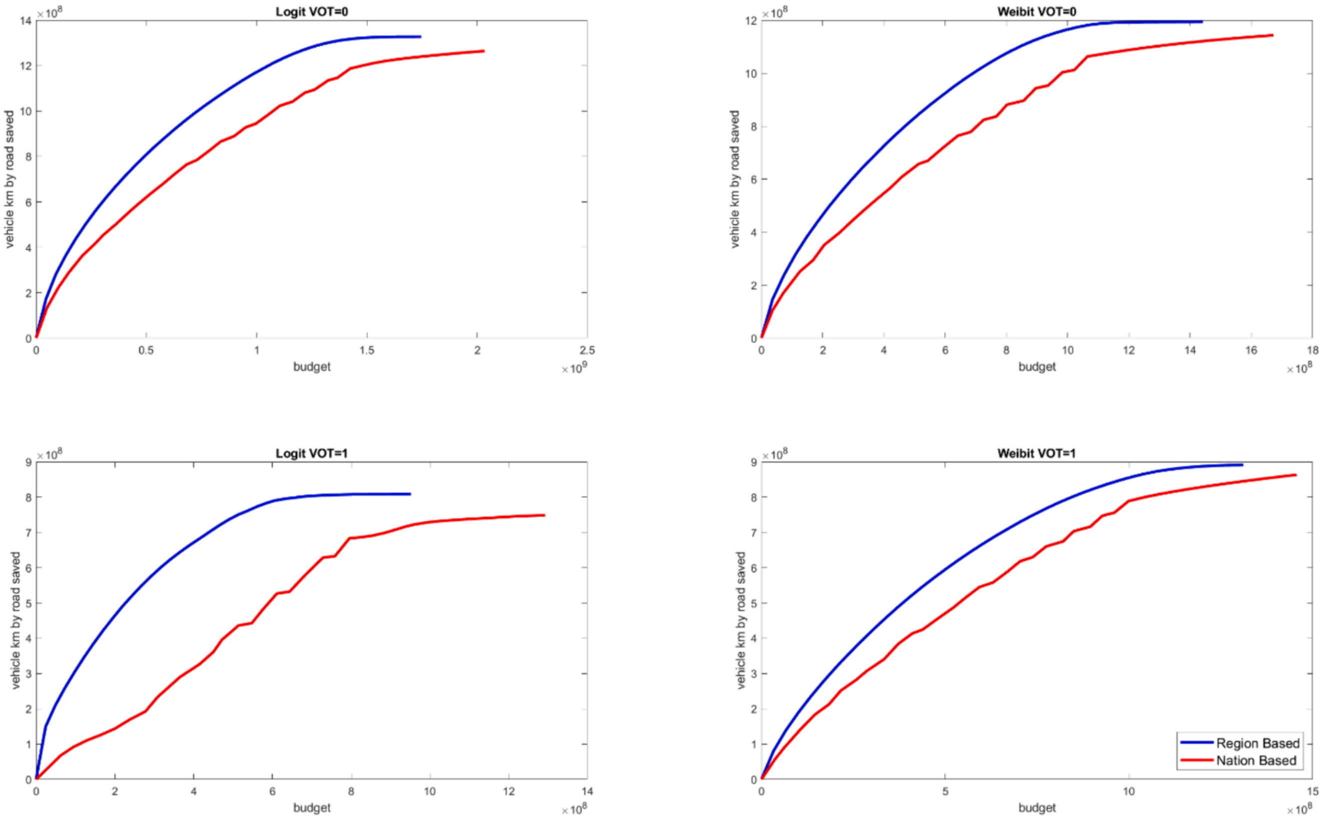


Fig. 3. Region-based incentive (blue lines) vs. nation-based incentive (red lines): freight vehicle·km by road saved from road (harmful mode) countrywide as a function of budget for Logit and Weibit models and VOTc = 0 or 1 €/ton/h. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different cargo values of time ($VOT_c = 0$ and 1 €/ton/h). Solving this problem is nontrivial, and a sequential heuristic based on grid searches and linear integer optimization subproblems has been proposed to allow applications on large-scale instances. The proposed approach was applied to a multimodal freight transport system in Italy to showcase its practical applicability and superiority compared to a nation-based optimized incentive scheme.

Overall, the results are encouraging. The proposed policy proved effective under both mode choice models and VOT_c values. The regional-based incentive scheme outperformed the national-based incentive scheme, yielding a more significant reduction in freight vehicle·km by road under the same budget. Furthermore, granted incentives were

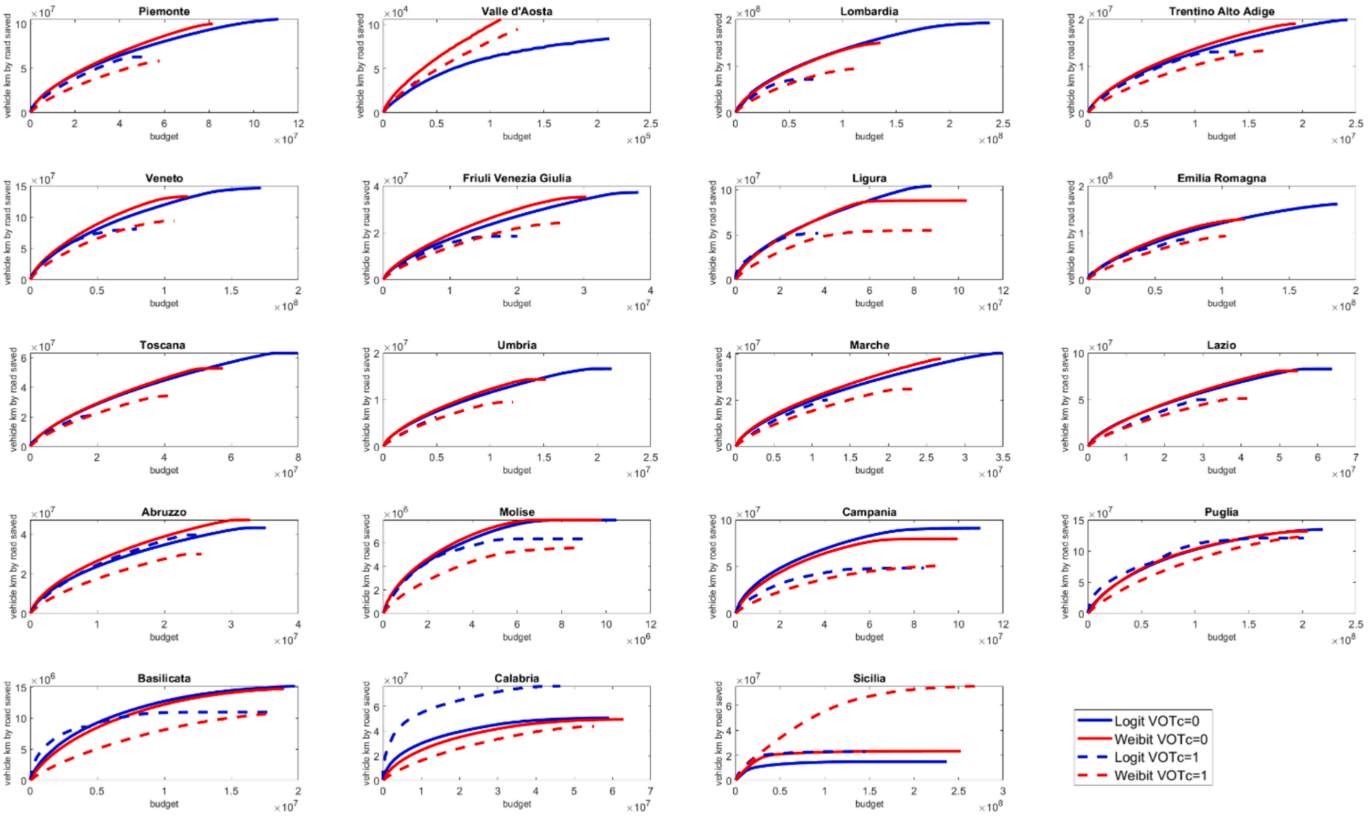
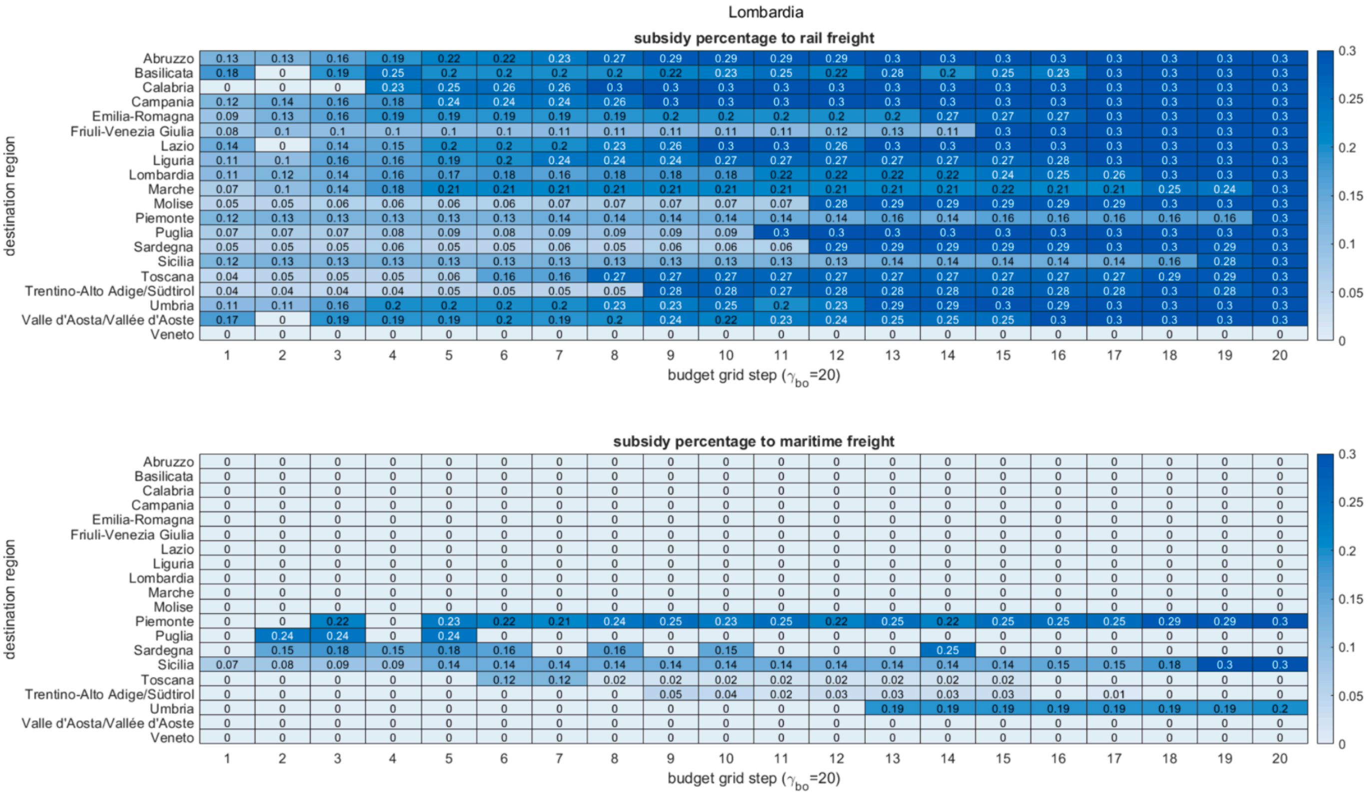


Fig. 4. Relationship for each region between granted incentive budget (x-axis) and corresponding amount of vehicle•km saved from road (harmful mode) countrywide. Note: different axes limits by region.



Lombardia

subsidy percentage to rail freight

destination region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Abruzzo	0.13	0.13	0.16	0.19	0.22	0.22	0.23	0.27	0.29	0.29	0.29	0.29	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Basilicata	0.18	0	0.19	0.25	0.2	0.2	0.2	0.2	0.22	0.23	0.25	0.22	0.28	0.2	0.25	0.23	0.3	0.3	0.3	0.3
Calabria	0	0	0	0.23	0.25	0.26	0.26	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Campania	0.12	0.14	0.16	0.18	0.24	0.24	0.24	0.26	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Emilia-Romagna	0.09	0.13	0.16	0.19	0.19	0.19	0.19	0.19	0.2	0.2	0.2	0.2	0.2	0.27	0.27	0.27	0.3	0.3	0.3	0.3
Friuli-Venezia Giulia	0.08	0.1	0.1	0.1	0.1	0.1	0.11	0.11	0.11	0.11	0.11	0.12	0.13	0.11	0.3	0.3	0.3	0.3	0.3	0.3
Lazio	0.14	0	0.14	0.15	0.2	0.2	0.2	0.23	0.26	0.3	0.3	0.26	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Liguria	0.11	0.1	0.16	0.16	0.19	0.2	0.24	0.24	0.24	0.27	0.27	0.27	0.27	0.27	0.27	0.28	0.3	0.3	0.3	0.3
Lombardia	0.11	0.12	0.14	0.16	0.17	0.18	0.16	0.18	0.18	0.18	0.22	0.22	0.22	0.22	0.24	0.25	0.26	0.3	0.3	0.3
Marche	0.07	0.1	0.14	0.18	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.22	0.21	0.21	0.25	0.24	0.3
Molise	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.28	0.29	0.29	0.29	0.29	0.29	0.3	0.3	0.3
Piemonte	0.12	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.16	0.14	0.16	0.16	0.16	0.16	0.16	0.3
Puglia	0.07	0.07	0.07	0.08	0.09	0.08	0.09	0.09	0.09	0.09	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Sardegna	0.05	0.05	0.05	0.06	0.05	0.05	0.06	0.05	0.06	0.06	0.06	0.29	0.29	0.29	0.29	0.29	0.3	0.3	0.29	0.3
Sicilia	0.12	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.16	0.28	0.3
Toscana	0.04	0.05	0.05	0.05	0.06	0.16	0.16	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.29	0.29	0.3
Trentino-Alto Adige/Südtirol	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.28	0.28	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.3	0.28	0.3
Umbria	0.11	0.11	0.16	0.2	0.2	0.2	0.2	0.23	0.23	0.25	0.2	0.23	0.29	0.29	0.3	0.29	0.3	0.3	0.3	0.3
Valle d'Aosta/Vallée d'Aoste	0.17	0	0.19	0.19	0.19	0.2	0.19	0.2	0.24	0.22	0.23	0.24	0.25	0.25	0.25	0.3	0.3	0.3	0.3	0.3
Veneto	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

budget grid step (γ_{bo}=20)

subsidy percentage to maritime freight

destination region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Abruzzo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Basilicata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Calabria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Campania	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Emilia-Romagna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Friuli-Venezia Giulia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lazio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Liguria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lombardia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Marche	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Molise	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Piemonte	0	0	0.22	0	0.23	0.22	0.21	0.24	0.25	0.23	0.25	0.22	0.25	0.22	0.25	0.25	0.25	0.29	0.29	0.3
Puglia	0	0.24	0.24	0	0.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sardegna	0	0.15	0.18	0.15	0.18	0.16	0	0.16	0	0.15	0	0	0	0.25	0	0	0	0	0	0
Sicilia	0.07	0.08	0.09	0.09	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.18	0.3	0.3
Toscana	0	0	0	0	0	0.12	0.12	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0	0	0	0	0
Trentino-Alto Adige/Südtirol	0	0	0	0	0	0	0	0	0.05	0.04	0.02	0.03	0.03	0.03	0.03	0	0.01	0	0	0
Umbria	0	0	0	0	0	0	0	0	0	0	0	0	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.2
Valle d'Aosta/Vallée d'Aoste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Veneto	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

budget grid step (γ_{bo}=20)

Fig. 5. Values of incentive percentages for rail (top) and maritime (bottom) freight for Lombardia region, by region of destination and budget limit in the range between 0 and $\gamma_{bo} = 20$, for Weibit model and $VOT_c = 0$.

heterogeneous across origin regions in terms of both total allocation and incentives for eco-friendly modes, highlighting the importance of differentiating incentives by origin–destination within a country. From a methodological standpoint, the robustness concerning the form of the mode choice model was also explored. Notably, the MNW model assumes an underlying multiplicative form of random utilities, making it sensitive to ratios between the utilities, whereas the additive form underlying the Logit model is sensitive only to absolute differences. The policy implications of the proposed incentives were tested under diverse modelling frameworks, consistent with the choice of operating scenarios with extremely different values of the cargo component of VOT.

A noteworthy advantage of the proposed approach is its practical implementation. Granting incentives based on the percentage reduction of the full transport cost implies the need for the beneficiaries to provide relevant information. On one hand, this drives the digitalization of the sector to collect and share data efficiently; on the other hand, it yields a substantially more comprehensive data collection by public bodies that are granting incentives.

Some research prospects were also identified. The first relates to applying the proposed method to other countries to analyse the impact of different freight demand patterns and multimodal network structures on the differences between nation- and region-based incentive schemes. This would be particularly interesting for France and Spain, both of which have recently granted incentives to non-road modes. Additionally, from a methodological standpoint, the mathematical properties of the proposed optimization problem can be further explored to identify more effective and near-optimal solution methods.

CRediT authorship contribution statement

Fulvio Simonelli: Conceptualization, Writing – original draft, Resources, Methodology, Formal analysis.. **Claudio Sterle:** Methodology, Writing – review & editing. **Adriano Masone:** Methodology, Formal analysis, Data curation, Writing – review & editing. **Daniela Tocchi:** Writing – review & editing. **Fiore Tinessa:** Resources, Writing – review & editing. **Andrea Mancuso:** Formal analysis. **Andrea Papola:** Writing – review & editing. **Vittorio Marzano:** Conceptualization, Writing – original draft, , Resources, Supervision.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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