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Driving modal shift on low-traffic railway lines through technological innovation: a case study in Piedmont (Italy) including hydrogen fuel-cells as an alternative

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Abstract

Sustainability - declined in social, environmental, and spatial forms - is a prerogative of rail transport. Hence, railway systems, with their low impact and high inclusivity, are the solution Europe is aiming at. However, some non-electrified secondary lines were suspended in recent years in different countries, including Italy, for economic and political choices. The line under investigation is the Saluzzo-Savigliano (Piedmont, Italy) for which the solution of forcing traffic to the road created queues, congestion, and an increase in local, besides a loss in the actual use of the time by travelers. This paper aims at providing a decision support method to drive the modal shift to the rail in low-traffic lines through innovation, simulating operation on the aforementioned line and evaluating consumption and emissions – in a WTW approach - of three different types of train: the diesel Minuetto, thus taking over the past operation, the tram-train, whose capacity is adequate to the demand, and the fuel cell train that should enter into circulation in Italy from 2023. To minimise consumption (kWh/km), an optimisation of the running curves is being suggested and operation is analysed with the use of a custom simulator; a comparison of the specific energy consumption (kWh/pass·km) and the emissions are thereafter proposed. Consequently, a multi-criteria analysis using Electre methodology is applied to assess which option is more convenient on the given route, performing also a sensitivity analysis to highlight the improvements to be made to obtain an optimal solution that is convenient both for railway undertaking and the end-user. The convenience of low-traffic railway lines is an issue to be solved to achieve a modal shift towards inclusive, economic, and environmental-friendly public transport and to increase the resilience of the involved area at the foot of Monviso, providing tourism development opportunities and efficient services for commuters, possible only by leveraging technological innovations.

Keywords: modal shift; low-traffic railway lines; emission control

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1. Introduction

The train is a winning means of mass transport, as it is an energy-efficient system with a low environmental impact. In fact, it is a transport system which, given the same amount of energy spent, moves more people than buses or private cars, taking up less space and emitting much less in terms of $g\ CO_2/pax \cdot km$ (European Environment Agency, 2021). Today, one of the prerogatives of trains is to reach higher speeds; but this often clashes with satisfying the territory, as increasing speed means selecting *nodes*, leaving out mid-sized and small towns, which, in turns, results in a loss of demand. Therefore, when designing modern transport systems, the necessity to connect large cities needs to be reconciled with maintaining at the same time the vitality of the surrounding area through comprehensive networks, permeating the hinterland, and covered by a local railway service; in this sense, secondary railway lines are of great value and it is useful to intervene on them in order to keep pace with the times, so that they can become *demand generators*. The Italian region of Piedmont has an extensive rail network thanks to a very responsive environment, characterised by a fruitful synergy between the public and private sectors. In addition to the main lines, unlike in other Italian regions, Piedmont has a dense network of complementary lines, accounting for 66% of the entire regional network (Regione Piemonte, 2022). However, in Italy, for some time now, there has been a widespread expression *prune out deadwood* to indicate the cutback of less productive secondary lines with a small user base. In June 2012, Piedmont suffered a major blow, with the closure of 12 lines, 460 km in total, because they were classified as inefficient. Some of these cuts took place without a stir: for example, part of the Airasca-Saluzzo line is used as a tourist attraction and only partly by freight trains for some workshops.

In the case of the Saluzzo-Savigliano line, which this study focuses on, however, the interruption of services pushed mayors and citizens to gather in protest, but unsuccessfully. There are no specific technical reasons for the shutdown of certain services. Certainly, the demographic scarcity of some areas contributed to make some more rural tracks less used, in fact in 2019 more than 74.5% of the people in Europe lives in urban areas. Other factors contributing to the disuse of secondary railway lines are the rate of motorisation (Italy ranks second in Europe after Luxembourg) and urban sprawl (Nechyba and Walsh, 2004). This phenomenon makes it difficult to create a public transport system that can serve the whole territory in a capillary and efficient way and, in fact, private car travel is favoured over any other means of transport. Despite the current trend, transport demand can, indeed, be shifted towards public transport using new technologies, helping to achieve a more socio-environmentally sustainable modal choice. The analysis carried out in this work can therefore become a key decision support method to reactivate or increase services on apparently unprofitable lines. First and foremost, the use of state-of-the-art rolling stock, such as tram-trains or hydrogen-powered trains, can reduce again congestion in the roads attracting mobility demand, and secondly, adopting an energy-efficient driving mode can cut operating costs and further reduce environmental impact. In this paper, an overview of the systems and alternatives involved in this study-case is initially given. In order to minimise consumption, an optimisation of the running curves is being suggested and operation is analysed with the use of a tailor-made simulator[1] and then, a multi-criteria analysis is carried out to establish which alternative would be the most convenient. Finally, a decision support method is presented under the assumptions made and conclusions are drawn concerning the study-case.

2. Overview of the system

2.1. The Saluzzo-Savigliano line

The area of the Monviso valley in Piedmont is of great natural and industrial value. It rises in between the cities of Cuneo and Turin, which is a major node connected to the Italian high speed-high capacity network and to the TEN-T corridors. The towns of Saluzzo and Savigliano hold a considerable artistic and cultural heritage, as well as being site of several manufacturing plants and some university campuses. The area is therefore vibrant and having an efficient transport system could provide even more opportunities for tourism and comfort for commuters. The Saluzzo-Savigliano section is a single track non-electrified line long 14.88 km, including 17% of curved section, an average gradient of 2.6‰ and a maximum of 17‰. In addition to two short bridges, there are three flyovers and numerous

[1] Our code is publicly available to facilitate reproducible research: https://github.com/simonagurri/railway-simulator

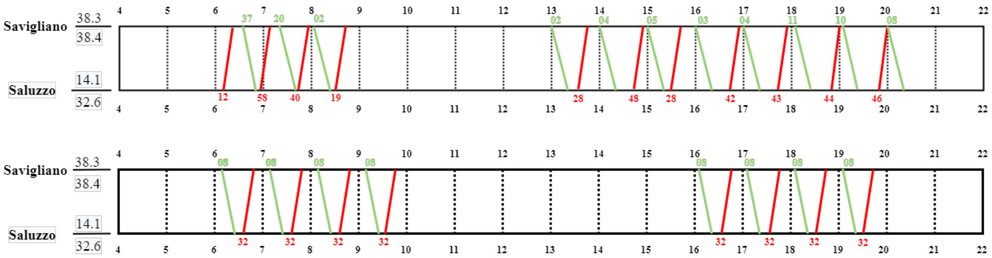

Fig. 1: Graphic timetables. Upper image: service before 2012; Bottom: service in 2019

minor infrastructural artworks. This line is connected to the Saluzzo-Cuneo section, interrupted as well, and to the rest of the Piedmont line through the Savigliano node, where the SFM7 (*Servizio Ferroviario Metropolitano line 7 - Railway metropolitan service of Turin*) makes frequent stops from and towards Turin. After being operated since 1857, the Saluzzo-Savigliano line has been closed to passenger traffic in 2012, then reopened in 2019 but closed again the following year.

2.1.1. *Past service*

A brief analysis of the past service is hereby presented. In 2012 there were 22 trains and 430 passengers per day while in 2019, when the service was resumed, there were 16 trains and 481 passengers as daily average (Fig. [1]). The growth of the number of passengers per train has hence increased the overall efficiency of the transport. A rise in the demand trend can be assumed, which is not covered by any service to date, since the line is currently used only by freight trains. The past services were carried out with a Minuetto diesel train, produced by Alstom and belonging to the Coradia Meridian family (Fig [3]). It began running on the Italian rail network in 2003 and it was specifically created to meet the demand for medium and short distance travel on low-traffic lines, which represented two thirds of the operating lines in Italy. The train was produced both in electric and diesel versions. Since the line is not electrified, the diesel-powered one will be benchmarked. At the beginning of 2000, the Minuetto was a state-of-the-art rolling stock, meeting customers' expectations for comfort and functionality and up-to-date from the environmental point of view. Obviously, nowadays, more than 20 years later, the stringent requests for emission control and the need to create a space which allows profitable travel time for commuters (e.g. electric sockets for recharging personal devices, bicycles stands for increasing the soft mobility option at destination), push for a renewed fleet for regional services.

2.1.2. *Potential demand*

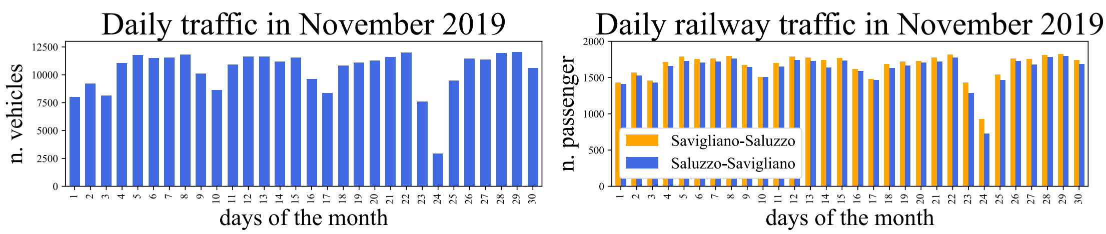

Fig. 2: On the left the vehicular traffic flow in November 2019. On the right prediction of daily railway traffic once the service is resumed. The data is obtained considering a constant annual growth rate and a modal shift of 20% from the vehicular traffic as of November 2019. Source: processing of data provided by 5T *(Transport and Traffic Control Center for Turin and Piedmont)*

As far as the potential demand is concerned, we could estimate an increase in mobility demand with respect to the data available for the year 2019 (Fig. [2]), considered to account for a pre-pandemic scenario. Although COVID-19 has reinforced the bias towards private cars policies have been enacted in recent years to encourage train use. Moreover, if new rolling stock is operated, it can become itself a demand puller, thanks to technological advances and increased comfort of the trains, inducing the commuters to conceive the public transport time as profitable for their daily routine. There is, in fact, the tendency to underestimate the time taken to travel by car and the overestimation of public transport one, resulting in the misleading belief that the first wins over the second in most cases. An objective analysis of the Saluzzo-Savigliano shows that the travel time at peak hours is longer for private cars, due to traffic jams and congestion (Table [1]).

Table 1: Travel Times Saluzzo-Savigliano

Transport system	Expected travel time (weekly average)
Car	19.5 ± 3.5 min
Bus	30 min
Train	14 min

For the purpose of this work, in Table 1, only the average value of travel times was considered. More information is available on the Agenzia della Mobilità Piemontese website *(https://mtm.torino.it/it/)* where detailed analyses on the quality of public transport service can be found.

Considering a constant annual growth rate of 0.016%, equal to the one between 2012 and 2019, the predicted potential demand in 2022 would result in 500 passengers and in 2023 of 507. Obviously, this estimated growth does not take into account possible increases due to the attractiveness of a new fleet, which would erode the road share. Figure 2 shows the predicted demand calculated summing up 507 passengers to the 20% of the vehicular traffic flow as in a pre-pandemic scenario (occupation of 1.2 passengers per vehicle), to account for modal shift. The average number of passengers per day is hence 1636 per direction, which means 204 passengers per train.

2.2. State-of-the-art rolling stock

The options considered for a renewed passenger fleet on non-electrified low-traffic lines are the hybrid tram-train and the hydrogen fuel-cell powered train.

Tram-Train. As already recalled, an innovative transport system becomes itself a demand puller; in this sense, the tram-train system is effective in serving a growing demand for transport, thanks to its interoperability which allows it to run on tramways as well as on railways. Even where there is no tram line and there are disused railway lines, a tram-train system is advantageous both for the lower cost of the rolling stock, which is lighter than a traditional train, and for the expansion and modernisation of the city, leaving open the possibility of building a tramway at a later date (Rizzetto, 2009). Today, the tram is successful in many cities because it is a low-emission, comfortable and high-performance vehicle but in the past this was not always the case: in Italy, the tram networks of 22 cities were dismantled, including that of the city of Saluzzo. One of the main reasons why the tram-train system has not been successful in Italy so far is the lack of unambiguous regulations reconciling the two; Given the well-known differences of tramways in track gauge, electrification, shock resistance, train driving (one instead of two drivers) compared to the train "Guidelines for tram-train systems" (12/07/2012, ANSF - Agenzia Nazionale per la Sicurezza delle Ferrovie - National Agency for railway safety) were drawn up to provide guidelines for the design and operation of such systems. Germany, on the other hand, has activated some application of this solution of transport and the most known case is in Karlsruhe, where there has been a 400% increase in demand for transport when fully operational. The vehicle considered in this work is hybrid, running with electric motors on the tram network and with diesel engines on the rail network when the latter is not electrified (Fig. [3]); this is the situation adopted in the German city of Kassel, which uses the Regio Citadis vehicle produced by Alstom. The tram-train would decrease the GHG emissions, though it would not guarantee zero CO_2.

Hydrogen fuel-cell train. The transport sector in Europe is responsible for about 25% of GHG emissions (European Commission, 2022), so the decarbonisation of this sector is a key point in achieving the energy transition from fossil fuels to renewable sources. Hydrogen seems to be the most promising resource to contribute to rapid decarbonisation, as it guarantees the operation of a zero-emission means of transport on a local level, with low noise (Piraino, Genovese, and Fragiacomo, 2021). The industry has been working since 2013 on a new generation fuel-cell train, intended to replace diesel passenger trains on non-electrified lines, which is well suited to small localities. The second option considered in this work is commissioned by Ferrovie Nord Milano in Italy (Fig. [3]), which builds on the platform of the Smart Coradia (POP) by adding a traction module containing the equipment needed to produce energy using fuel cells. This train is oversized for the demand on this line, but it is still worth considering.

It does not require any new infrastructure for its transit, so it could run immediately on non-electrified lines without interrupting the service. A brief comparison of the three options is given in Table [2].

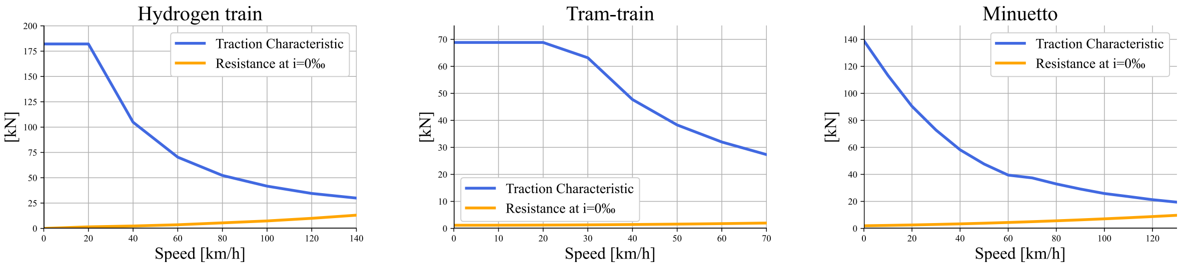

Fig. 3: From left to right: Fuel-cell train, Tram-train and Minuetto traction and resistance characteristics

Table 2: Trains Comparison - Characteristics of the three rolling stocks

	Minuetto	H_2 train	Tram-train
Max speed	130 km/h	140 km/h	70 km/h
Max number of passenger	306	500	290
Mass at max load	125.75 t	201.65 t	62.8 t

3. Methodology

3.1. Simulation

In order to consider an energy-efficient driving style, a parametric optimisation method was used to minimise energy usage for the three trains (Table [2]). Regenerative braking was not taken into account - even if it could be used for the fuel-cell train to recharge the battery present on board for the peak power requirements - because the line is not electrified. The classical formula for solving the problem of train motion was used, (Eq. [1]):

$$F_m(v) - F_{mech}(v) - R(x, v) = M \cdot \frac{dv}{dt} \tag{1}$$

Considering that, during power mode, the mechanical braking force is null ($F_{mech} = 0$), while, during braking mode, the traction force provided by the motors is zero ($F_m = 0$). $R(x, v)$ represents the resistances and M the mass of the train. The four standard phases of train motion have been considered: acceleration, steady-state, coasting and braking phases. The constraints of the energy optimisation problem are given by a set of equalities and inequalities, which account for the continuity of the speed in between the different phases, the maximum traction force available, the maximum velocity attainable, and the maximum acceleration allowed for passenger comfort. The estimation of CO_2 emissions was made considering Emission Inventories for diesel rail vehicles, and no CO_2 emission is considered for the fuel-cell train, which would reduce the dependence on fossil fuels.

3.2. Multi-criteria analysis

The final step in the planning process of a transport system is to evaluate the proposed scenarios, and then find the best alternative that meets the needs behind the demand. The steps needed to carry out this kind of assessment are evaluating the internal and external impacts (such as those affecting supply or demand and congestion, safety, air quality, GHG and noise) and to quantify them with their own unit of measurement. Multi-criteria analysis (MCA) methods make it possible to easily consider different aspects, not only of economic nature, and therefore monetisable, but also of social, environmental and territorial nature, measured in quantitative or qualitative terms. The process is rational and objective and offers a basis to guide the decision-maker's choice. The final evaluation consists of comparing and ordering the set of alternatives based on the proposed criteria, each taken into consideration with its relative weight, which measures the importance of that criterion in formulating the final evaluation; a certain combination of weights constitutes a *point of view*. Multi-criteria analysis is described by a matrix, which is called *decision matrix*, whose rows represent the different alternatives and whose columns represent the criteria of judgement defined in relation to the different objectives (system of objectives), set by the decision maker. Among the MCA

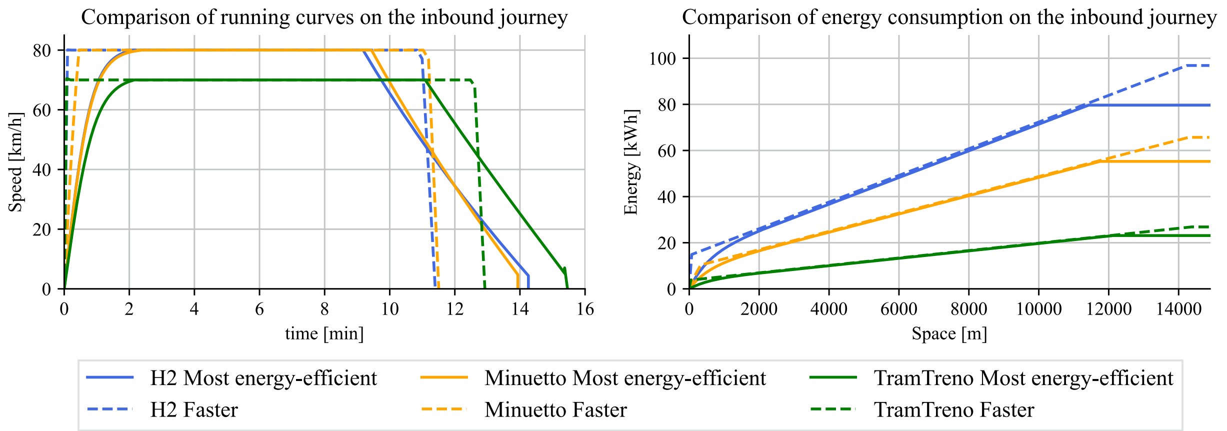

Fig. 4: Running curve comparison (time-speed) for the three trains. For each one the most energy-efficient and the fastest curves for the given parameterization are shown.

methods, there is Electre (Benayoun, Roy, and Sussman, 1966), which models the outranking relation, aggregates the results with concordance and non-discordance tests and then classifies the alternatives in the problem from an outclassing graph. The outranking relation is constructed independently for each pair of alternatives; given alternatives a and a', the outranking S is defined as follows:

- $a\ S\ a'$ (a outranks a') if there is sufficient evidence to claim that a performs at least as well as a' on the n criteria and there is no good reason to claim otherwise;
- $a\ -S\ a'$, if the above conditions do not subsist.

4. Results and discussion

The parametric simulation used allows modelling the train's running curves as in Figure [4]. For the sake of simplicity, a monotonically decreasing acceleration parameterization was considered for the initial phase of the motion, while a constant deceleration was taken into account for the braking one. A total of one million simulations were carried out with different values of acceleration and deceleration, and different lengths of the coasting phase, to construct the Pareto curve of solutions (Bruno et al., 2015); finally, the simulations on the curve that yielded the minimum travel time and the lower energy required were chosen. It can be seen in Table [3] that the most efficient vehicle results to be, at these conditions, the tram-train, which by virtue of its much lighter weight consumes significantly less kWh. The fastest and less energy-consuming curves for the considered parameterization of the acceleration for three chosen trains can be found in Figure [4].

Table 3: Performance Comparison

	Minuetto	Tram-train	H_2 train
Travel time [min]	14.26	15.46	13.937
Energy consumption [kWh]	55.27	23.10	79.64
Fuel/passenger [$kg/pass$]	0.0024	0.0010	0.0007
CO_2 emission factor [$g/pass*km$]	0.0004	0.0002	0
CO_2 total emission [$g/pass$]	0.0066	0.0028	0
$kWh/(pass*km)$ max #pass	0.0121	0.0052	0.0107
$kWh/(pass*km)$ effective #pass	0.0181	0.0074	0.0262

The kWh/pass*km were calculated for both maximum vehicle capacity and expected average turnout. Given the kWh, the fuel consumption was estimated by referring to the calorific values of diesel and hydrogen, and then, through the emission inventory, the CO_2 emission was estimated for vehicles impacting on GHG emission. The Table [3] shows the comparison of performance for the rolling stock on a trip for the most efficient driving style. Eventually, the multi-criteria analysis (Norese, 1996) is carried out with the Electre II method to establish the actual convenience of

Table 4: Decision Matrix

	g_1	g_2	g_3	g_4	g_5
W	0.4	0.2	0.2	0.1	0.1
a_T	-0.73	-4	-290	-0.66	7
a_H	-1.07	-11	-500	0.5	9
a_M	-1.01	-5	-306	0.44	6

a vehicle over the others. In the Table [4] is possible to find the decision matrix used in the first phase of the analysis. The alternatives available are the three trains: Tram-train (a_T), Hydrogen train (a_H) and Minuetto (a_M). The criteria considered (g_i) are: g_1, the consumption calculated per actual turnout [kWh/passenger*km]; g_2 the cost per vehicle [Million €]; g_3 the available seats; g_4 the acceleration performances [m/s^2]; g_5 the comfort on a scale from 1 to 10. In line W the weights attributed to each criterion are shown. The highest weight is given to the criterion of consumption per passenger km in order to reduce both environmental impact and operating costs, while less weight is given to comfort considering that the line is short and the service is fast. The sum of the normalised weights must be 1. The concordance index is chosen among the natural thresholds to obtain strong and weak outranking relations and cycles, i.e., graphs in which the initial node coincides with the final node are excluded. Both concordance and discordance index values must be between 0 and 1. Here below, it is possible to find in Table [5] the concordance matrix, in Table [6] the discordance matrix, in Table [7] the credibility matrix, in Table [8] the values of the preorder from above, from below and the final preorder and, finally, in Table [9] the dominance matrix. The values of the different matrices have been calculated using the Electre II method (Benayoun, Roy, and Sussman, 1966).

Table 5: Concordance Matrix

	a_T	a_H	a_M
a_T	-	0.9	1.0
a_H	0.1	-	0.2
a_M	0.0	0.8	-

Table 6: Discordance Matrix

	a_T	a_H	a_M
a_T	-	0.0095	0.0
a_H	1.0	-	0.9238
a_M	0.0762	0.0143	-

Table 7: Credibility Matrix

	a_T	a_H	a_M
a_T	-	Ss	Ss
a_H	0.0	-	0.0
a_M	0.0	Ss	-

Table 8: Ranking Matrix

	Ascend	Discend	Average
a_T	1.0	1.0	1.0
a_H	3.0	3.0	3.0
a_M	2.0	2.0	2.0

Table 9: Dominance Matrix

	a_T	a_H	a_M
a_T	-	P+	P+
a_H	P-	-	P-
a_M	P-	P+	-

The outranking graph (Fig. 5) shows that the tram-train results as the preferred solution, in fact, this rolling stock is the smallest, the least expensive and the one with less consumption.

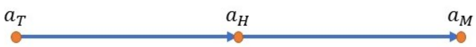

Fig. 5: Outranking graph

We proceed then to make a sensitivity analysis, changing the weights given to the criteria (Table [10]), and we obtain that the solution $a_T\ S\ a_M$ is stable.

Table 10: Other points of views - set of weights

	g_1	g_2	g_3	g_4	g_5
W_2	0.3	0.3	0.1	0.1	0.2
W_3	0.2	0.2	0.2	0.2	0.2

Obviously, we could add criteria relating to GHG emissions, or consider a smaller hydrogen train, such as the iLint (Alstom), which is more proportionate to the demand on the line. In this case, the hydrogen train could become competitive again. In fact, the data provided for the analysis relate to a train designed for lines with higher traffic flows, but the modularity of the Smart Coradia platform could allow the design of a train with fewer places, and therefore less weighty. In addition, it should be emphasised that the hydrogen train is the only train with locally zero emissions and the lowest fuel consumption per passenger. When it comes to on-board comfort, the fuel cell train gets the highest score: it is a new generation train, with more space than a light rail vehicle such as a tram-train, and the fuel cell used to produce energy is noiseless as opposed to an internal combustion engine.

5. Conclusion

This analysis demonstrates how new technologies can make the reactivation of some rail services competitive again, attracting passengers from road traffic. In fact, using a vehicle like the tram-train, which is light and well-dimensioned for the demand on the line, could allow to reduce operating costs and divert traffic from the road back to the railway. The process used is summarised in Fig. [6] and can be a useful tool for decision-makers.

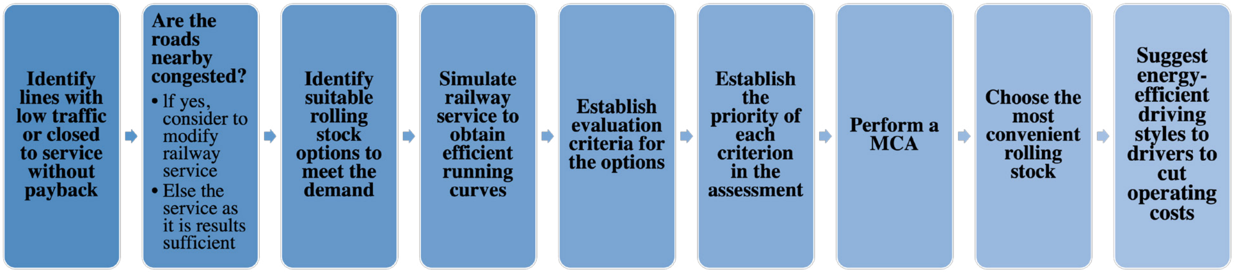

Fig. 6: Decision-Making process

Given the environmental policies in force today, the train is clearly still the most convenient and eco-friendly means of transport. In addition, increasingly comfortable and up-to-date trains make it possible to exploit travel time as a useful part of everyday life. Concerning interoperability, the use of this type of train makes it possible not to require electrification on lines with scarce traffic, where the investment might not be repaid: through new-generation signalling systems such as ERTMS with virtual balises and therefore aided by GNSS, it is possible to further reduce costs, both due to the use of fuel and to the maintenance of the line itself, becoming the technology itself an attractor of transport demand and an incentive for supply. The inclusion and territorial continuity provided by secondary lines must, hence, be supported by political initiatives and incentivised to optimise environmental, economic and social sustainability.

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