Doctoral Dissertation
Doctoral Program in Energy Engineering (35th Cycle)

Cable driven innovative systems for urban transport: engineering, design and energy consumption

By

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Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and do not compromise in any way the rights of third parties, including those relating to the security of personal data.

Stefano BAZZOLO

2023

* This dissertation is presented in partial fulfilment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo).

Ai miei Maestri.

A mio papà, che mi ha insegnato chi è un padre,

A Sergio, che mi ha insegnato chi è un mentore,

A Luca, che mi ha insegnato chi è un fratello.

“Nous sommes comme des nains

juchés sur des épaules de géants”

Acknowledgment

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I thank Luca Testa, my friend who taught me, who was an only child for many years, what it means to have a brother; I believe that the affection and esteem that bind us can overcome any kind of adversity. Thanks go to my Dromt partners Luca, Dario, Alessandro, Davide and Gianluca: together with them and thanks to them, I am building a dream, which has become a project, then a company. We have the ambition to leave this world a little better than we found it, and I firmly believe that if we continue to work together, no goal can be too high, and no goal too ambitious.

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Scope of the research

The study carried on during the PhD path and described in this PhD thesis starts from the acknowledgement that the current paradigm of the urban mobility, strongly based on the private car, is not sustainable from social, economic, energy and so environmental points of view.

It should immediately be emphasised that this Ph.D thesis is part and result of a Ph.D. programme in apprenticeship. This last, unlike an exclusively or predominantly academic doctoral programme, has as its objective a strong integration with the host company and the more immediate practical impact of the research activity. In this context, the contribution to science, typically and necessarily expected from a university Ph.D. programme, in this case is the engineering and design - entirely innovative and not found in the literature except by the candidate himself and his tutors - of a cable-driven transport system suitable for immediate applications, including the urban ones, that can be used by any user (not just for skiers), of which the entire engineering process is analysed: state of the art, engineering, calculations, design, energy assessments, quantification of the daily capacity under different operational conditions, energy consumption, estimation of emissions, comparison of energy consumption with modal alternatives for mobility, up to and including the realisation of the first system in the world, in construction in Switzerland in 2023.

The Chapter 1- Introduction focuses on the limits of the private car based current urban mobility paradigm, with particular emphasis on congestion, pollutants and CO2 emissions, road safety, limitation in the growth of the cities, consumption of soil and low utilization rate, that underline that it is necessary to define a disruptive change in the urban mobility sector. In the last decades, researchers developed PRTs (personal rapid transits), mobility systems trying to maintain the strengths of the private cars and to overcome their disadvantages, but the PRT installations worldwide are still rare. In this context, Cable APMs (automated people movers) were developed from the reliable and mature cable car technology, *id est* APMs where the motion is given to vehicles through the grip of a hauling rope.

The needs of the urban mobility demand to define a new mobility system suitable to overcome the private car constrains, keeping its strengths, find correspondence in the exigence of cable car market: the aim is to detect different markets to the traditional tourist and mountain one, which can be affected in the coming years, according to several converging studies, by an important contraction due to the challenges of global warming, which will reduce the duration of the ski season and will increase operating costs, thus decreasing the economic attractiveness of the sector. Despite the entry in the urban mobility sector can be a good opportunity to manage the contraction of their traditional mountain market, the installation of cable cars in urban contexts are still unusual, and relegated to very particular contexts, such as South American metropolises (the cases of Medellin- Colombia and La Paz- Bolivia are mentioned) where the need to overcome highly populated neighbourhoods with a low impact on the ground is central.

In order to cover the gap between the needs of the passengers and the traditional cable cars, new systems are appearing on the market in which traditional cableway technology is supported by technologies of automotive derivation. In this framework, the *CableSmart* system is developed. It is a hybrid system derived from the cable-car technology, whose vehicles can move in two alternative ways:

- Through the gripping to a hauling rope, as a conventional gondola ropeway;
- Through motorised wheels installed on the bogie, in a similar way to a monorail system.

The **Chapter 2- State of the art** provides a disquisition about the currently available academic knowledge about the cable car urban installation and, in particular, about *CableSmart* performances.

After an historic excursus covering the evolution of the innovative urban transport systems, intended as systems used for the public transportation of people deriving from the traditional road or railway technologies, circulating in exclusive and protected path and using full automated technologies ([R31]), the papers regarding the *CableSmart* system are cited.

In particular, [R33] calculated the energy consumption of an urban installation of *CableSmart*, moving in the stations through motorized wheels, and among the line through the gripping to a hauling rope.

[R32] analyzed in deep the friction due to the rollers, that represents one of the higher energy losses in the rope stretches, and, through analytic modeling and experimental measures, concluded the real losses for each roller are roughly one third lower than the conventional value imposed by the in-force norms.

[R34] analyzed the energy consumption in a rail branch of a *CableSmart* installation, and investigated the effect of a photovoltaic plant and an energy storage system in terms of reduction of energy impact of the system, through simulations in different cities.

Finally, the Chapter 2 ends with a qualitative analysis about the cost of different types of cable car systems, provided by [R36].

The **Chapter 3- transport systems for the overcoming of differences in high** provides the description of the traditional systems used in urban context for the circumstances where it is necessary to overcome high slopes. In particular, strengths and weaknesses of the traditional systems are described and listed, and it is underlined that traditional systems (inclined lift, funicular railway, cog railway, APM with traction by rope and with vehicles with detachable grip, to-and-fro ropeway, continuous circulating monocable traditional ropeway, and bicable gondola) are not able to fully intercept the needs of the passengers and the requirements imposed by the urban fabric.

The above-mentioned mismatch between the needs of the demand on one hand and the traditional systems presented by the offer on the other hand can be overcome by hybrid system derived by cable-car technologies as *CableSmart*. In the **Chapter 4- Description of CableSmart system**, a detailed illustration of the technical components of the hybrid system is provided, with emphasis on the way in which it is able to match the strengths of a cable car system with the ones of a rail-based system. In fact, *CableSmart* technology allows to reconcile the advantages of the traditional gondola, such as the ability to easily overcome large differences in altitude and natural obstacles with low impact on the ground of the system, with the strengths characteristic of a transport system on suspended monorail, such as the easy adaptation to the urban fabric, the possibility of having a curvilinear paths and the presence of slender intermediate stations that can be easily integrated into the urban context and environment.

The **Chapter 5- Normative framework** resumes the main sources of the current normative framework, describing the guidelines for fully automated cable driven passenger transport systems, the European legislation as well as the Italian one. In addition, the chapter provides an overview about the self-driven regulation and the railways and subways regulation.

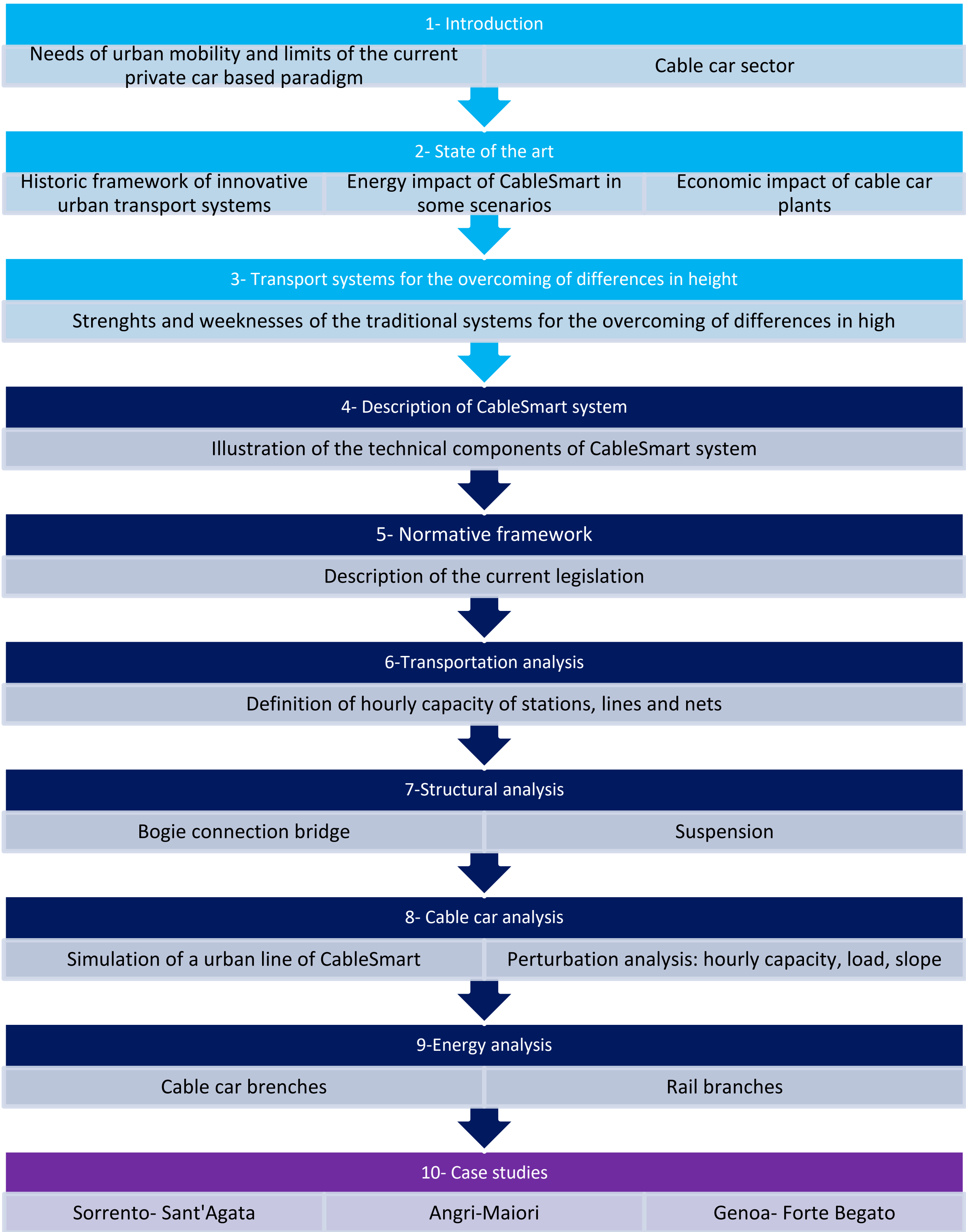
The following chapters contain the guidelines about the design of the CableSmart installations. In particular:

i) **Chapter 6-Transportation analysis** faces the topic from a transportation point of view, defining the hourly capacity of the branches, of the stations and of the net;
ii) **Chapter 7- Structural analysis** describes the structural verification of the more critical elements of the system in terms of forces solicitations, *id est* the bogie connection bridge and the suspension;

iii) **Chapter 8- Cable car analysis** collects the analysis carried on about the design of an urban line of *CableSmart*, in its cable-car branches. By using SIF (or CDP, cableway design package), a software developed for the calculation of longitudinal profile of a cable car line, an urban and horizontal *CableSmart* line is defined. In addition, in the Chapter 7, an in-depth perturbation analysis is provided, in order to characterize the energy consumption of the installation changing the hourly line capacity, the slope and the load scenarios.

The energy impact defined in the previous chapter is examined in a detailed way in the **Chapter 9- Energy analysis**, that provides a list of the energy consumption of a *CableSmart* installation, both in its cable car branches and in its rail ones, in different path and load scenarios.

Finally, **Chapter 10-Cases studies** declines the theoretical elements described in the previous chapters in three real case studies where the CableSmart system appears to adhere optimally to the particular transport requirements.


1- Introduction
Needs of urban mobility and limits of the current private car based paradigm
Cable car sector
2- State of the art
Historic framework of innovative urban transport systems
Energy impact of CableSmart in some scenarios
Economic impact of cable car plants
3- Transport systems for the overcoming of differences in height
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Perturbation analysis: hourly capacity, load, slope
9-Energy analysis
Cable car brenches
Rail branches
10- Case studies
Sorrento- Sant'Agata
Angri-Maiori
Genoa- Forte Begato

Abstract

The current paradigm of urban mobility, still heavily unbalanced towards private cars as the main means of transport, clearly shows its unsustainability from a social, economic, energy and - consequently - environmental point of view. Nonetheless, private car remains the main way by which passengers satisfy their transport needs in urban areas, due to the undoubted advantages that it shows, such as the complete customization of the journey in terms both of route and of scheduling, the high standard of comfort and the lowest perceived cost.

It is therefore necessary, in order to remove the limits of the evolution of the cities and the quality of life of citizens, to define a transport supply able to maintain the typical strengths of the private car, but to remove its unsustainable points, providing the traveller the possibility to use his time during his mobility.

In this context, as part of the PhD program and jointly with the Italian company "Dimensione Ingenierie", which has been operating in the ropeway sector for decades, the innovative *CableSmart* transport system was developed. It is a hybrid system derived from the cable-car technology, whose vehicles can move in two alternative ways:

- Through the automated gripping to a hauling rope, as a conventional gondola ropeway;
- Through motorised wheels installed on the bogie, in a similar way to a monorail system.

CableSmart fits in the contexts of the C-APMs (Automated People Movers derived from the cable car technologies) systems and merges the advantages:

- of a typical cable car system, in terms of overcoming of natural and anthropic obstacles with a low soil impact;
- of a rail-based system, in terms of easiness of insertion in the urban fabric and definition of curvilinear paths;
- of a PRT (Person Rapid Transit) system, in terms of passenger comfort, very low waiting time and customization of the path.

The reference normative for the design of C-APMs is made up of the UNI/TR 11735 document: "Guidelines for the design of fully automated people transport systems with cable traction [R1]. As highlighted by the title, the standard aims to present guidelines for the design of the system which can be the basis for drafting a Technical Specification, but does not in itself constitute a specific regulation. In addition to the main guideline about the transport design of a CableSmart urban line, its structural computation and the line calculation based on the Italian cable-car regulation framework, an in-depth analysis about the specific energy consumption [kWh/(passenger·km)] and specific emission [gCO_2/passenger/km] is performed with several load configurations, hourly carrying capacity, path and technologies, and shows the high energy efficiency of the CableSmart system.

In addition, an overview of the main design challenges that the hybrid system can overcome is presented, with reference to three real case studies, corresponding to as many feasibility studies:

- Sorrento- Sant'Agata: Connection between the city centre of Sorrento and the village of Sant 'Agata sui due Golfi, placed on a hill area at the centre of the Sorrentine Peninsula. In order to minimize the impact of the plant in the Sorrento city centre, the rail stretch is designed in underground tunnel; while the cable-car stretch allows to run across high differences in high;

- Angri- Maiori: Connection between the railway station of Angri, in the Neapolitan hinterland, the coastal town of Maiori, consenting to define a mobility link between the Amalfi Coast and the Pompeii archaeological area. The vehicles equipped with thermic comfort system allow passengers to travel comfortably the almost 15 km - 50-minute journey;
- Genoa- Forte Begato: Connection between the port area of Genoa and a mountain zone beside the Ligurian capital city. The line is divided by an intermediate station in two stretches with different situations: the first one, crossing the highly urbanized and anthropised Genoa district of Lagaccio requires technical solutions to manage urban needs, while the second one presents characteristics typical of a mountain line.

Through a multi-variable analysis that took in consideration the needs the requirement imposed by the path, the needs of the demand and the energy consumption, the above-mentioned feasibility studies demonstrated that, in circumstances where the needs of urban integration and passenger comfort are key requirements, the hybrid system is able to match the needs of the demands and the necessity of the context in a better way than the traditional systems for overcoming differences in high.

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Chapter 1

1. Introduction

1.1 Framework

The main topics of this PhD thesis are the description of *CableSmart*, an innovative hybrid urban mobility system derived by the cable car technology and the analysis that show its competitiveness compared to traditional public transport systems.

The need to change the current urban public transport paradigm is also underlined by the Transport White Paper issued in 2011 by European Commission ([R1]) which emphasizes the need to push towards decarbonisation (i.e. the reduction in the energy mix of fossil sources) also in the transport sector (to date, the transport sector covers 96% of energy needs through crude oil and its derivatives), in order to:

i. reduce the economic exposure of the European continent, which in 2010 imported oil for around 210 billion euros.
According with [R **3**], the consumption of crude oil derived fuels is around 18.77 millions of litres of gas and 29.85 millions of litres of diesel (diesel has high consumption because heavy vehicles and cars traveling high distances normally use diesel fuel).

ii. reduce greenhouse gases emissions, with the aim of keeping global warming below 2^{O}C.
According with Eurostat and as reported in the following *Figure 1* ([R4]), the impact in EU-27 of the transport system in the overall use of energy consumed in 2006 was 31.49%, and changed from 18.73% in Finland, that is a Country with high green sensibility, to 59.09% in Luxemburg, little Country with small

incidence of industries. The value related to Italy, *id est* 33.82%, was consistent to the European average. How have these values changed in the years? Not much, as the following *Figure 2* [R5] demonstrates, showing that the data reported in the *Figure 1*, despite they were +15 years old, are still consistent with the actuality.

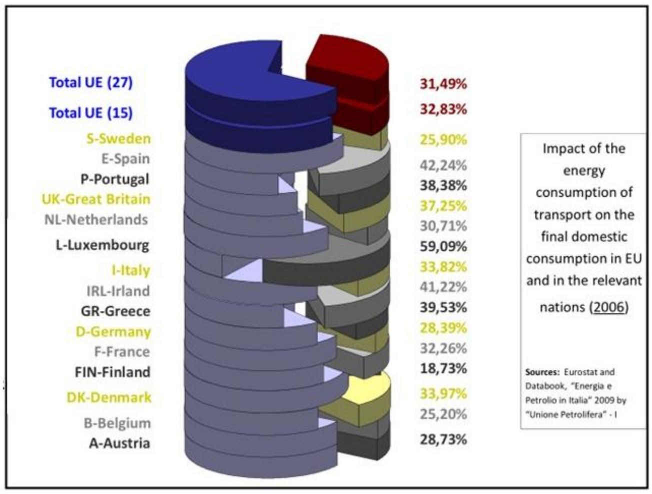


Figure 1-Incidence of the transport sector in the overall energy consumption in Europe, for each Country

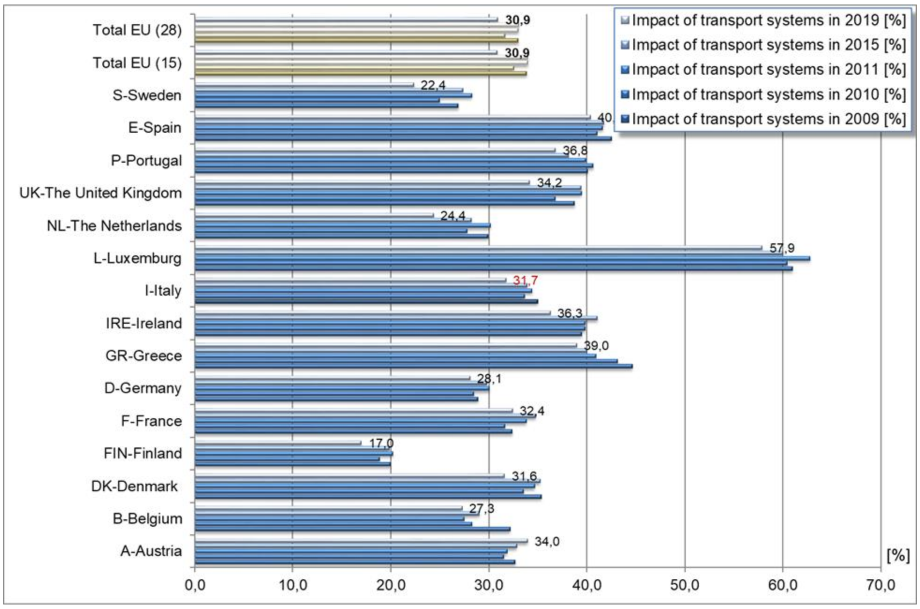


Figure 2-Incidence of the transport sector in the overall energy consumption in Europe, for each Country, during the years (data related to 2009, 2010, 2011,2015 and 2019 -most recent data in 2023- are reported)

Moreover, in the transport field, crude oil is almost in monopoly conditions: 96% of the energy in the mobility sector is given by derived of crude oil. So, the impact of the mobility field in the greenhouse gases emission is far from negligible.
Considering the subdivision of energy consumption by transport mode, great part (82.5% in Europe in 2004, and around 85% in Italy in 2019) of the energy due to the transport sector was consumed in 2004 by road transportation, as reported in the following ***Table 1*** [R4]. Also here, how this incidence has evolved in the years? Not much again as the *Table* ***2*** [R7] demonstrates.

EU-25				
Transport modes	1990	2004	1990-2004 Variation (%)	Share on the overall energy consumptions, 2004 (%)
Road	227'957	290'013	27%	**82.5%**
Railway	9'125	9'250	1%	**2.6%**
Air	28'378	47'420	67%	**13.5%**
Inland navigation	6'578	5'047	-23%	**1.4%**

Consumption by transport modality in 1990 and 2004, in 1000 *toe, tonne(s) of oil equivalent*
[Source : Campbell, 2007]

Table 1-Consumption by transport modality in 1990 and 2004

EU-25						
Transport modes	1990	2004	2010	1990-2004 Variation (%)	2004-2010 Variation (%)	Share of the overall energy consumption, 2010 (%)
Road	227'957	290'013	299'700	27%	3.3%	**82.6%** ~85%, I
Railway	9'125	9'250	7'400	1%	-20%	**2%** ~1.6-3%, I
Air	28'378	47'420	49'800	67%	5%	**13.7%**
Inland navigation	6'578	5'047	5'900	-23%	+17%	**1.7%**

306'200	Road **(94,5%!)**
6'500	Rail
6'100	Domestic aviation
5'100 *(2019)*	Domestic navigat.

Consumption by transport modality in 1990, 2004 and 2010, in 1000 *toe, tonne(s) of oil equivalent,* plus updating at 2021
[Source : Campbell, 2007 ; EU Transport – Statistical Pocketbook 2012, until 2021]

Table 2-Consumption by transport modality in 1990, 2004, 2010 and 2019 (updated in 2021). Light blu values are related to Italy.

iii. reduce road congestion and therefore the accessibility gap between central and peripheral areas;
iv. develop the economic sector, as the transport industry directly employs around 10 million people and contributes around 5% to GDP in European Union.

Furthermore, the aforementioned [R1] Ente Nazionale Italiano di unificazione, norm "UNI/TR 11735- Guidelines for the design of fully automated people transport systems with cable traction", 2018

[R2] acknowledges that the reduction of the dependence of the transport system on oil must take place while maintaining the efficiency of the current transport system and without reducing the mobility of travellers; and it is therefore necessary that new modes of transport emerge that allow the mobility of a greater number of passengers, preferably reserved for the last kilometres of the route and using clean vehicles.

So, although technological development and research allow the adoption of private cars with lower unitary energy and environmental impacts (in terms of kWh/km and gCO_2/km), as reported in the following *Figure 3* [R4], in order to further reduce the dependence of the transport system on petroleum-derived fuels it is also necessary to act on the offer of public transport.

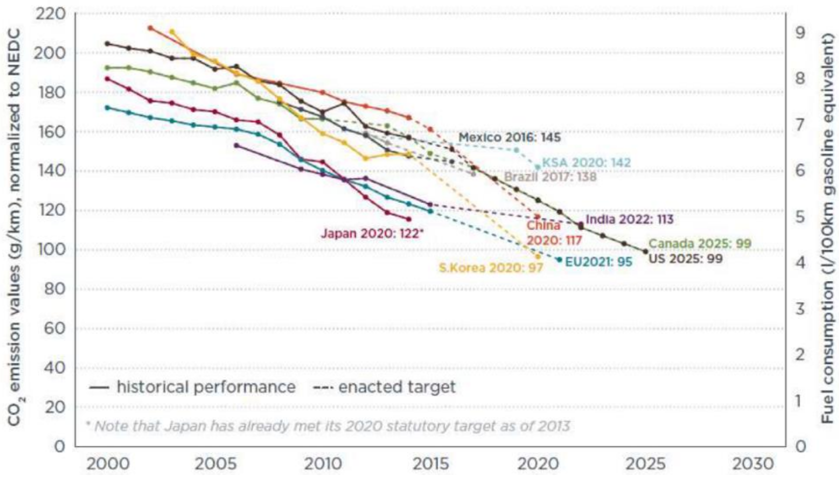


Figure 3-Comparison of global CO_2 regulations for passengers cars

It is precisely in this context that the *CableSmart* system operates, as it will be described in this PhD thesis.

1.2 Urban Mobility

The mobility of people, goods and information has been a fundamental dimension of the development of the human civilization, acting as a driver for the evolution of humanity in a social, military, technological and economical point of view.

For instance, the extended net of roads among Europe, Asia and Africa, and maritime trade routes in the Mediterranean Sea (that the ancient Romans called “Mare Nostrum”, such was the sense of possession of their internal lake) made up for centuries the skeleton and the nervous system of the Roman Empire, and allowed people, goods and information to run in a few days among all the Empire.

In the early 18^{th} century, the knowledge of the net of road in Europe become fundamental for Napoleon to manoeuvre his army and reach a competitive advantage on his enemies’ armies. Among his soldiers, it was famous the sentence “the Imperator wins the war with our legs, non with our weapons”, in order to emphasize how important, the logistic skills were.

In the same decades, the expansion towards West of the United States of America was allowed by the building of several railways line running in East- West direction. This topic, in addition to link the huge cities in the North of the American East Cost (such as Philadelphia, Boston and New York City) to the rising city in the middle West (as Chicago), politically linked the northern American states with the new states and territories in the middle West, and this was one of the strategical factors that facilitate the victory of the American civil war by the Unionist.

In recent years, globalization, which strongly connect each other Countries worldwide was made possible by a dense net of maritime routes, air routes, rails and routes that link and connect the whole world and that allow the fast mobility of people and goods.

The urban mobility deserves a separate discussion

Few days ago, the world population has passed 8 billion people; of these, about 60% live in urban areas. The urban population is exponentially growing, and it overcame, during the first decade of this century, the rural population, as reported in the Figure 4.

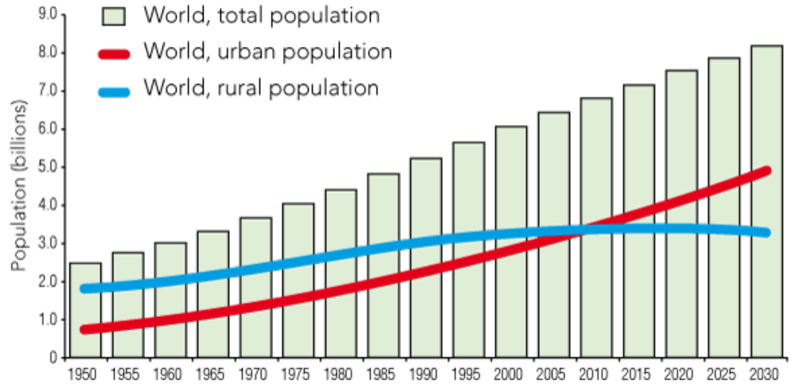


Figure 4-Total, urban and rural world population in function of the year, from 1950 to 2030 (prediction)

Figure 5-City growth: comparison of Miami city centre in 1960s and in 2010s

According to [R4, whose summary data are collected in Table 3, in 2016 there were worldwide 1,063 cities, hosting more than 4 billion people. It is foreseen that in 2030 cities with more than 500,000 inhabitants will be 1.393 (+31%), and they will host more than 5 billion people (+25%).

World's population by size class of settlement, 2016 and 2030						
	2016			2030		
	Number of settlements	Population (millions)	Percentage of world population	Number of settlements	Population (millions)	Percentage of world population
Urban	..	4 034	54.5	..	5 058	60.0
10 million or more	31	500	6.8	41	730	8.7
5 to 10 million	45	308	4.2	63	434	5.2
1 to 5 million	436	861	11.6	558	1 128	13.4
500 000 to 1 million	551	380	5.1	731	509	6.0
Fewer than 500 000	..	1 985	26.8	..	2 257	26.8
Rural	..	3 371	45.5	..	3 367	40.0

Table 3-Urban and rural world population in 2016 and 2030 (prediction)

In parallel with the urban population, in the last decades, also the demand of urban transportation has grown, and this trend will continue in the next years. So, an analysis about the needs of the mobility demand and about the technique of the mobility offer cannot ignore the relationship between the transport systems and the concepts of cities.

Between 1831 and 1925, London was the most populated city in the world, and it was the first European city to reach 1 million of inhabitants after the Trajan Rome (II century). Almost simultaneously to the achievement of the 1 million of citizens, in the first half of the 19th century, London was struck by numerous cholera epidemic, caused by poor hygienic conditions due to overcrowding and to the transport system. At the time, the most common means of urban transportation consisted of horses and carriages pulled by horses, and providing transportation for one million of inhabitants was cause of degradation of hygienic conditions due to the dejections of the hundreds of thousands needed horses.

This was a real bottleneck for the development of cities during the 19th century, so much so that it was common opinion for the urban planners that one million inhabitants was a natural limit imposed on the growth of urban agglomerations. This problem resolved itself, when internal combustion engine technology made it possible for cars and buses to replace animal-powered systems.

Nowadays, the private car remains the main transport system for urban mobility, particularly for mobility demanders coming outside from the centre of the city, due to the lack of comfortable connection between the suburbs and the city centres. The following Figure 6 Campbell, EU Transport – Statistical Pocketbook, 2019

[R8] show that in almost all the 11 cities of the sample the share of urban mobility covered by the private car is over the 50%.

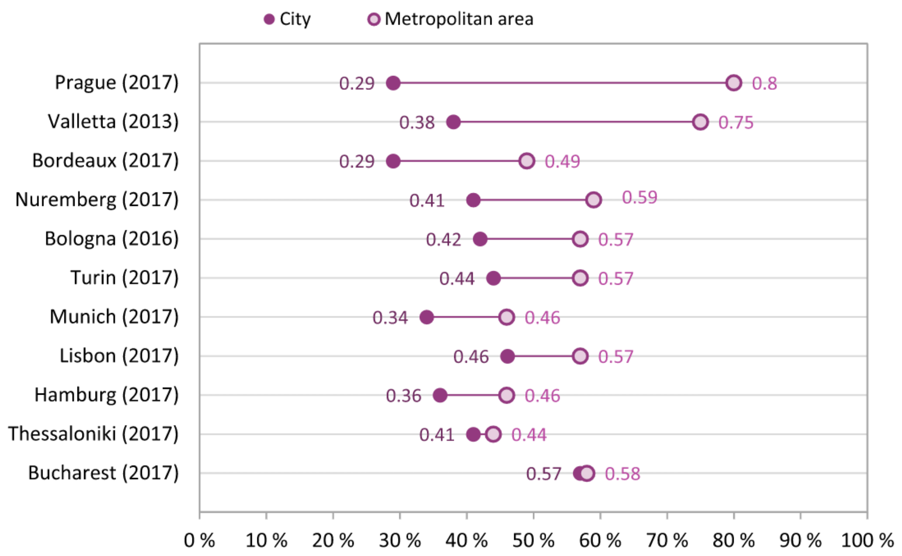


Figure 6-Modal share of private vehicles in a sample of 11European cities and metropolitan areas surrounding cities

In the Italian framework, in provincial capitals, the offer of urban mobility by local public transport (LPT) is given, in terms of passengers*km, principally by bus and tramways (63%), followed by subway (27%), as reported by [R11].

According to some recent literature [R9] [R10], the structural changes will largely depend on the habits of people pre-COVID-19: those who tended to use a private vehicle (car or motorbike) are likely to use it more, while those who previously relied on public transport could switch to cycling, micro-mobility or walking. Most probably, this will be a transitory behaviour; however, surely public and multimodal mobility will face greater difficulties than private motorized vehicles, due to the rigorous access regulation systems adopted on public transport to prevent infection and whose time application cannot be predicted exactly. In the short term, a strengthening of private mobility will most likely occur, which will have to be contrasted with policies aimed at promoting integrated mobility solutions that favour the use of pedestrians and bicycles over short distances and in urban areas, and the adoption of solutions for co-modality and flexible transport services over long distances. The use of MaaS through ITS must also be encouraged and strengthened, together with an increasingly pervasive process of digitalization in all transport areas, process that has been accelerated by COVID-19.

Figure 7 Trips in Turin, January 13 - July 16, 2020

As shown in the following Figure 8 [R12], different urban transport systems cover different areas in the length of line- hourly capacity plan.

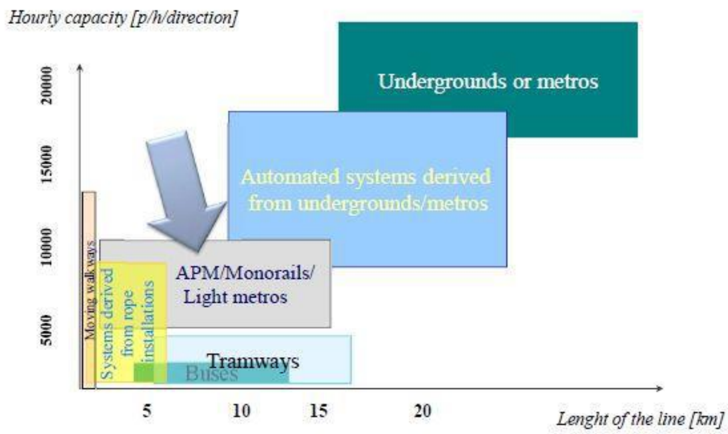


Figure 8-Classic range of use, in terms of length of the line and hourly capacity, of urban transport systems

In particular, buses and tramways find their application field in middle line distance (typically 5-15 km) and relatively low hourly capacity (until 5,000 passengers per hour per direction), while underground technology is used when it is demanded mobility with high distances and high hourly capacity.

When the needs of urban mobility are intermediate between the tramways and undergrounds systems (or system derived by undergrounds), monorails, light metros and APMs find their natural field of application.

The actual urban mobility system, where the major part of the urban mobility demand is satisfied by the private car, shows several issues:

- Congestion
  According to [R13], in EU countries, traffic and congestion in urban areas means a loss of 4,500 minutes per driver per year, corresponding to more than 9 working day per driver per year wasted. In terms of money, congestion entails every year the loss of around 20 billion of euros.
  Moreover, all the time passes traveling by car can be considered (particularly for the driver) wasted time, because driving a car is incompatible with performing other activities (e.g.: working, see a movie…)

- Pollutant emissions
  The internal combustion engine, due to inefficiencies in the combustion process, it produces and releases pollutants such as NOx and fine particles into the atmosphere.
  Despite having undergone a drastic reduction in recent years (-45% in the last 15 years), deaths by pollution are affecting the European's quality of life: according to [R14], in European countries at least 238,000 people died prematurely in 2020 due to $PM_{2.5}$ pollution above WHO guideline level of 5 µg/m^3, and 49,000 people died prematurely due to nitrogen dioxide exposure. Moreover, air pollution causes a decrease in the health conditions of the inhabitants, also having a strong economic impact in terms of increased health expenditure: for instance, in 30 European countries more than 175,000 people lived with chronic disability due to chronic obstructive pulmonary diseases caused by $PM_{2.5}$ pollution exposure.

- CO_2 emissions
  Globally, in 2019 the anthropic activities have caused the emission into the earth's atmosphere of more than 35 $GtCO_2$; and this value is hugely grown in the last year: in the last 30 years, more CO2 has been released into the atmosphere in the last 3 years than in the entire history of human industrialization[R7], as reported in Figure 9

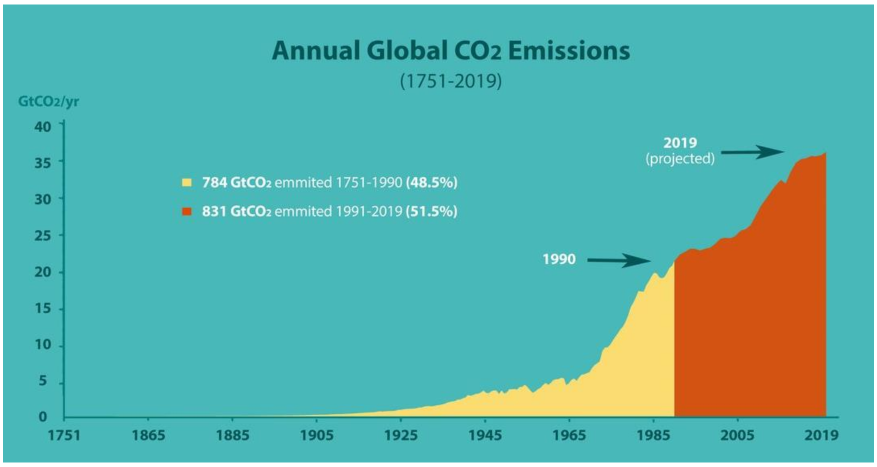


Figure 9-Anthropic emission of CO2 in function of the year

The impact of the transportation sector in terms of CO_2 emissions is about the 15% of the total[R16], as graphically shown by the following Figure 10. Reasoning at low granularity, according to [R17], a typical passenger car vehicle emits about 4.6 tons of carbon dioxide per year.

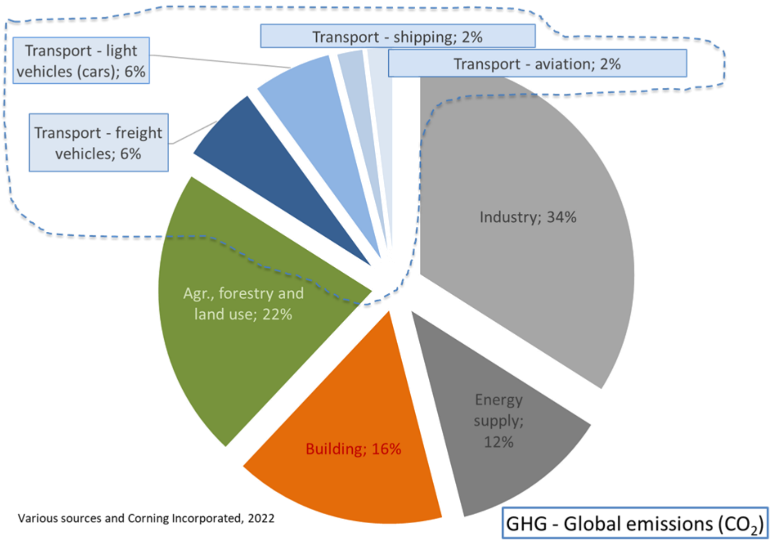


Figure 10-Sources of the anthropic emission of CO_2

The carbon dioxide CO_2 is the greenhouse gas with the greatest impact, in absolute terms, on the increase in global temperature. For this reason, the current main paradigm of urban mobility, strongly based on internal-combustion-engine private cars, does not seem to be compatible with the achievement of the numerous international agreements signed almost unanimously by the world community. For instance, it is cited the 2022 UN Climate Change Conference (COP27) which took place in Sharm El-Sheikh between 6th and 20th November 2022 and that renewed the Paris and Glasgow agreements on the need to limit global warming to well below 2^{O}C compared to the pre-industrial age.

- Road safety

In 2021, in Italy, 151,875 road accidents occurred, causing 204,728 injuries and the death of 2.875 people (around 49 deaths per 100,000 inhabitants) [R18], id est almost 8 death per day. According to [R19], the following Figure 11 shows the roads death rate, in terms of number of dead people per million of inhabitants, of the 27-EU Countries: in Europe, 44 people per 100,000 inhabitants dead every year due to traffic incidents. In other words, every European has every year a probability of 0.44‰ to die in road accidents.

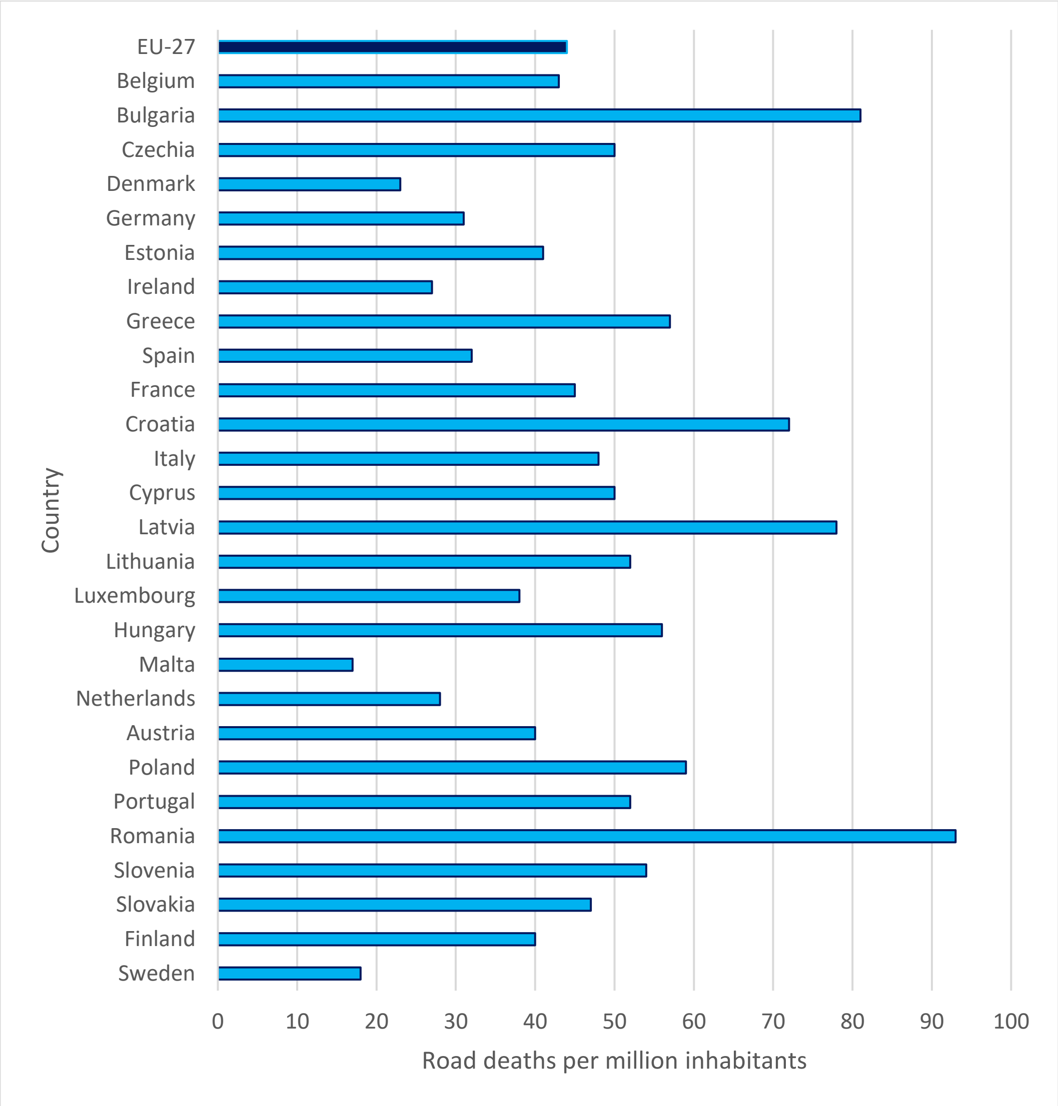
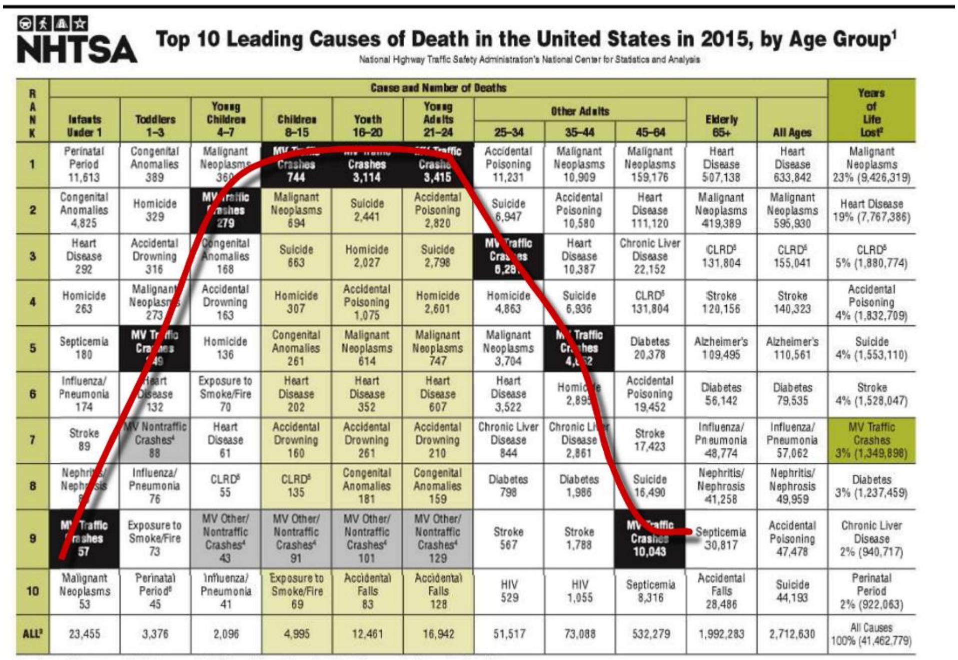


Figure 11-Road deaths per European country

Moreover, as reported in the following Figure 12 ([R20]), traffic incidents are the main cause of death for Americans between and 24 years.


NHTSA Top 10 Leading Causes of Death in the United States in 2015, by Age Group[1]

National Highway Traffic Safety Administration's National Center for Statistics and Analysis

RANK	Cause and Number of Deaths											Years of Life Lost[2]
	Infants Under 1	Toddlers 1–3	Young Children 4–7	Children 8–15	Youth 16–20	Young Adults 21–24	Other Adults 25–34	Other Adults 35–44	Other Adults 45–64	Elderly 65+	All Ages	
1	Perinatal Period 11,613	Congenital Anomalies 389	Malignant Neoplasms 360	MV Traffic Crashes 744	MV Traffic Crashes 3,114	MV Traffic Crashes 3,415	Accidental Poisoning 11,231	Malignant Neoplasms 10,909	Malignant Neoplasms 159,176	Heart Disease 507,138	Heart Disease 633,842	Malignant Neoplasms 23% (9,426,319)
2	Congenital Anomalies 4,825	Homicide 329	MV Traffic Crashes 279	Malignant Neoplasms 694	Suicide 2,441	Accidental Poisoning 2,820	Suicide 6,947	Accidental Poisoning 10,580	Heart Disease 111,120	Malignant Neoplasms 419,389	Malignant Neoplasms 595,930	Heart Disease 19% (7,767,386)
3	Heart Disease 292	Accidental Drowning 316	Congenital Anomalies 168	Suicide 663	Homicide 2,027	Suicide 2,798	MV Traffic Crashes 6,28[illegible]	Heart Disease 10,387	Chronic Liver Disease 22,152	CLRD[5] 131,804	CLRD[5] 155,041	CLRD[5] 5% (1,880,774)
4	Homicide 263	Malignant Neoplasms 273	Accidental Drowning 163	Homicide 307	Accidental Poisoning 1,075	Homicide 2,601	Homicide 4,863	Suicide 6,936	CLRD[5] 131,804	Stroke 120,156	Stroke 140,323	Accidental Poisoning 4% (1,832,709)
5	Septicemia 180	MV Traffic Crashes [illegible]49	Homicide 136	Congenital Anomalies 261	Malignant Neoplasms 614	Malignant Neoplasms 747	Malignant Neoplasms 3,704	MV Traffic Crashes 4,[illegible]62	Diabetes 20,378	Alzheimer's 109,495	Alzheimer's 110,561	Suicide 4% (1,553,110)
6	Influenza/ Pneumonia 174	Heart Disease 132	Exposure to Smoke/Fire 70	Heart Disease 202	Heart Disease 352	Heart Disease 607	Heart Disease 3,522	Homicide 2,89[illegible]	Accidental Poisoning 19,452	Diabetes 56,142	Diabetes 79,535	Stroke 4% (1,528,047)
7	Stroke 89	MV Nontraffic Crashes[4] 88	Heart Disease 61	Accidental Drowning 160	Accidental Drowning 261	Accidental Drowning 210	Chronic Liver Disease 844	Chronic Liver Disease 2,861	Stroke 17,423	Influenza/ Pneumonia 48,774	Influenza/ Pneumonia 57,062	MV Traffic Crashes 3% (1,349,898)
8	Nephritis/ Nephrosis [illegible]	Influenza/ Pneumonia 76	CLRD[5] 55	CLRD[5] 135	Congenital Anomalies 181	Congenital Anomalies 159	Diabetes 798	Diabetes 1,986	Suicide 16,490	Nephritis/ Nephrosis 41,258	Nephritis/ Nephrosis 49,959	Diabetes 3% (1,237,459)
9	MV Traffic Crashes 57	Exposure to Smoke/Fire 73	MV Other/ Nontraffic Crashes[4] 43	MV Other/ Nontraffic Crashes[4] 91	MV Other/ Nontraffic Crashes[4] 101	MV Other/ Nontraffic Crashes[4] 129	Stroke 567	Stroke 1,788	MV Traffic Crashes 10,043	Septicemia 30,817	Accidental Poisoning 47,478	Chronic Liver Disease 2% (940,717)
10	Malignant Neoplasms 53	Perinatal Period[6] 45	Influenza/ Pneumonia 41	Exposure to Smoke/Fire 69	Accidental Falls 83	Accidental Falls 128	HIV 529	HIV 1,055	Septicemia 8,316	Accidental Falls 28,486	Suicide 44,193	Perinatal Period 2% (922,063)
ALL[3]	23,455	3,376	2,096	4,995	12,461	16,942	51,517	73,088	532,279	1,992,283	2,712,630	All Causes 100% (41,462,779)

Figure 12-Causes of death per cause. Traffic incidents are underlined in black

- <u>Limitation on the growth of the cities.</u>

As cited before, the mobility framework can drive the cities development. Similarly to the end of the 19th century, when the evolution of the cities was limited by unwanted consequences of the urban mobility system, largely composed of horses, in these years world is facing a bottleneck in the city growth and in the citizens' quality of life, given by the effect of the current private car-based mobility system.

In fact, it is not possible to design a disruptive concept of cities without changing the private car-based mobility system, anchored to a 19th century technology.

For instance, China Communist Party, the highest organ of the People's Republic of China, in 2016 decreed to plan the building in the next years of smart and private car free cities to manage the relocation in new urban areas of around 300,000,000 people (almost the whole population of the United States of America) by 2030 [R21].

Other example to smart city designed re-thought the concept of urban agglomeration is under construction in Neom, Saudi Arabia. It is a 170km- length linear city under construction on the coast of the Red Sea, designed to have no cars, streets or carbon emissions.

Figure 13-Concept of The Line city, Saudi Arabia

- Consumption of soil
  In many cities, land consumption and its unavailability are a binding element for the construction of new roads or the expansion of the existing one. This is cause of inertia in the capacity of the transport offer, in terms of roads, to follow and adapt to the demand.

- Low utilization rate
  In Italy, every car owner uses the car on average 85 minutes per day, for 286 days per years [R22]. This means that on average an Italian car is used only for the 9% of the time, and for the remaining 91% of the time it represents a useless cost.

Despite the above-mentioned weaknesses and constrains, the private car continues to be the main mean of transportation in urban context, because it can match same important needs of the mobility demander, that the traditional public transport systems are not able to achieve:

i) It has a perceived minor cost than public system, as the passenger has not to buy a ticket for the journey, and the hidden cost as depreciation of the vehicle are usually underestimated by the driver;
ii) It has elevated standards in terms of comfort, thanks to ancillary systems as air conditioning and info-tainment;
iii) It allows a complete customization of the journey, in terms both of the timing, and of the route.

So, in order to overcome the current private car- based urban mobility framework, it is necessary to concept new public transport systems, able to match the over-mentioned needs.

In this context, in the last decades PRTs (personal rapid transit) were developed. They are mobility system suppling “on demand” transport with a dense net of lines and with relatively small vehicles (6-10 passengers) in order to be able to provide a large customization in terms of path and schedule.

The installations that can match the PRTs’ characteristics are very rare. There are two reasons why current People Movers and PRTs are today actually underused:

1) They are based on technologies developed between 1960 and 2000 that were not considering the smartphone, AI, big data and electrical driverless cars technologies’ impact;

2) They are based on railways technologies and norms, which are very stringent and have prevented these systems from being economically competitive with traditional means of transport

For this reason, the adoption of PRTs is still very marginal and relegated to specific contexts (e.g., airports) that have transport needs and constraints very different from those typical of urban mobility. However, as shown by Figure 14, PRT installations are just a few worldwide and cover an overall distance in the order of 20 km.

Figure 14-Location and main information about the PRTs installation worldwide

Although the practical application of PRTs installations has not yet found wide adoption, the research for a system that is both "personal", i.e., customizable on the precise needs of the passenger's journey, and "transit", understood in the American meaning of public means of transport, continues in the transport sector public.

One of the results of these research and innovation in the urban mobility transports are the Cable-APMs, Automated People Movers where the motion is given to vehicles through the grip of a hauling rope. A particular type of C-APM is CableSmart, innovative transport hybrid transport system derived from the cable car technology, where the motion can be given to each vehicle through the gripping on a hauling rope (as a traditional gondola) or through motorized wheels installed on the carrier assembly of the vehicle.

The description of this type of transport system is provided in detail in the next chapters, but preliminary considerations about how it can overcome the typical issues of a private car-based transport system, as they are previously mentioned, are collected in Table 4

Private car issue	*How C-APM can overcome the issue*
Congestion	Gondolas' vehicles have a typical carrying capacity of 8÷10 passengers, and the vehicles follow one another with intervals of a few seconds (10÷20s). So, the high carrying capacity of this type of system is achieved reducing the passenger waiting interval, in the absence of queues
Pollutant emissions	The main pollutant emission for an internal combustion engine, technology providing energy for the great part of the private cars in circulation, are carbon monoxide CO, nitrogen oxides NOx, hydrocarbons HC and particulate matter PM for a diesel engine and carbon monoxide CO, nitrogen oxides NOx and particulate matter PM. Instead, electric motors, typically used by the innovative transport systems and in particular by the C-APM, do not have a located impact on terms of pollutant emission. However, it is important to emphasize that a fair comparison between different transport systems in terms of pollutant emissions should be carried out calculation the sum of the effects, so considering both the local "Tank to Wheel" impact and the "Well to Tank" impact associated with the production of the source of energy, thus defining the global impact of "Well to Wheel".
CO_2 emissions	The average specific energy consumption of a private car, according to the American bus association cited in [R33] is around 3,555 Btu/pass/mi = 0.64738 kWh/pass/km, that produce a specific emission of 268.66 gCO2/pass/km using the emissions per unit of energy as defined in [R49]. The average emission of e C-AP system is hugely lower, as preliminary cited in the literature ([R33][R34]) and as deepen in the following chapters.
Lack of safety	In cable car installation history, serious accidents have occurred in recent decades, which have had high media visibility as they have involved many people. It is the case of the cable car incidents in Cavalese (Trento, 1976), where 42 people died in the deadliest cable car incident in history due to an overlap of the carrying rope with the hauling rope, which resulted in the shearing of the carrying rope;

	or of the most recent accident in Stresa-Mottarone cable car (Verbania, 2021) which resulted in 14 deaths. Despite the statistics being affected by the “king Kong effect” of the above-mentioned incidents, cable car remains one of the safer transport system, having a passenger deaths of 0.006 per 100,000,000 passenger mile, value much lower than the ones in passengers car (0.56), buses (0.02), railroad passenger trains (0.03) and comparable with the datum referred to the scheduled airlines (0.002) [R23]
Limitation on the growth of the cities.	CableSmart can be a disruptive technology able to overcome the traditional concept of private-car based cities and to allow the definition of inhabitant-based cities
Consumption of soil	Similarly to a traditional cable car, also in CableSmart transport system the aerial track allows to have a very limited impact to the soil, and it can be installed, respecting the minimum clearances imposed by the normative, even in already densely urbanized areas. The only part of the system that have a punctual impact to the ground are the towers and the stations
Low utilization rate	Being a public transport system, the utilization rate is calculated by considering the travel of several passengers. However, it will be the task of the designers and planners to design lines with an hourly flow rate consistent with demand

Table 4-Overcoming of the main private car weaknesses of the hybrid CableSmart transport system.

As the Table 4 underlines, the current urban mobility paradigm, based on the private car utilization, shows important and critic constrains, that are limiting the development of the cities and the quality of the life of their inhabitants.

The PhD pattern described in this PhD thesis analyses a transport system (which will be described in detail in the following chapters) which aims to be part of the solution to the problems set out above.

1.3 Cable car sector

The economic contribution of the cable car sector is far to be negligible[1], and it is expected to growth with a compounded average growth rate (CAGR) of 11.9%/year in the 2019-2027 period [R24]

$$CAGR = (\frac{X_n}{X_0})^{\frac{1}{n}} - 1$$

Where:

- X_n: value of the market at the end of the considered period;
- X_0: value of the market at the begin of the considered period;
- n: number of years in the considered period.

According to [R25], the countries where the sector is more developed, in terms of monetary dimensions, are the Alpine ones, that contribute to more than 50% of the total market, as reported in the following Figure 15. In fact, mostly of the cable car new installations are serving ski resort and are used as cableway installation designed to carry skiers, and the cable car installed for public transportation purpose are less than one third, as shown in the *Figure **16***

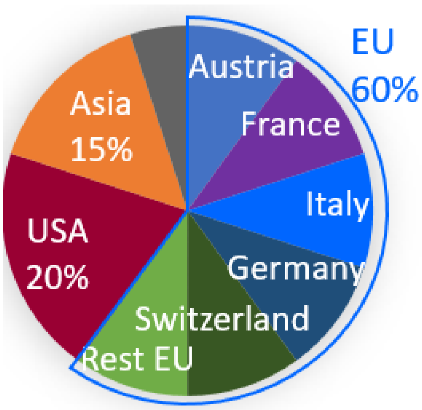


Figure 15-Current splitting of cable car market by countries

[1] Cable car sector has worldwide a value of US$ 3.667 Billions

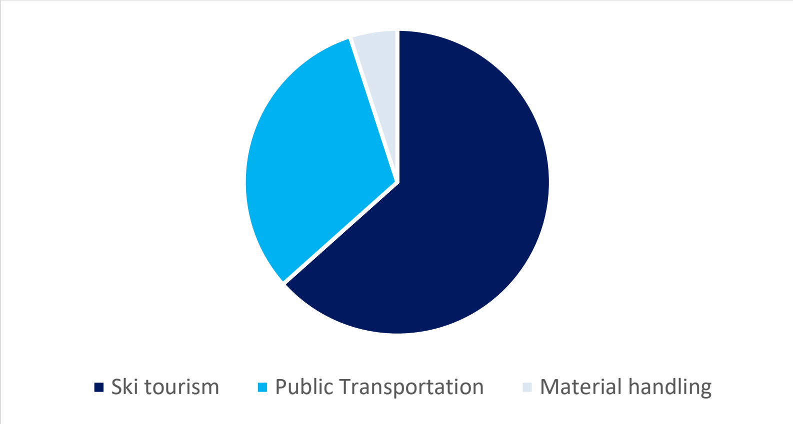


Figure 16-New cable car installation by sector

However, in the near future, a sharp slowdown in the ski lift sector is expected, due to the following causes:

- Market saturation, in particular way in the Alpine countries, where ski resorts have already developed all the areas where skiing is technical possible and economically sustainable;
- Competitive alternative markets to the mountain tourism industry sector, which reduce the demand of ski experience, of skiers' transportations and, so, of cable car installations;
- Global warming, that is strongly challenging the economic viability of skiing in many mountain areas, and is reducing the duration of the ski season. Many studies agree that, in the thirty-year period 2020-2050, the global average temperature will increase by about 1.5°C, with a consequent increase in altitude, with the same meteorological, climatic and snow conditions, of about 230m.

For these reasons, many cable-car manufacturers are trying to expand the opportunities of the ropeway market, finding a natural landing place in the urban public transport sector.

In fact, cable car installations are able to match same technical needs associated to the urban transportation, as the possibility to overcome anthropic or natural obstacle with low impact to the ground, and to overcome high difference in height with a limited energy consumption. In recent years urban mobility systems based on cable cars have been born, in which cable car installations constitute the nervous system of the transport network:

i) "Metrocable"[R26][R27] in Medellin, Colombia (6 lines, 14.62 km) is a network of cable cars serving the suburbs of the city of Medellín, connecting the favelas of the Colombian metropolis to the city centre and having a direct connection with the underground net, in multi-modal stations. The low impact to the ground of the cable car system allows to pass through the densely built neighbourhoods of the outskirt of the city, overflying them and also avoiding security issues associated with passing through areas affected by a high crime rate.

Figure 17-Picture of a line of "Metrocable" installation in Medellin- Colombia

ii) "Teleferico" [R28], [R29] in La Paz, Bolivia (10 lines, 33 km) represents the longest cable car network in the world. The system serves for the connection between La Paz, at an average altitude of 3,600 m above sea level , with the city of El Alto, located on a plateau at an altitude of 4,100 m above sea level The Teleferico system uses approximately 1,500 vehicles with detachable grip to obtain an overall capacity of approximately 34,000 passengers/hour for each direction.

As for the Medellin case, also in La Paz the cable car system was ideal for flying over critical areas in terms of natural and anthropic obstacles; moreover, the cable car technology is able to efficiently overcome the 500 m of difference in height between the terminal stations located in La Paz city centre and in El Alto.

Figure 18-Picture of a line of "Teleferico" installation in La Paz- Bolivia

Despite the above-mentioned installation of traditional cable car in urban areas allows to efficiently solve several issues of the mobility system of the two cities, the adoption of cable cars in urban context have not boomed yet. In fact, the traditional cable car technology has several constrains and weaknesses that prevent it from fully intercepting the needs related to urban mobility, as:

- Impossibility to define curvilinear path between two stations;
- Vehicles without electrification on board, that cannot host air-conditioning, lighting, video-surveillance or infotainment system;
- Impossibility to customize the route.

For these reasons, hybrid systems of cable car derivation are appearing on the market, which maintain the undoubted advantages of a cableway system and overcome its limits. The system CableSmart, whose description and design are the object of the following chapters, is an example of the above-mentioned hybrid systems.

Chapter 2

2. State of the art

The above-mentioned weaknesses and limitations related to the current private-car based urban mobility paradigm, and the possible alternative transport systems were object of several detailed analysis, that produced a wide contribution to the scientific and academic literature. In this chapter, an overview of the main topics collected in the existent literature is provide.

In [R31], authors provided an overview about the innovative transport system, defined as system used for the public transportation of people deviating from the traditional road or railway technologies, circulating in exclusive and protected path and using full automated technologies.

Regarding cable car-based systems, authors underlined that first urban application date back to the first years of the XX century, when cities as Paris, Chicago and San Francisco (*Figure* ***19***) adopted funicular railways, where carriages was moved through their gripping to a cable, to which the motion was conferred by steam engines and, in San Francisco after 1940, by the electric motor.

Figure 19-Picture of a carrier in the San Francisco funicular railway in 1920s

Parallel to car-based systems, rail-based system was developed and adopted in the last decades. The first application of this type of plant was installed between 1898 and 1903 in Wuppertal (Germany) the first suspended railway. Monorail-based system forcefully entered in the market of the public transportation system during the 1960s: it is cited for instance the application in Châteauneuf-sur-Loire (France, 1960, *Figure* ***20***), where the carriage, equipped with tires, travelled suspended on a beam inside which its wheels were enclosed. Now, monorail technology is reliable and widespread, so that manufacturers supply specimens in their catalogue.

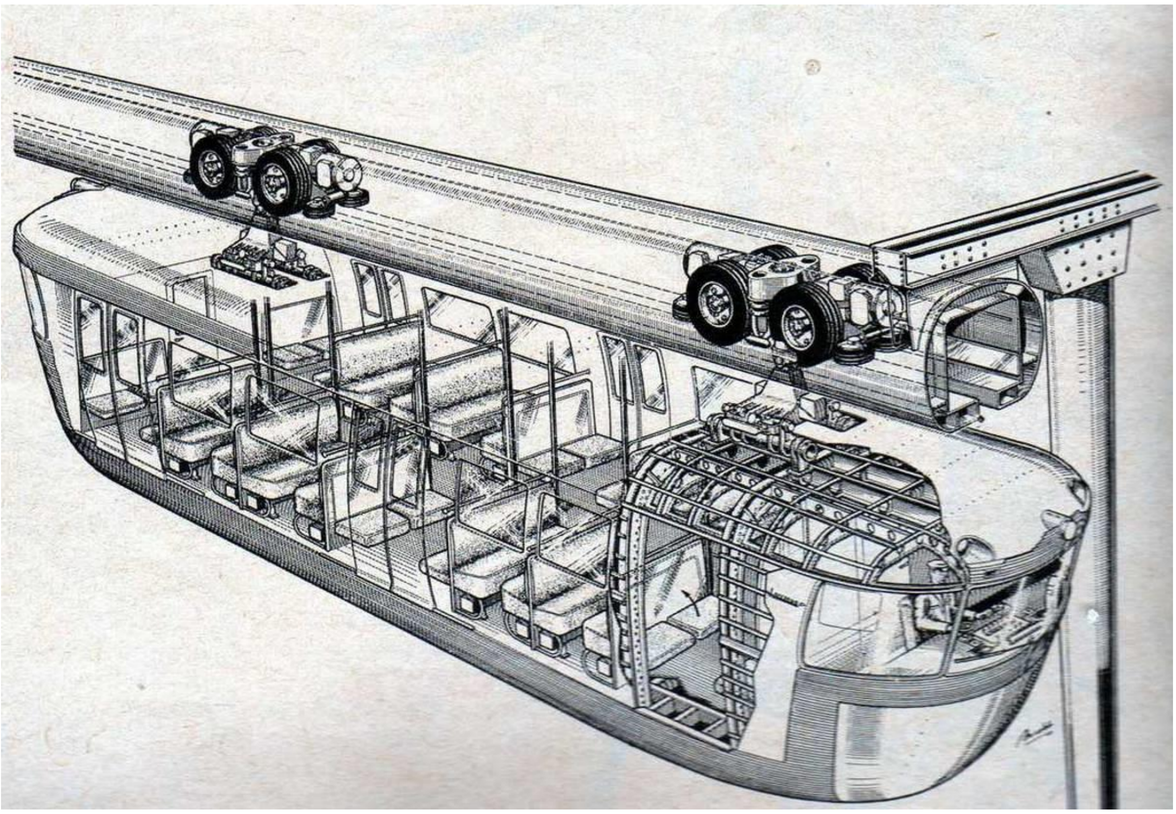


Figure 20-Technical drawing of carrier in the Châteauneuf-sur-Loire mobility system

A second generation of innovative system was developed in 1980s: thanks to the evolution in the automation technologies, cheaper, more reliable and more safety systems were installed, allowing the evolution from small installation in peculiar environment (e.g., amusement park, or airports) to transversal application in urban fabrics.

The first worldwide completely automatic metro was built in Lille (France) in 1983: it is the VAL (vehicule automatique lèger), and it use vehicles with rubber wheels that circulate on a protected path through steel or concrete rails.

In the same years, automation also allows to evolve toward the urban mobility the cable car technologies. More recent example of this type of plant, in the Italian contexts, are:

- Cascina Gobba- San Raffaele Hospital (Milano, 2000, *Figure 21*): funicular to-and-fro system connecting the ring road with the hospital, in a 645m length path and with a carrying capacity of 1,450 passengers per hour

Figure 21-Picture of the line of Cascina Gobba- San Raffaele mobility system

- Minimetro (Perugia, 2018): completely automatic semi-continuous circulating plant where the vehicle, able to contain 50 passengers, moves in a double track path through gripping to a rope ring. In proximity to the stations, the vehicle disengages by the hauling rope, and decelerate its motion, allowing the comfortable embarking and disembarking of the passengers, and returns in the line accelerating thanks to acceleration rollers derivate from the traditional detachable grip gondola technology.

Figure 22-Picture of the line of Minimetro mobility system in Perugia

A new concept of systems for urban mobility was introduced in the 1970s: these are the above-mentioned PRTs (personal rapid transit), system where a dense network of small vehicle with high customization in terms of path and scheduling is able to satisfy the mobility demand through a house-to-house service. Despite the high potentiality of these technology, the operative examples of PRTs installation in the world are yet very unusual:

it is cited, as example, the West Virginia University PRT in Morgantown (West Virginia, *Figure 23*)

Figure 23-Picture of the line and of vehicles of WVU PRT in Morgantown

One of the innovative technologies evolving in the context described by [R31] is the CableSmart system, that uses vehicle derived by the detachable grip gondola technology, adding them a set of motorized wheels. In this way, the CableSmart hybrid system can move through two alternative ways:

- Thanks the gripping to a hauling rope, as a gondola;
- Autonomously, Thanks to the motorized wheels installed on the bogie.

The performance, in terms of energy specific consumption and in terms of specific emission, of the CableSmart hybrid system have been analysed by [R32], [R33] and [R34]

In particular, [R33] simulated an urban installation of CableSmart, moving in the stations through motorized wheels, and among the line through the gripping to a hauling rope.

Calculating the ordinary resistance and the force giving the acceleration of the vehicle during the rail stretch, and the losses due to the frictions in the cable stretch, authors defined in 0.05 kWh/passenger/km the specific energy consumption of the CableSmart system, calculated with a realistic load factor of 62.5% (in average, every 8-seats vehicle hosts 5 passengers), as shown in *Figure 24* and *Figure 25*.

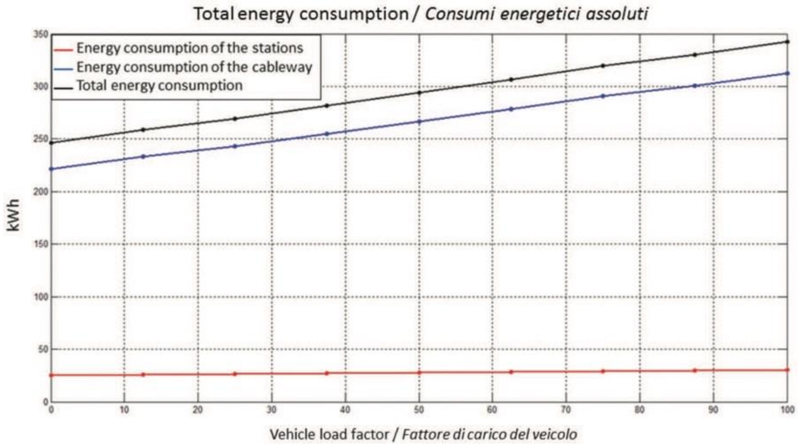


Figure 24-Total energy consumption of CableSmart

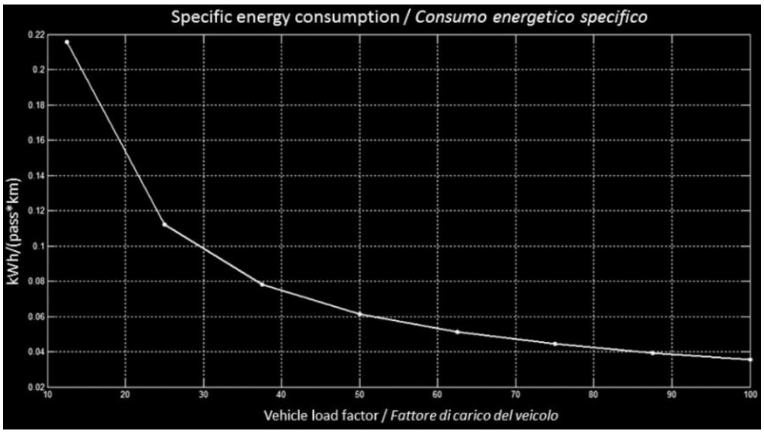


Figure 25-Specific energy consumption of CableSmart

The above-mentioned results of [R33] were defined with the assumption, legitimated by the Italian normative, that every roller causes a friction equal to the 3% of the vertical load acting on it. In [R32], authors challenge this assumption, defining a model to calculate the entity of the friction losses.

Authors underlined that the friction between the metal rope and the rubber on rollers is one of the most impact energy losses in a system derived from the cable-car technology, and found an analytic methodology to assess the generation of heat in the ropeway rollers with rubber band under cyclic loads, that causes hysteresis losses and friction. In fact, despite the energy loss for each roller is not high (it can be quantified in some hundreds of watts, compared to the hundreds of kilowatts provided by the motor of the gondola plant) the presence of hundreds of rollers in a line makes the losses by rollers one of the major sources of energy dissipation a cable car installation.

By treating the rollers as a set of infinitesimal spring placed in the circumference of the roller, and the rope as an ideal steel cylinder, authors defined a model to have as output the heating map of the rollers, index of the energy losses by friction.

A comparison between the real behaviour of a roller in terms of surface temperature (*Figure 26*) and the simulated one (*Figure 27*) is reported below.

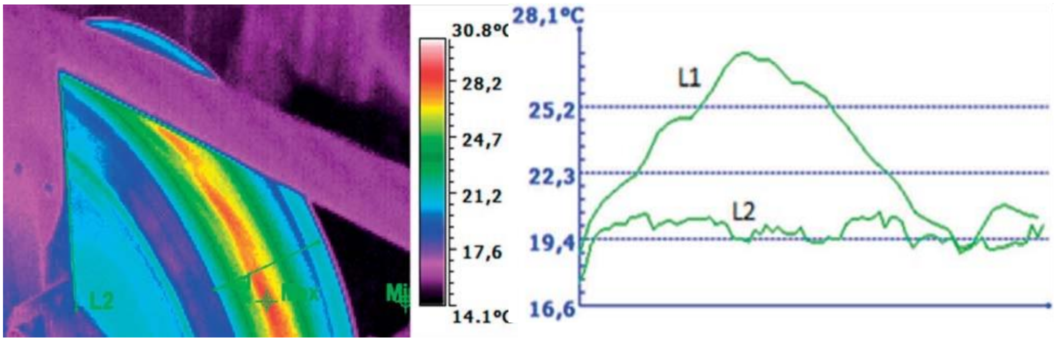


Figure 26-Thermal image of a roller in Dolonne- Plan Chècrouit gondola during the operations (left) and temperature of the profile (right, the x axis corresponds to the not-linear space along the green lines in the picture).

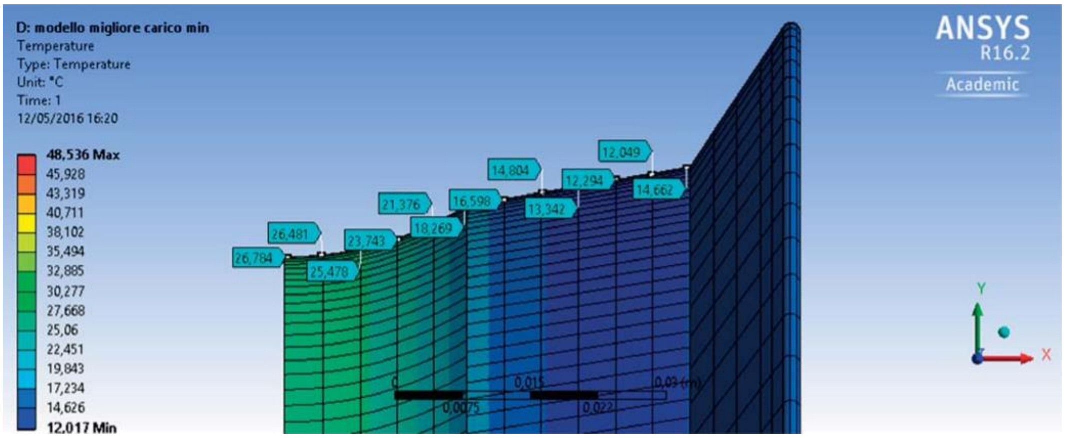


Figure 27-Temperature of the rubber surface of the Ansys simulation

The analysis carried out by authors allowed to define a mathematically based value in terms of energy losses per roller, and to quantify it in 1% for the hysteresis losses in the simulation carried on about the gondola connecting Dolonne and Plan Chécrouit (Courmayeur, Aoste), to which another supposed 1% for the losses due to the geometric deformation of the rollers is to be added.

So, authors concluded that the real losses for each roller are in the order of 2% of the vertical load on the roller, compared to the conventional value imposed by the norms of 3%. So, authors proved and quantified a further energy save in cable cars and system derived from cable car technology.

While [R33] and [R32] analysed the cable stretch of the CableSmart system, the rail stretch behaviour, in terms of energy performance, was investigated by [R34], that considered both the energy needed for the motion of the vehicle (ordinary resistances, acceleration) and the energy utilized for the comfort of the vehicle. Unlike the case of the traditional cable car technology, CableSmart's vehicle are in fact equipped by electrical system on board, so, they can host video-surveillance, climatization, ventilation and infotaitment system.

Authors calculated the average value of specific production of the CableSmart installation as 0.0269 kWh/passenger/km, and performed different simulations with the same supposed plant installed in different locations: in fact, while the energy for the motion depends only by the type of the system and by its utilization, the energy used for the thermic comfort of the cabin depends dramatically by the weather and by the external temperature. The below reported Table 5 shows the summary results of the comfort load depending by the city of installation for each city for each season, and the Figure 28 details the results considering the load for a CableSmart installation in Torino in the summertime. In Table 6 the spit for each season for each city between energy used for the motion and energy used for the comfort is shown: in critical weather condition, as the summertime in Dubai City, the energy required by the theriacal comfort of the cabin is almost equal to the energy required for the motion of the vehicle.

		Turin	London	Dubai City	New Delhi
Winter	Heating [kWh]	14,353	11,067	1,718	5,407
	Air-conditioning [kWh]	0	0	929	0
	Lighting [kWh]	446	440	396	420
Spring	Heating [kWh]	6,167	7,754	0	0
	Air-conditioning [kWh]	0	0	7,133	9,136

	Lighting [kWh]	299	305	339	336
Summer	Heating [kWh]	94	2,544	0	0
	Air-conditioning [kWh]	3,693	567	15,282	11,490
	Lighting [kWh]	263	264	263	295
Autumn	Heating [kWh]	5,294	5,811	0	0
	Air-conditioning [kWh]	0	0	9,704	5,866
	Lighting [kWh]	404	401	371	397

Table 5-Energy load for heating, air-conditioning and lighting of a cabin for each considered city of installation for each season

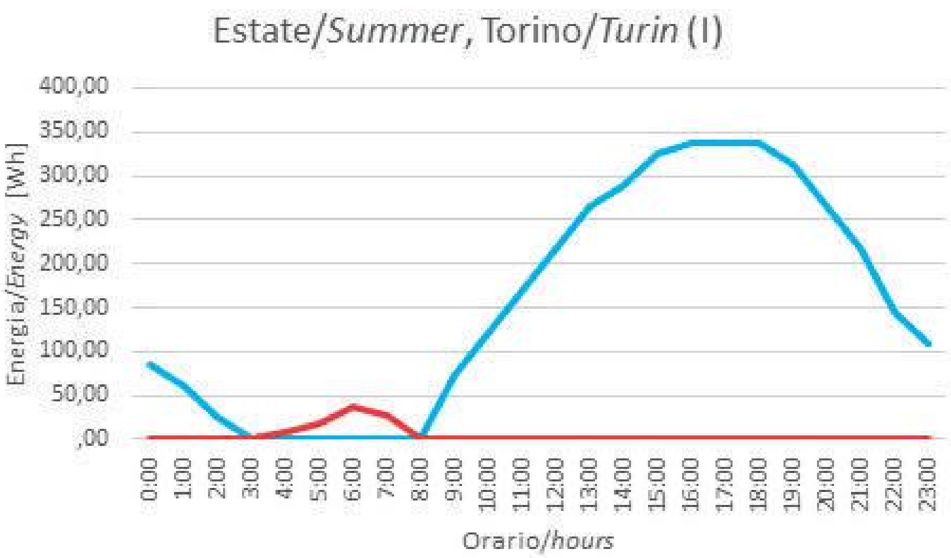


Figure 28-Energy used for heating (red line) and air-conditioning (light blue line) for each hour of the day for an average summer day in Torino

	Torino *Turin*	Londra *London*	Dubai City	Nuova Delhi *New Delhi*
Inverno ***Winter***	Comfort= 47% Movimento=53% *Comfort= 47%* *Movement=53%*	Comfort=43% Movimento=57% *Comfort=43%* *Movement=57%*	Comfort=31% Movimento=69% *Comfort=31%* *Movement=69%*	Comfort=36% Movimento=64% *Comfort=36%* *Movement=64%*
Primavera ***Spring***	Comfort=37% Movimento=63% *Comfort=37%* *Movement=63%*	Comfort=39% Movimento=61% *Comfort=39%* *Movement=61%*	Comfort=38% Movimento=62% *Comfort=38%* *Movement=62%*	Comfort=41% Movimento=59% *Comfort=41%* *Movement=59%*
Estate ***Summer***	Comfort=33% Movimento=67% *Comfort=33%* *Movement=67%*	Comfort=32% Movimento=68% *Comfort=32%* *Movement=68%*	Comfort=47% Movimento=53% *Comfort=47%* *Movement=53%*	Comfort=43% Movimento=57% *Comfort=43%* *Movement=57%*
Autunno ***Autumn***	Comfort=35% Movimento=65% *Comfort=35%* *Movimento=65%*	Comfort=36% Movimento=64% *Comfort=36%* *Movement=64%*	Comfort=41% Movimento=59% *Comfort=41%* *Movement=59%*	Comfort=36% Movimento=64% *Comfort=36%* *Movement=64%*

Table 6-Percentage division of the energy required by the load

Moreover, in [R34], authors simulated the energy behaviour of a photovoltaic plant and an energy storage system working as energy sources for the load of the CableSmart installation. Results underlined that energy directly coming from photovoltaic system or generated by the photovoltaic plant and passing through the batteries (as not needed by the energy load of the CableSmart system at the same time then its generation) enter in the energy mix reducing until to 70% the energy impact of the plant on the electric grid.

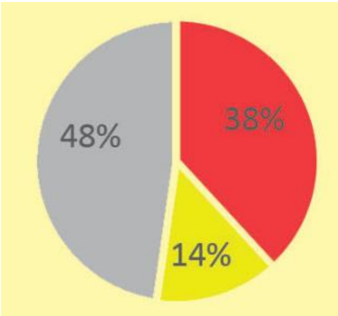


Figure 29-Pie chart of the energy mix of a simulated CableSmart installation in Torino during the summertime

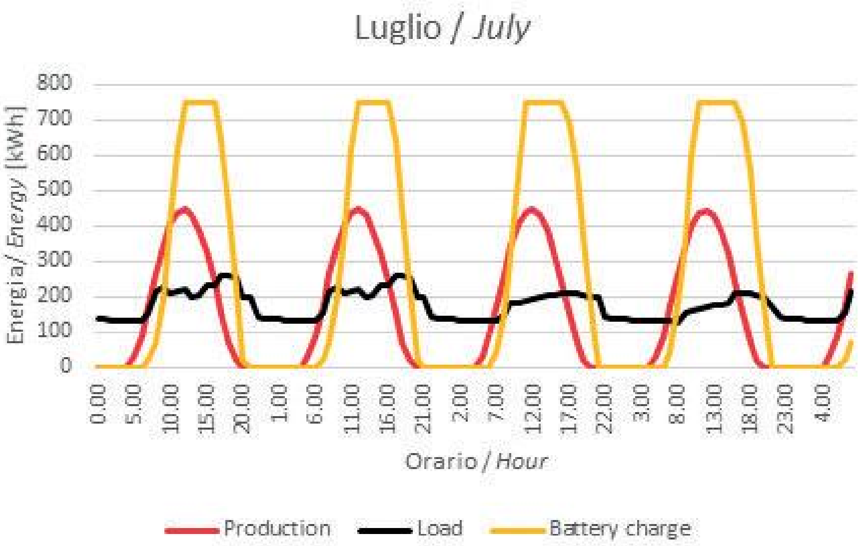


Figure 30-PV production (red line), battery charge (yellow line) and energy load (black line) of a CableSmart installation in average Thursday-Sunday days

For what concerns traditional cable car plants in urban environments, [R35] underlines that the factors that can influence the choice by the decision makers among bus, light rail, metro or traditional CPT (cable propelled transit) are:

- Topological conditions: CPTs are suitable for overcoming natural barriers (e.g.: mountains, valleys, rivers);
- Legal framework, changing dramatically by the County (for instance, authors underline that in Austria the installation of cables over residential areas is not allowed). This Ph.D. thesis, in its Chapter 5, face the topic of the normative, with emphasis on the European and the Italian ones;
- Passenger flow: the flexibility of traditional CPTs is limited;
- Weather conditions: CPTs, utilizing technologies developed for mountain extreme conditions, can operate with strong winds, and the limit for the operations, in terms of wind speed, is approximately 60- 100 km/h;
- Urban structure and functionality: stations for traditional CPTs can present issues in terms of insertion in the urban fabric.

[R36] performed an analysis about the consequences of the implementation of the (at the time) new Italian regulation of cableway installation designed to carry person defined by the D.D.337 dated 16.11.2012 [R40]. It is underlined that, despite the above-mentioned Decree [R40] has been recently replaced by the new normative reference [R39], the framework of the Italian normative remained almost unchanged, as the modifications introduced by the new decree are punctual and marginal. However, an overview of the main contains and impositions defined by the new Ministerial Decree

In paper [R36], the effect of the simplification in the norms introduced in 2012 receiving the II European Directive 2000/9/CE [R41] are investigated, with particular emphasis on the economical point of view, analysed taking into consideration [R42], that define the following formula as a benchmark of the calculation of the economic impact of a cable car plant in mountain context and underlining that the general formula cannot take into account the greater costs of the urban installations.

$$P = S * E * D * [A'L^2 + B'L + C') + (Q - Q') * (AL^2 + BL + C")]$$

Where:

- P = conventional building cost [Euro];
- L = Inclined length of the installation [m];
- Q = allowed hourly capacity [passengers/hour] (or cabin capacity [passengers], for double-cable to and fro cableway);
- The parameters A’, B’, C’, A”, B” and C” depends by the type of the cable car plant and, as the since 2006, when [R42] was issued, the high inflation hugely increase the economic value of a cable car installation, it is not considered useful to mention them in this document.

Although the above-mentioned formula is not able to explain the increase in costs that the cable car market faced in the last years, the comparative qualitative analysis among different cable car type of installation provided in [R36] and reported in *Table 7* is still consistent with the reality. It shown that the monocable cable cars are economically viable in terms of building costs, but more expensive in terms of running costs compared with other cable car, lift or tape- based systems.

Sistema *System*		Caratteristiche / norme con effetti sui costi *Features / rules affecting the costs*							
		di investimento *Building cost*					di esercizio *Running cost*		
		Complessità impiantistica *Plant complexity*	Complessità infrastrutturale *Infrastructural complexity*	Pendenza max. superabile *Maximum slope*	Altezza max dal suolo *Maximum height from ground* (m)	Accesso disabili non deambulanti *Accesso disabili non deambulanti*	Personale di terra (manovra/controllo) *Ground staff (operation/control)*	Personale di bordo *Board staff*	Personale di soccorso *Rescue staff*
Funicolare terrestre *Funicular*		M	H	M	0	Y	Y	N	N
Funivia bifune vai e vieni *To and fro cableway*	Salvat. vert. *Vertical rescue*	M	L	M	M	Y	Y	Y/N	Y
	Salvat. orizz. *Horizontal rescue*	M	M	M	H	Y	Y	Y/N	Y
Funivia monofunea moto continuo *Monocable cable-car*	Collegam. permanente e motocontinuo *Permanent link and continuous motion*	L	M	M	M	Y/N	Y	N	Y
	Collegam. temporaneo e moto continuo *Temporary link and continuous motion*	M	M	M	M	Y/N	Y	N	Y
	Collegam. permanente e moto unidirez. intermitt. o vel.variabile *Permanent link and one-way intermittent motion or variable speed*	L	M	M	M	Y/N	Y	N	Y/N
Ascensore *Lift*	Verticale *Vertical*	L	L/M	H	0	Y	Y/N	N	Y/N
	Inclinato *Inclined*	L	L/M	M	0	Y	Y/N	N	Y/N
Nastro *Tape*	Scala mobile *Escalator*	L	M	M	0	N	N	N	N
	Marciapiede Mobile *Moving walkway*	L	M	L	0	Y/N	N	N	N

Table 7-Qualitative influence of the technical rules of different system features on the building and running cost

Finally, a complete, inclusive and in-depth explanation about the cable cars description, designing, managing, operations and legislation is recently issued in [R37].

Chapter 3

3. Transport systems for the overcoming of differences in height

In order to provide a description of the technological framework that the market currently offers in terms of public transport systems for overcoming difference in height in urban context, this chapter presents a qualitative description of these systems, highlighting their strengths and weaknesses.

3.1 Inclined lift

Inclined lifts find common application as urban transport systems, in order to connect two areas of the city located at different altitudes.

The inclination of inclined lifts is normally constant, although there are models with moving floors that can be used on variable slopes. According to current legislation, the slope should be in any case between 15 degrees (27%) and 75 degrees (373%).

The cabins are equipped with an intercom for emergency communications and do not require the presence of personnel on board.

The traction takes place through a rope operated by a winch installed in the mountain station, in similar way of a vertical elevator. The vehicle moves on rails, and the maximum speed is 4 m/s = 14.4 km/h.

Inclined lifts are hectometric transport systems, which are used only for tracks long a few hundred meters. Since inclined lifts are "to-and-fro" systems, their increase in length causes a proportional penalty in terms of hourly capacity. For instance, it is mentioned that an inclined lift with a length of 400m has an hourly capacity of about 450 passengers per hour in each direction.

Figure 31-Picture of an inclined lift

Strengths	**Weaknesses**
✓Low cost of installation and maintenance	χ Straight path constrains
	χ Low flow rate
	χ Path normally with a constant slope, without concavity and convexity
	χ Relatively low top speed
	χ Hectometric application field, not usable for sections longer than a few hundred meters

Table 8-Summary table of pros and cons of an inclined lift

3.2 Funicular railway

Funicular railway is a system where two counterbalanced vehicles connected by an upper hauling rope or a rope ring, move on one or more railway-type runways.

In the double-track funiculars, which are more expensive and take up more space, each direction has its own runway; on the other hand, if there is only one track, halfway through it is necessary to create a doubling section (exchange) to allow the crossing of the two carriages. This exchange has no mobile mechanical elements, because the direction of each car is entrusted to the configuration of sliding wheels (one pair of wheels has a double rim and the other pair is flat) mounted on the carriages.

The environmental impact in terms of land consumption is relatively high, and it can be reduced by building tunnels.

The carriages are similar to the railway convoys, with the exception that in the funicular case the carriages are not motorized, since the traction is transferred to the vehicle through a rope and the motor unit is located in the upstream station. Furthermore, the flooring of the vehicle (normally "custom" engineered according to the slope of the line) is designed to be as horizontal as possible along the sloped line, in order to increase the on-board comfort; in recent years, systems with variable depth surfaces have appeared on the market, in order to allow high comfort with non-constant slopes.

Normally two carriages, or two convoys of "counterweighted" carriages, with a capacity of up to 200-300 passengers circulate along the line.

The traction is transmitted to the carriage through a hauling rope, which winds around the pulley of the engine winch, normally with a double groove, located in the mountain station. Usually, the rope runs centrally between the rails, supported and guided a few centimetres above the ground by special rollers.

Normally, the drive is guaranteed by one or more electric motors, assisted by diesel auxiliary engines which come into action in case of emergency.

The running line is made up of railroad-like tracks.

The maximum speed permitted by the norms [R39], that find application for funicular railways also, as they are rope-way plants] is 14 m/s = 50.4 km/h, and this value has been raised in the 2021 norm [R40] from 12m/s = 43.2 km/h prescribed in the 2012 normative, but the system accepts relatively low accelerations and decelerations, due to the high inertia of the system (the carriages are relatively large and heavy).

The high maximum operating speed, together with the configuration of the vehicles, which being derived from the railways can accommodate a few hundred people, allows land-based funicular systems to reach high hourly capacities, even in the order of a few thousand people per hour direction. It should be emphasized that the terrestrial funicular is a to-and-fro system, therefore, other factors being equal, the capacity decreases linearly with the length of the route.

The altimetric profile of the route can have a variable slope, but convex profiles (with convexity downwards) are preferable: if the profile has a concave upwards, the rope tends to rise from the ground, and accompanying rollers are necessary to avoid rope lifting. In order to maintain the altimetric profile consistent with the desired one, it is possible to build civil works such as tunnels, bridges and viaducts.

The funicular can overcome very steep gradients: the steepest funicular in the world was inaugurated in 2019 in Schwyz, Switzerland, and reaches a gradient of 110%.

The stations have dimensions and length compatible with those of the carriages, if these are very long to accommodate numerous passengers and therefore increase the hourly capacity of the system, there will be stations with very long embarkation and disembarkation platforms.

From an energy point of view, the funicular features high efficiency and excellent performance, since the weight of the car going downhill supplies part of the energy necessary for the carriage to go uphill in the opposite direction. In the past decades water funicular systems were common, in which the carriages had a tank in the lower part that could be filled with water to vary their weight and ensure the balance of the system: in the case of a loaded carriage going uphill and a carriage going downhill empty, the tank of the latter was filled with water to increase its weight and allow the other carriage to climb. In this system, traction was therefore guaranteed by the weight of the carriage going downhill (connected by a rope to the one going uphill) without installing an engine unit.

Figure 32-Picture of a funicular ropeway, in the switch area

Figure 33-Picture of the rails of a funicular railway, with deflection rollers in the foreground

Strengths	**Weaknesses**
✓High speed	χ High installation cost in case of surface line, very high installation cost in case of line in tunnels
✓High hourly capacity	χ Not suitable for concave profiles
✓Suitable for long paths	χ Long construction times due to the need to expropriate many areas and/or to carry out expansive tunnel excavations
✓Very low energy consumption and consequent low emissions	χ High maintenance costs
✓Limited number of operators and consequent low operating cost	χ Stations with large footprint and noisy
✓Very high functional reliability	
✓Insensitivity to atmospheric phenomena	
✓Possibility of making curvilinear lines and intermediate stops	
✓Ability to overcome high differences in high	
✓Vehicles stop completely at the stations	

Table 9-Summary table of pros and cons of a funicular railway

3.3 Cog railway

One of the main limitations in terms of utilization of traditional railway systems is the slope: in fact, the steel-steel contact between rails and wheels guarantees high energy performance due to the limited friction, but limits the slope of the track to a few tens of points per thousand to avoid to exceed the adhesion limit. In fact, traditional railway lines have a gradient limit at operating speeds of 35‰; this limit can be overcome by limiting the speed, and slopes in the order of 70‰ - 80‰ can be reached.

Beyond this value, a traditional railway system does not guarantee the steel-steel adhesion between wheel and rail. It is therefore possible to exceed this limit only by engaging the cog, with which it is possible to reach a slope of 374‰ (slope record).

The cog railway is able to overcome steep slopes because it is not bound by adhesion limits: the vehicle hooks up through one or more toothed wheels mounted on board of the vehicle itself to a toothed track, normally placed between the two running tracks.

There is no international regulation on the rack railway, but the reference regulation is the Swiss "*Disposition d'exécution à l'ordonnance sur les chamin de fer*", which links the maximum operating speed to the slope: the greater is the slope, the slower is the speed. For steep slopes the speed is therefore very low: it goes from a maximum speed of 10m/s = 36km/h relative to a slope of 70‰ to a minimum speed of 3m/s = 10.8km/h relative to a slope of 370‰.

The racks are fully integrated with the railway line: the carriages use the ordinary railway seat and, when necessary, engage the cog. A carriage that can travel both traditional sections and very sloping sections with a rack should in any case have a floor surface within acceptable inclination limits with respect to the ground in terms of comfort.

Traction is provided by locomotives powered by diesel engines or by electric motors which receive electricity from electric lines running parallel to the railway line (similar to electric railways). Unlike the previously described solutions, in which the engine is located in one of the stations, in the case of the rack railway the engine is located on the vehicles.

Figure 34-Picture of the cog railway Genova Principe- Granarolo

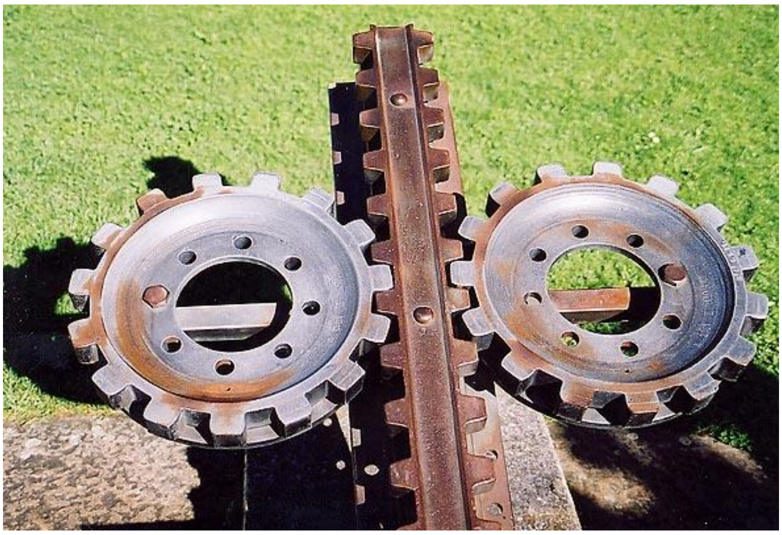


Figure 35-Picture of the cogwheel- toothed track coupling

Strengths	**Weaknesses**
✓High speed	χ High installation cost in case of surface line, very high installation cost in case of line in tunnel
✓High capacity	χ Relatively high impact on the ground, similar to a railway
✓Suitable for long tracks (there are no theoretical limits about the track length)	χ Long construction times due to the need to expropriate many areas and/or to carry out expansive tunnel excavations
✓Limited number of operators and consequent low operating costs	χ Maximum speed inversely proportional to the slope overcome
✓Very high functional reliability	
✓Insensitivity to atmospheric phenomena	
✓Possibility of making curvilinear routes and intermediate stops	
✓Interchangeability with the traditional railway network	

Table 10-Summary table of pros and cons of a cog railway

3.4 Automated people movers (APM) with traction by rope and with vehicles with detachable grip

Automated People Movers (APM) are fully automatic public transport systems normally used on a small scale, in areas such as amusement parks or airports, even if they have found an -albeit infrequent - application also in urban areas: it is mentioned by way of example the “Metro mover” system of Miami-Florida. In general terms, traction can be provided to the vehicle via electrification of the line, or via a rope.

Experience with rope-operated automated systems for public transport (Automated People Movers, APM) is relatively limited, as not many systems have been built to date. However, their importance today is much more significant than in the past due to their considerable competitiveness in terms of energy consumption (in terms of kWh/pass/km), since they do not require an on-board engine nor, consequently, a transmission mechanics to the wheels or a structure suitable for supporting the relative loads: the transmission of power is left to a mechanical component with little inertia to motion, such as a steel rope. Therefore, these systems are also highly attractive from an environmental point of view, since the engine and the related noise emissions can be confined to a protected area, the station. On the other hand, it should be emphasized that the station area is not free from noise pollution caused by the operation of the motor unit.

As previously reported, the urban uses of cable-operated automated people movers are still rare, but not non-existent: the "Mini Metro" system of Perugia has been active since 2008, which connects the terminal stations of "Pian di Massiano" and "Pincetto" through a route just over 3km long with 5 intermediate stations.

In this recently developed system, the vehicles move on a rail and are clamped to a pulling rope which guarantees their traction.

The vehicles have a capacity of about 50 passengers each, and the velocity at full speed is about 6 m/s = 21.6 km/h. The runway is of the railway type and is double: in this way vehicles in opposite directions can cross at any point of the track, but against the line its impact on the ground increases.

It is a continuous system (it is not a to-and-fro system), in which numerous vehicles can follow one another in line. For this reason, the hourly capacity can be very high (even higher than 5,000 people/hour in each direction), and it does not depend on the length of the route.

With regard to the line, significant gradients can be tackled, the route can be curvilinear and there can be numerous intermediate stops, which however do not affect the hourly capacity of the system.

Figure 36-Picture of the Metro Mover installation in Miami-Florida

Figure 37-Picture of the Mini Metro installation in Perugia (Italy)

Strengths	***Weaknesses***
✓Very high hourly capacity, not dependent by the length of the route	χ High installation cost in case of surface line, very high installation cost in case of line in tunnel
✓Insensitivity to atmospheric phenomena	χ Relatively high impact on the ground, similar to a railway one χ
✓Possibility of making curvilinear paths	χ Long construction times due to the need to expropriate many areas and/or to carry out expansive tunnel excavations
✓Possibility of making numerous intermediate stations	χ High operating costs χ High maintenance costs

Table 11-Summary table of pros and cons of automated people movers (APMs) with traction by rope and with vehicle with detachable grip

3.5 To-and-fro ropeway

The to-and-fro ropeway derives from the terrestrial funicular, with the difference that the runway is aerial and the tracks are therefore replaced by the carrying ropes, which in recent applications are two for each direction of travel.

Similarly to all the to-and-fro lifts, also for the double-cable aerial ropeway the hourly capacity is directly proportional to the payload of the vehicles and inversely proportional to the length of the line.

Since the plant is to-and-fro, the two vehicles, which can have a capacity higher than a hundred people, are bound to the two opposite sides of the hauling rope (which, by shifting, guarantees the motion of the carriages) go back and forth between the upstream station and downstream one.

If the line profile does not allow a single span and requires the presence of intermediate towers, the speed is limited to 10m/s = 36km/h.

Line towers can be very high (even over 100m) and, therefore, they have a high environmental impact; however, this system allows a large distance between supports with a consequent easy overcoming of critical areas, natural and/or artificial obstacles. The line, being overhead and not having a fixed impact on the ground, has a limited "continuous" impact: with the exception of towers and station, this system does not impact the ground. In the event of a blockage of the lift, the evacuation of passengers from the vehicles takes place via a special auxiliary vehicle.

The footprint of the stations depends on the size of the vehicles, but typically the stations have a high impact on the ground and a difficulty of insertion due to their size. Furthermore, since the engine group is located in one of the two stations, the noise pollution associated with the stations is not negligible.

Due to the size and acoustics of the stations, there is limited use of this technology in urban areas. As an example of urban application, it is mentioned the "Roosevelt Island" aerial cableway in New York City, which connects Roosevelt Island with the Upper East Side of Manhattan parallel to the Queensboro bridge.

The layout of the line is bound to be completely straight, and intermediate stations are not possible.

The construction costs are significantly higher, with the same hourly flow rate and other boundary conditions, compared to those of other aerial systems.

Figure 38-Picture of an aerial to-and-fro ropeway

Figure 39-Picture of the aerial to-and-fro ropeway "Roosevelt Island" in New York City- NY

Strengths	***Weaknesses***
✓Possibility of flying over the underlying town with limited impact on the ground	χ Limited hourly capacity. Moreover, the hourly capacity is inversely proportional to the length of the line
✓Limited sensitivity to atmospheric phenomena (especially wind)	χ Cumbersome stations that are difficult to integrate into the urban fabric
✓Possibility of installing a limited number of towers	χ High installation cost
✓Limited energy consumption	
✓Limited ordinary and extraordinary maintenance costs	
✓Limited number of operators and consequent low operating costs	
✓High functional reliability	

Table 12-Summary table of pros and cons of aerial go-and-fro ropeways

3.6 Continuous circulating monocable traditional ropeway

The traditional monocable gondola lift is an aerial cableway system with vehicles having a capacity of 8÷10 passengers which follow one another with intervals of a few seconds (10÷20s). The high capacity, which can even exceed 3,000 passengers per hour per direction, is therefore achieved through a system with vehicles having relatively low capacity, but which transit with very high frequency. In this way, waiting times are very short (in the order of a few seconds).

Furthermore, the described system is a continuous system, in which the hourly capacity is independent by the length of the route, but depends only by the capacity of each vehicle and on the time interval between two successive vehicles (therefore on their number).

The vehicles are equipped with seats, but, as they are not normally electrified, they are typically not air conditioned and ventilated.

During the station equipment, the vehicles travel at reduced speed, around 0.3 m/s, to allow passengers to get on and off. It is therefore underlined that, during the embarkation and disembarkation phases, the vehicle is not stationary, but continues its motion, albeit at low speed; this feature can be limiting in terms of convenience and universal use of the system. The vehicles are then accelerated, and clamped to a carrying-hauling rope, reaching a speed of up to 6m/s = 21.6 km/h in line.

The towers have the function of supporting the cables to which the vehicles are clamped, and they are normally made of steel pillars (since the stresses and heights related to this type of support are lower than the ones related to to-and-fro ropeways, whose supports are typically made of reticular beams). At the top of the towers, it is installed a head with a system of rollers consisting of several balancers formed by 2 to 4 rollers each, with the function of supporting and routing the rope. The rocker arms, arranged at the ends of the muzzle, are not rigid in movement, but adapt to the deflection angle of the rope at each of its variations, preventing any derailment. The rollers are made of highly resistant aluminium and they maintain the characteristics of lightness typical of the material.

The towers normally have a height of between 10m and 50m, therefore they are smaller than the supports of a to-and-fro cable car, but they are more numerous, as the length of the spans does not normally exceed 150-250m. However, the impact on the ground of the technical solution described in this paragraph is very limited; for this reason, traditional mono-cable gondola lifts have found application in urban contexts, particularly in South America (e.g., the above-mentioned located in La Paz-Bolivia and in Medellin-Colombia), where the need to overcome densely built-up areas such as the favelas required to minimize the impact on the ground of the system.

It should be noted that this system defines a ground overflight constraint for a strip approximately 15 m wide; in this band there are no particular limitations as regards the agricultural use of the land but there are constraints for building, and access must be allowed for any online rescue, if this were to take place by lowering the passengers.

The stations have important dimensions, even if they typically have a lower height than the to-and-fro cable cars ones. Furthermore, the motor group is housed in the driving station (which can be the upstream or downstream station), which is therefore not exempt from the production of noise pollution.

Historically, the traditional monocable cableway developed by looking at the needs of mountain transport, as a lift for skiers and sportsmen. This has led, together with the first mentioned way of embarking and disembarking passengers (which, taking place with the vehicle in motion, albeit at a very low speed, can present problems for passengers with reduced mobility), to a reduced reliability of the system, which frequently requires maintenance. The recent numerous urban applications of this technology, which require a much higher number of operating hours than mountain transport and demand high levels of reliability and very low probability of plant downtime, are driving technological developments towards an increase in performance in terms of reliability

Figure 40-Picture of an urban traditional monocable gondola

Figure 41-Picture of the urban traditional monocable gondola linking Barcelona with Montjuic, with emphasis on towers

Strengths	***Weaknesses***
✓Medium-height overflight of the town below, with reduced encumbrance on the ground	χ High number of line towers
✓High hourly capacity, which does not depend by the length of the line	χ Limited vertical maximum clearance to allow passengers to descent to the ground in the event of a system failure
✓Very short waiting time (a few seconds)	χ Line layout constrained to be straight
✓Low installation cost, as: - civil works are punctual, in the tower installation areas; - the weight and the cost of the material is lower than other systems (eg rail based) - the construction time (and the related labor cost) is less than that of solutions with heavier infrastructure	χ Greater sensitivity to wind and weather conditions
✓Reduced energy impact	χ High maintenance cost
✓Ability to overcome high differences in heigh	χ Reduced reliability
	χ Large footprint and noisy stations
	χ Impossibility to define stretches in tunnels

Table 13-Summary table of pros and cons of monocable traditional gondola

3.7 Bicable gondola with detachable grip vehicles with one or two carrying ropes

This type of system combines the strengths and weaknesses of the bicable aerial gondola and the detachable gondola. In fact, these are systems equipped with fixed carrying ropes on which high-capacity vehicles slide, clamped to a ring of hauling rope. In particular, this technology allows very high capacities (even in the order of 5,000 people/hour in each direction) with vehicles having a capacity of up to 40 people. Typically, the vehicles do not have seats, and the passengers travel "standing up"; which, together with the fact that non-electrified vehicles do not allow air conditioning and ventilation, lowers the level of comfort.

The high hourly capacity is therefore achieved thanks to vehicles with high capacity (higher than that of mono-cable gondola vehicles) and relatively high frequency (slightly lower than that of mono-cable gondola lifts), in the order of a few tens of seconds. Similar to single-cable technology, the double-cable gondola lift with detachable vehicles is also a continuous transport system whose hourly capacity is not linked to the length of the line. Furthermore, this system allows high overflights with few lines supports, but normally requires the viability of the underlying line as the evacuation of passengers from the vehicles in the event of a breakdown typically takes place by lowering passengers to the ground.

However, the impact of the line on the ground is modest, since the supports, although larger in size than those of the single-cable gondola supports, are smaller in number. The stations, on the other hand, are large and bulky.

The presence of a greater number of ropes compared to single-rope technology and of supporting ropes ensures that this system is less sensitive to atmospheric events, in particular to gusts of wind.

Figure 42-Picture of a bicable gondola with detachable grip vehicles with two carrying ropes (1)

Figure 43-Picture of a bicable gondola with detachable grip vehicles with two carrying ropes (2)

Strengths	***Weaknesses***
✓Very high hourly capacity	χ High installation costs
✓Relatively short wit times	χ Large footprint of the stations
✓Possibility to fly over natural and anthropic obstacles at high altitude	
✓Less sensitivity to the wind compared to the monocable gondola	
✓Limited number of towers	

Table 14-Summary table of pros and cons of bicable gondolas with detachable grip vehicles with one or two carrying ropes

Chapter 4

4. Description of CableSmart system

In the previous chapter an overview, of the traditional urban transport plant to the overcoming of differences in high was provided, and it was underlined as they are able to match only partially the needs and the will of the urban passengers, and the constrains imposed by the urban fabric.

In particular, ropeways with detachable grip have found traditional use and have been developed in the field of mountain tourist transportation. According to their functional needs, the traditional vehicles were designed for the transport of sportsmen (normally skiers or hikers), having the objectives of personal comfort and safety only in the background: vehicles are in fact suitable for journeys of few minutes, and normally, due to lack of electrical power on board, they cannot be video surveillance and/or air-conditioned Also, the traditional cable car technology does not allow curvilinear paths, the trajectories are therefore bound to straight segments; and does not allow sections in tunnel, due to the considerable size of the stations and to the large angle of oscillation of the vehicle clamped to the rope, what increases the size of the boundary shape.

Due to the above-mentioned limitations, detachable grip ropeways do not have found widespread use in the context of urban public transportation, despite the undoubted merits that they present: in fact, there are still few examples of application of traditional cable cars to solve purely urban mobility needs, mostly (as written in the previous chapters) concerning South American metropolises with very different needs from the European cities.

Figure 44-Picture of the urban public transport system through traditional monocable gondola in Medellin- Colombia

In general, the technological limitations that have not allowed the traditional ropeway technology of expanding into the urban transport sector are:

i) Non-electrified vehicles do not allow ventilation, heating and air conditioning systems;

ii) Vehicles do not stop completely at the station, avoiding the comfortable load and unload of passengers with mobility difficulties, of with baggage;

iii) The stations have a large size and a high complexity, so it is difficult to integrate them in the urban fabric;

iv) Traditional ropeway technology allows only straight trajectories, not allowing curvilinear sections.

The overcoming of the above-mentioned technological constraints of the traditional cable cars is induced by recent technological advances in the automotive field and in particular of "smart" and electric mobility, which has made it possible to redirect towards urban mobility the cableway transport industry, until recently relegated to tourist/mountain transport. In this context, the hybrid CableSmart system originates from the grouping of detachable grip cableway. This technology allows to define stretches of multi-kilometric length, with high gradients (up to 100%=45 degrees), and it is particularly suitable for overcoming natural and/or urban obstacles.

This innovative transport systems CableSmart retains the easiness of overcoming gradients and obstacles with a low impact on the ground, and a very low energy consumption, but it allows to overcome the constraints of traditional ropeway technology thanks to the joint adoption of cableway technologies and derived smart railways and automotive technologies.

In particular, CableSmart technology is a hybrid system, where the propulsion can be transmitted to the vehicle in two alternative ways:

- Through a rope, in a similar way to a traditional cable car. In those segments, the vehicle is clamped to the hauling rope, and the movement takes place thanks to the rope. The ancillary systems and thermal comfort inside the vehicle are however guaranteed by the batteries mounted on board of the vehicle.
- Through motorized wheels mounted on the top of the vehicle, which are powered by batteries and supercapacitors mounted on the vehicle; in particular, supercapacitors, that have high power density and that have a long life in terms of charge-discharge cycles provide the energy for the acceleration of the vehicle, while lithium batteries provide the energy for the cruise scenario. In these segments, the system operates in similar way than a suspended monorail.

Therefore, each vehicle travels along segments of line where it is clamped to one or more carrying-hauling ropes and stretches in which it is supported by one or more suspended monorails.

The described technology allows to reconcile the strengths of the traditional gondola, such as the ability to easily overcome large differences in altitude and natural obstacles with low impact on the ground of the system, with the strengths characteristic of a transport system on suspended monorail, such as the easy adaptation to the urban fabric, the possibility of having a curvilinear paths and the presence of slender intermediate stations (similar in size to a bus stop) that can be easily integrated into the urban context and environment.

Operating mode	
On rope	***On motorized wheels***
✓Possibility to overcome high differences in high	✓Adaptation to the urban fabric, and possibility to have routes with reduces curvature radii
✓Possibility to easily overcome natural and anthropic obstacles	✓Small stations, with reduced size and complexity
✓Low impact to the ground	

Table 15-Comparison between the features in the two operation modes of the hybrid rope-motorized wheels transit system

The electric power supply of the vehicles, jointly with their construction characteristics, allows them to run fully independently when they are not clamped to the rope; and the easy load and unload of passengers from vehicles, completely stopping in the station, close to protected gates (similar to a vertical elevator) with the consequent comfortable utilization by passengers with pushchairs and bicycles or by passengers with reduced mobility.

Furthermore, hybrid CableSmart systems is able to guarantee video surveillance, air conditioning and the installation of a screen in which the passenger can consult the itinerary data, as well as the customization of his own route, for instance by choosing whether to stop at an intermediate station or continue the journey. Thanks to the limited capacity of each vehicle (6-10 passengers), to video surveillance, and to the easy management of passenger flows, this system allows easy adaptation to the legislation concerning interpersonal distancing in the event that problems similar to those induced by the Covid-19 crisis will be faced.

Traditional cable car	***Hybrid CableSmart system***
✓Allows the overcoming of high differences in high	✓Allows the overcoming of high differences in high
✓Allows the overcoming of natural and anthropic obstacles	✓Allows the overcoming of natural and anthropic obstacles
✓Has low impact to the ground	✓Has low impact to the ground
χ Designed for sporty passengers, vehicles are not adequately electrified and they do not allow the adoption of ancillary systems (air conditioning, video surveillance…)	✓Designed for urban passengers, has electrified vehicles allowing integration of air conditioner, monitors and video surveillance systems
χ Vehicles proceed in the station at reduced speed, even in the phase of loading/ unloading of passengers	✓The vehicle completely stops in the stations, allowing the easy load and unload of passengers with baggage or bicycles, or of passengers with mobility difficulties
χ Allows only straight trajectories	✓Thanks to the possible design of curvilinear paths, it enables its efficient integration into the urban fabric
χ The stations are big-sized and with high level of mechanical complexity, so they produce acoustic pollution	✓Has small and easily integrable stations
χ Limited hours of use per year and high maintenance cost	✓Low maintenance costs and hours of operation per year consistent with the needs in urban mobility sector

Table 16-Comparison between strengths and weakness in traditional cable car system and in hybrid CableSmart system

4.1 Line

About the line, the hybrid CableSmart system can have two kinds of segments:

- On rope. Line suitable for the overcoming of high difference in height or natural or anthropic obstacles with very low impact to the ground;
- On rail. Line allowing high winding of the path, with the possibility to define curves with low radius.

Figure 45-Sketch of an installation of a hybrid rope-motorized wheels system: the segment through rope, suitable to high sloped line, is indicated in red, while the segment in rail, allowing the definition of curves with small radius, in indicated in blue.

Line- Cable car stretches

In rope segments, the hybrid CableSmart system operates in the same way as a traditional gondola: motion is in fact guaranteed to the vehicle by its clamping to one or more carrying-hauling ropes.

Regarding the number of cables, the hybrid system can be designed with one or two hauling ropes. The bicable hybrid system, which provides for the vehicle to be clamped to two hauling ropes, involves significantly higher costs with greater vehicle stability in strong winds conditions.

Monocable	**Bicable**
Lower installation costs	Higher installation costs
More exposed to strong swings in case of critical conditions in terms of wind	Increased wind resistance in case of critical conditions

Table 17-Summary comparison between monocable and bicable technology, related to the hybrid system

The position of the line tower, that -jointly with the stations- are the only points of ground impact of the line- should be defined minimizing their environmental impact and maximizing their integration with the surrounding environment, of course with the constrain to be compliant with the current legislation

Normally, the towers of the system are made in galvanized steel; and they are made up by a central stem, by a crossbar, by a device for lifting the rope, by the roller assembly, and by electrical equipment such as anemometers (positioned in areas of greater wind exposure).

The towers and roller assembly can be of three types:

1) Compression, in which the rope is held in a low position;

Figure 46-Picture of a compression tower

2) Support, in which the rope is lean in high position

Figure 47-Picture of a support tower

3) Support-compression, that can act both as support as a compression roller

Figure 48-Picture of a support-compression tower

Similarly to a ropeway system with temporary clamping, when the vehicle enters the station its clamp opens and the vehicle decouples its kinematic quantities from those of the rope.

In the station, it moves through the motor wheels installed above the suspension, in a similar way to what happens in the rail segment.

Line- Rail Stretches

Vehicles are equipped with motorized wheels installed on the bogie, that can provide motion to the vehicle. In these segments, the vehicle is not clamped to the rope and it rum on a fixed runway, in a similar way than a suspended monorail system. The electric motors integrated in the motorized wheels are powered by the battery system located on board the vehicle. The maximum speed reachable in the sections by rail is around 4 m/s.

In these line segments, the system is not limited by the constraints typical of a traditional ropeway system, but has the typical strengths and weaknesses of a wheel-based system. In particular, it is possible to define curvilinear and sinuous paths, with curves having a radius minimum around 3m, if travelled at reduced speed.

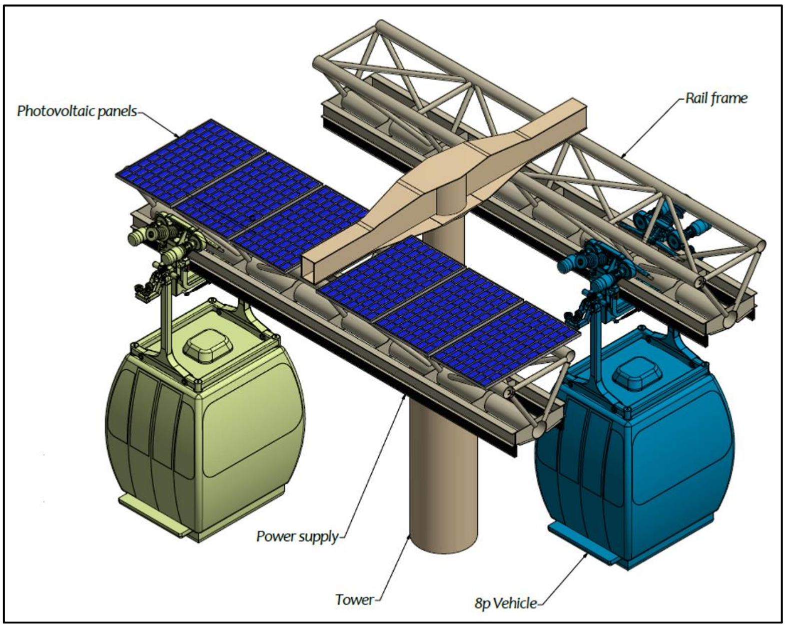


Figure 49-Technical drawing of a treat of hybrid system, in its rail segment. Over the rail, it is possible to install solar panels to provide energy to be directly used or to charge the batteries and the supercapacitors located in the vehicles and providing energy for their motion

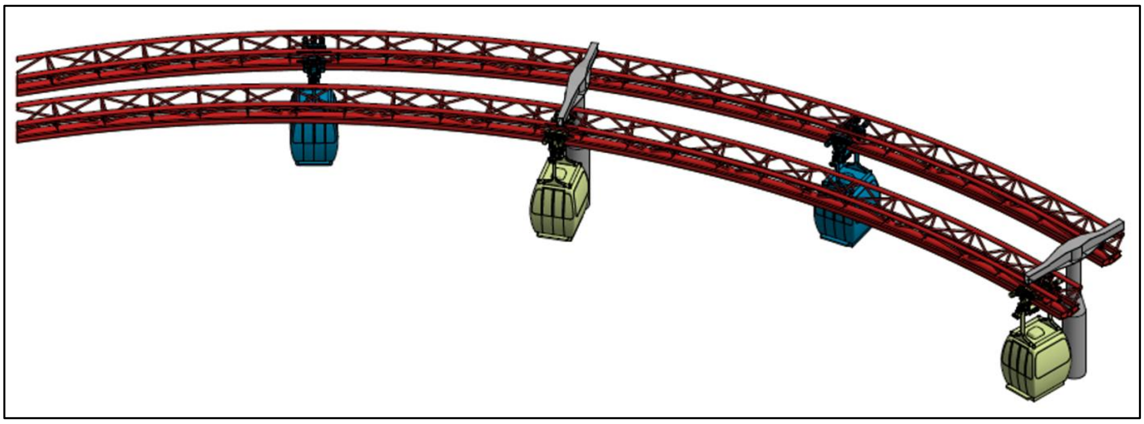


Figure 50-Technical drawing of a treat of hybrid system, in its rail segment. In this type of segment, it is possible to design paths with relatively low curvature radius

It emphasized that the rail required by the hybrid CableSmart system is significantly lighter (a linear weight of approximately 300 kg/m is assumed) compared with a traditional monorail one. The loads of the vehicles of the hybrid system, derived to the gondola ones, are in fact an order of magnitude lower than the weight of a vehicle of a traditional monorail.

4.2 Vehicles

The vehicle is composed by grip-bogie, suspension and cabin, whose internal dimensions allow to house typically 6 to 10 sitting passengers. It is equipped with: battery pack and supercapacitors for energy store, lamination system, air conditioning, communication and control systems; self-propelled and clamp to grip it to the carrying-hauling rope.

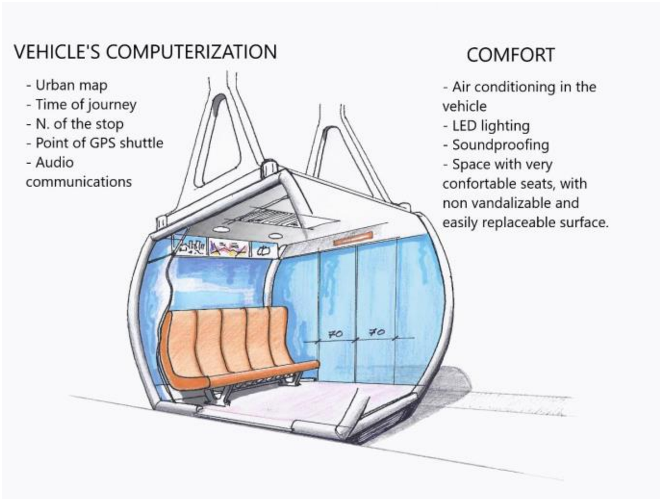


Figure 51-Sketch of a hybrid vehicle

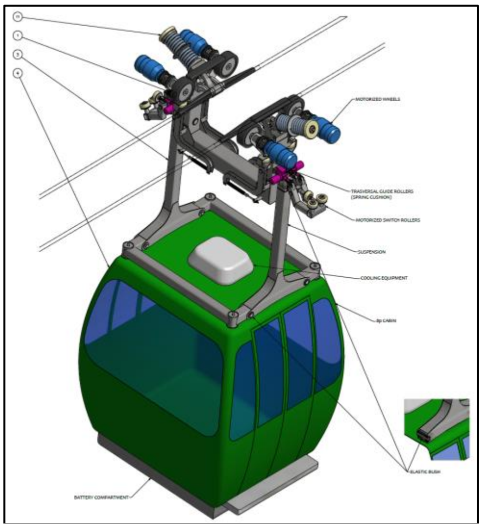


Figure 52-Technical drawing of a hybrid vehicle (1)

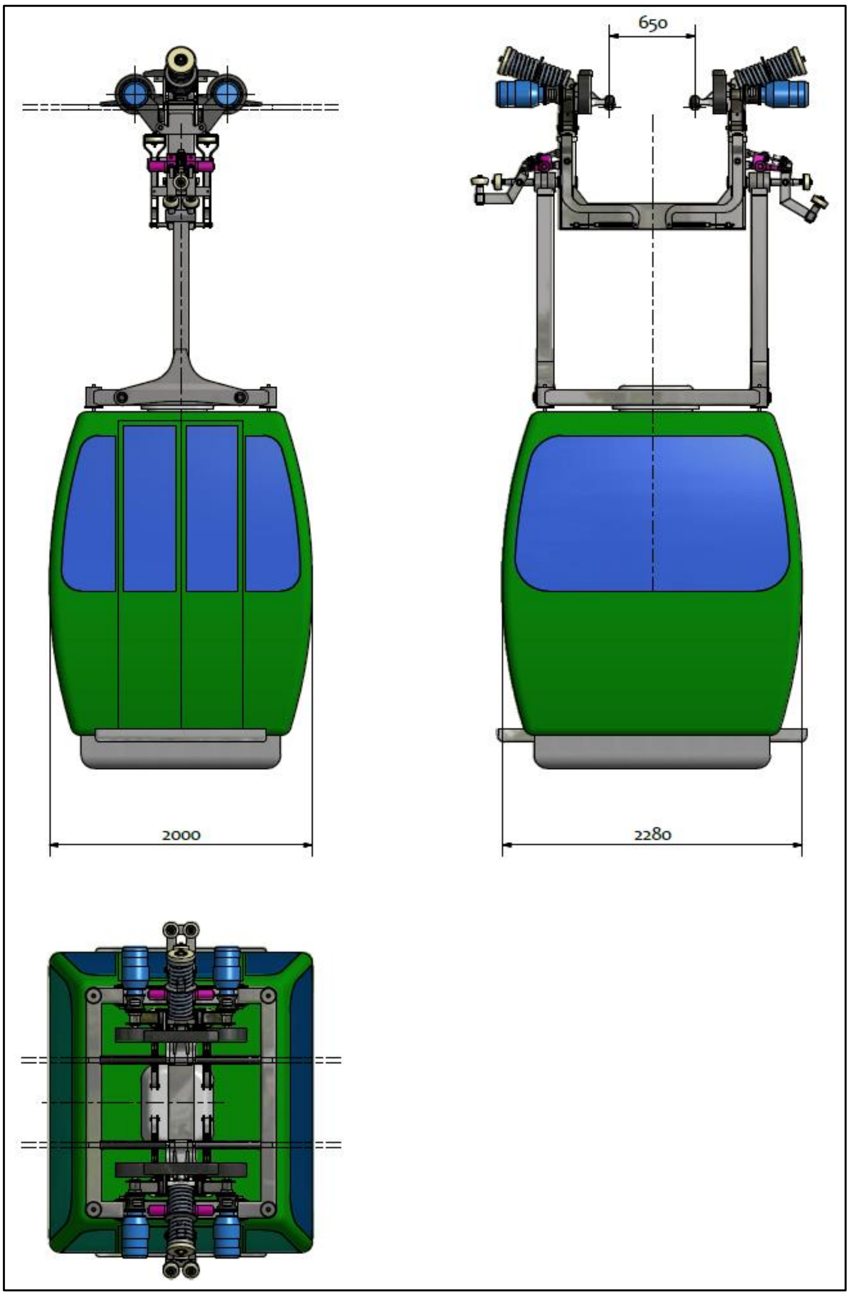


Figure 53-Technical drawing of a hybrid vehicle (2)

Grip- Bogie

The grip-bogie, is composed of one (if the system is monocable) or two (if the system is bicable) parts each of which includes two rubber motorized wheels; two independent electric motors to supply power to the wheels; one clap to grip the vehicle to the carrying-hauling rope.

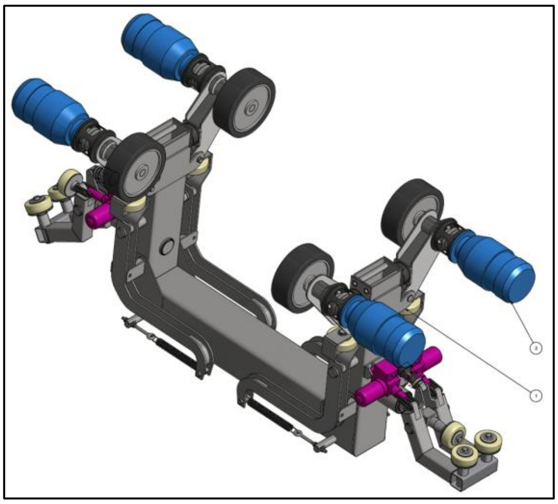


Figure 54-Technical drawing of the grip bogie of the hybrid vehicle (1)

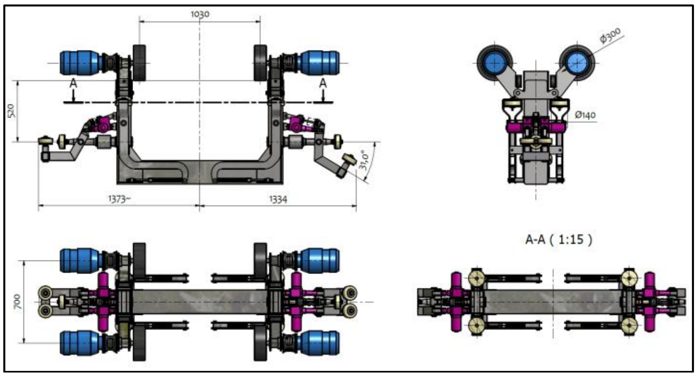


Figure 55-Technical drawing of the grip bogie of the hybrid vehicle (2)

Suspension

The suspension transfers the load from the cabin to the grip, it is hinged at the grip height. In this way the vehicle remains in a horizontal balance independently from line slope. In addition, it houses ducts for wires passage from cabin to bogie.

Cabins

The cabin can typically host 6 to 10 passengers seated, it has interior height and door headroom above 2.20 m, it can house luggage with big dimensions and bulky object like bicycles and wheelchairs for people with handicap. Battery pack and supercapacitors are housed in the bottom of the cabin. Inside the cabin, audio-video communication system, the keyboard for user system interface and video surveillance are located.

Battery pack and supercapacitors

Batteries and capacitors are hosted in the bottom part of the cabin.

During the cable segments, they do not intervene in the energy balance as regards the movement of the vehicles (since this is guaranteed by the attachment to the carrying-hauling cable), but only as regards the ancillary systems of thermal comfort, safety and info-tainment. On the other hand, in the rail segments, as well as supplying energy for the ancillary systems, batteries and supercapacitors allow the movement of the vehicles. In particular, supercapacitors, that have high power density and that have a long life in terms of charge-discharge cycles provide the energy for the acceleration of the vehicle, while lithium batteries provide the energy for the cruise scenario.

Charging of energy storage systems takes place for a small part thanks to direct connection with photovoltaic panels installed on the surfaces of the vehicle, and for the most part through sliding contacts located in the stations.

For particularly critical rail segments in terms of length, and for climatic conditions that require high energy for vehicle comfort, it is possible to define sliding contacts along the line, in the rail sections, in order not to over-design the capacity of the accumulation (which would cause a huge increase in the weight of the vehicles with a consequent increase in their inertia and a worsening of the energy performance of the system) and to guarantee having energy for motion and the comfort of the vehicles.

4.3 Stations

Traditional detachable grip gondola technology allows vehicles to decelerate at the station entrance, to move at reduced speed inside the station and to accelerate when leaving it. When the vehicle is not clamped to the rope (unplugging its kinematic characteristics to those of the rope, constantly moving at line speed, typically 5-6m/s) it advances thanks to the contact with a set of tires mounted in the station and connected to each other through belts, which receive motion from the rope and transfer it through contact.

Since these tires move at different speeds, they allow acceleration and deceleration of the vehicle, bringing it to the speed of the rope during the acceleration phase and slowing it down to low speeds when entering the station.

Figure 56-Detail on the tires mounted on the stations of traditional cable-car plant, that trigger the motion to the vehicle, allowing it to change its speed in the stations

Instead, since the vehicles of the hybrid CableSmart system are self-propelled, their motion in the stations is guaranteed by the motorized wheels mounted on board the vehicle itself. So, the stations are significantly slimmer than the traditional ones, as the complex above-described mechanisms for the movement of vehicles in the stations are not present. The hybrid CableSmart system thus allows a considerable simplification in terms of station components, defining a slimmer and not noisy station, that can be easily integrate inside the urban fabric.

Thanks to its station functionality, the hybrid CableSmart system therefore makes it possible to overcome the limits of the traditional ropeway technology, allowing:

i) High system reliability and reduced maintenance costs. In traditional technology, when a failure occurs in one of the countless devices dedicated to the movement of vehicles in station, the entire plant is stopped, with repercussions on the performance of the whole line. The hybrid system greatly reduces the complexity of the station, significantly reducing the probability of plant failure.
In addition, traditional systems need to frequent and expensive maintenance (3 man-hours of maintenance are considered for each hour of system operation), to monitor the degradation and possibly replace the complex mechanisms made up of wheels and belts that allow the movement of vehicles in the station. The hybrid system, in which the vehicle is self-moved at the station, greatly reduces the complexity of the system and the need for maintenance;
ii) Reduction of the energy impact of the plant. In traditional technology, the stations are highly energy-consuming elements due to absorption energy of the complex movement system. The hybrid CableSmart system allows a strong reduction in terms of power consumption by eliminating devices in the stations dedicated to the movement of the vehicles;
iii) Complete stop of the vehicle in the stations, allowing the comfortable loading in and unloading from the vehicle by passengers and allowing full usability of the transport system also for passengers with reduced mobility. At the station, the vehicle completely stops its run for a few seconds, automatically opens its doors, simultaneously with the platform doors, allowing boarding and landing of passengers in a similar way to an elevator, after, vehicle doors close and it accelerates.

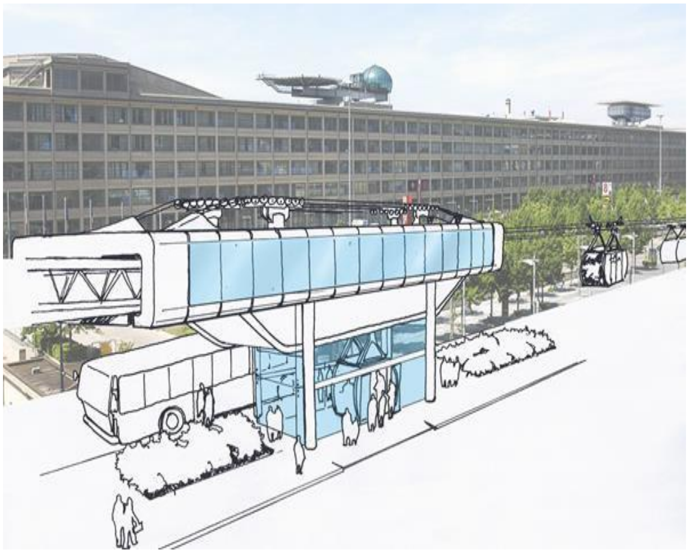


Figure 57-Sketch of a station on hybrid system

Chapter 5

5. Normative framework

The reference normative for the design of C-APMs is made up of the UNI/TR 11735 document: "Guidelines for the design of fully automated people transport systems with cable traction [R1]. As highlighted by the title, the standard aims to present guidelines for the design of the system which can be the basis for drafting a Technical Specification but does not in itself constitute a specific regulation.

In this chapter, an overview about the Guidelines, the European legislation and the Italian one is provided. As regards the operational design of the rope-borne part of the rope-self propelled hybrid system, since it is completely similar to a gondola lift when it is clamped to a rope, it must comply with the in-force cable car legislation, collected in the following chapters.

On the other hand, as regards the regulatory framework of the hybrid system in the rail segments, the regulations concerning self-driven cars and railway systems were assessed. So, an overview about the regulation for self-driven cars and for railways and subways is mentioned, with the objective to underline the aspects of similarity and difference between the technology described in this Ph.D. thesis and the other cited transport systems.

5.1 Guidelines for fully automated cable driven passenger transport system

The guidelines mentioned and described in this chapter deal, in a systematic and coordinated manner, with the requirements, general criteria and modalities for the engineering and design of fully automated cable driven passenger transport systems.

The purpose of the guidelines is to outline a methodology for the engineering and design of new fully automated, fully reserved[2] or overhead passenger transport systems, also recognized in the literature as APM (*Automated People Movers*), with particular reference to cable -driven systems (C-APM).

Such guidelines are aimed at outlining the procedural principles to be referred to for the design of a fully automated cable-driven passenger transport system named C-APM.

The aim of these guidelines is thereafter to provide the service specificities of an automatic transport service in an urbanised or heavily man-made environment, not for sports or recreational use, thus excluding typical transport services for mountain areas and theme parks.

In such urban environments, there are therefore various aspects and regulatory issues - legislative and technical standards - for the design not always peculiar to traditional ropeways, which were originally conceived for other environments. The possibility of transporting accessory elements, access by all kinds of people - including those with walking, visual or acoustic difficulties - is therefore contemplated, according to the regulations in force relating to the latter, referred to in the guidelines on occasion.

What is described does not overlap or contradict the existing technical standards, however - as shown in such guidelines - it expands on them in order to guarantee accessibility to the general public, provide for escape routes and related technologies aimed at service quality, energy efficiency and safety, also by the staff, remotely located in the appropriate control rooms.

The following Italian legislation reports the guidelines for fully automated cable driven passenger transport systems.

[2] It is therefore rendered suitably inaccessible to accidental or deliberate intrusion.

1	Terminology	UNI EN 1907	Terminology
2	General requirements	UNI EN 12929-1	Requirements for all installations
		UNI EN 12929-2	Additional requirements for reversible bicable aerial ropeways without carrier truck brakes
3	Calculations	UNI EN 12930	Calculations
4	Ropes	UNI EN 12927-1	Selection criteria for ropes and their end fixings
		UNI EN 12927-2	Safety factors
		UNI EN 12927-3	Long splicing of 6 strand hauling, carrying hauling and towing ropes
		UNI EN 12927-4	End fixings
		UNI EN 12927-5	Storage, transportation, installation and tensioning
		UNI EN 12927-6	Discard criteria
		UNI EN 12927-7	Inspections, repair and maintenance
		UNI EN 12927-8	Magnetic rope testing (MRT)
		UNI EN 12385-8	Stranded hauling and carrying-hauling ropes for cableway installations designed to carry persons
		UNI EN 12385-9	Locked coil carrying ropes for cableway installations designed to carry persons
5	Tensioning devices	UNI EN 1908	Tensioning devices
6	Mechanical devices	UNI EN 13223	Mechanical devices
7	Carriers	UNI EN 13796-1	Grips, carrier trucks, on-board brakes, cabin, chairs, carriages, maintenances carriers, tow-hangers
		UNI EN 13796-2	Slipping resistance test for grips
		UNI EN 13796-3	Fatigue tests
8	Electric devices	UNI EN 13243	Electric devices
9	Civil works	UNI EN 13107	Civil works
10	Precommissioning inspection, maintenance, operational inspection and checks	UNI EN 1709	Precommissioning inspection, maintenance, operational inspection and checks
11	Recovery and evacuation	UNI EN 1909	Recovery and evacuation
12	Operation	UNI EN 12397	Operation
13	Quality assurance	UNI EN 12408	Quality assurance
14	Prevention and fight against fire	UNI CEN/TR 14819-1	Part 1: Funicular railways in tunnels
		UNI CEN/TR 14819-2	Part 2: Other funicular railways and other installations

Table 18-Summary of Guide lines for fully automated cable driven passenger transport systems

5.2 Regulation UE 2016/424

The normative European framework is composed by the Regulation 2016/424 [R43], approved by the European Parliament and by the European Council of 9th March, 2016, entered into force in 2016 and replacing the Directive 2000/9 [R44].

The change of the regulatory instrument aided by the European Union is due to the need to standardize the legislation in force in all the member states, since "the scope, the essential requirements and the conformity assessment procedures must be identical in all the Member States" (point 4 of the considerations in [R43]). It was therefore in the interest of the European legislator to define a binding legal act, such as the Regulation, which must be applied in all its elements throughout the European Union; while the directive is a lighter legal act, which indicates an objective that all EU countries must respond to, and which refers the provisions for its implementation to the individual member States.

5.3 Italian legislation

Italian legislation is made up of the norms listed below. It is emphasized that Italian norms are not in contrast with the European legislation, but -possibly- they provides additional requirements consistent with the European framework.

- DECRETO MINISTERIALE 18th September 1975 “Norme tecniche di sicurezza per la costruzione e l'esercizio delle scale mobili in servizio pubblico” (only for the operation part)

- DECRETO DEL PRESIDENTE DELLA REPUBBLICA 11th July 1980, n. 753 “Nuove norme in materia di polizia, sicurezza e regolarità dell'esercizio delle ferrovie e di altri servizi di trasporto”
- CIRCOLARE DG n° 201, 16th September 1983 “DPR 11/07/1980, n° 753. “Approvazione del materiale rotabile per le ferrovie pubbliche in concessione od in gestione commissariale governativa, per le ferrovie private di seconda categoria (ed i raccordi a queste assimilati), per le tramvie extraurbane e per le metropolitane”
- DECRETO MINISTERIALE n° 23, 2nd January 1985 “Norme regolamentari in materia di varianti costruttive, di adeguamenti tecnici e di revisioni periodiche per i servizi di pubblico trasporto effettuati con impianti funicolari aerei e terrestri”
- DECRETO MINISTERIALE 4th August ì 1998, n. 400 “Regolamento generale recante norme per le funicolari aeree e terrestri in servizio pubblico destinate al trasporto di persone” (v. DM 392/2003)
- DECRETO LEGISLATIVO 12th June 2003, n. 210 “Attuazione della direttiva 2000/9/CE in materia di impianti a fune adibiti al trasporto di persone e relativo sistema sanzionatorio”
- CIRCOLARE N° 19/03 PROT 972 (EX TIF 4) 21st November 2003 “Procedure per l’accertamento dei requisiti di idoneità alla circolazione dei filoveicoli omologati ai sensi del decreto ministeriale del 10 luglio 2003, n. 238 destinati al trasporto di persone”

- DECRETO MINISTERIALE 5th December 2003, n. 392 “Regolamento concernente modifica dell'articolo 7 del decreto del Ministro dei trasporti e della navigazione 4 agosto 1998, n. 400, recante norme per le funicolari aeree e terrestri in servizio pubblico destinati al trasporto di persone”.
- LEGGE 24th December 2003, n. 363 "Norme in materia di sicurezza nella pratica degli sport invernali da discesa e da fondo"
- DECRETO DIRIGENZIALE 18th February 2011 “Disposizioni per i direttori ed i responsabili dell'esercizio e relativi sostituti e per gli assistenti tecnici preposti ai servizi di pubblico trasporto, effettuato mediante impianti funicolari aerei e terrestri, ascensori verticali ed inclinati, scale mobili, marciapiedi mobili, montascale, piattaforme elevatrici ed impianti assimilabili”
- DECRETO MINISTERIALE 4th April 2014 “Norme Tecniche per gli attraversamenti ed i parallelismi di condotte e canali convoglianti liquidi e gas con ferrovie ed altre linee di trasporto”
- DECRETO DIRIGENZIALE n° 288 17th September 2014 “Requisiti e modalità di abilitazione del personale destinato a svolgere funzioni di sicurezza sugli impianti a fune in servizio pubblico (capo servizio, macchinista, agente di stazione e di vettura”
- DECRETO DIRIGENZIALE n° 101 09th March 2015 “Disposizioni relative all’esercizio degli ascensori in servizio pubblico destinati al trasporto di presone”
- DECRETO 21st October 2015 “Approvazione della regola tecnica di prevenzione incendi per la progettazione, costruzione ed esercizio delle metropolitane”
- DECRETO 1st December 2015, n. 203 “Regolamento recante norme regolamentari in materia di revisioni periodiche, di adeguamenti tecnici e di varianti costruttive per i servizi di pubblico trasporto effettuati con funivie, funicolari, sciovie e slittinovie destinate al trasporto di persone”
- DECRETO DIRIGENZIALE n° 144 18th May 2016 “impianti aerei e terrestri. Prescrizioni tecniche riguardanti le funi”

- DECRETO DIRIGENZIALE 11th May 2017 “Impianti aerei e terrestri. Disposizioni tecniche riguardanti l’esercizio e la manutenzione degli impianti a fune adibiti al trasporto pubblico di persone”
- DECRETO LEGISLATIVO 28th February 2021, n. 40 “Attuazione dell'articolo 9 della legge 8 agosto 2019, n. 86, recante misure in materia di sicurezza nelle discipline sportive invernali”
- DECRETO DIRIGENZIALE n° 172 18th June 2021 “Disposizioni e specificazioni tecniche per le infrastrutture degli impianti a fune adibiti al trasporto di persone”

5.4 Overview about the self- driven cars regulation

[R45] defines an automatic driving vehicle as a "vehicle equipped with technologies capable of adopting and implementing driving behaviours without the active intervention of the driver, in certain road environments and external conditions”.

The SAE (Society of Automotive Engineers) identifies six levels of automation, shown in the following Table 19 and in the following Figure 58

Level	Description
Level 0	No autonomy: The driver has to take care of every aspect of driving, without any type of electronic support.
Level 1	Driving assistance: The driver has total and full responsibility for driving, but is supported at an information level (in the form of visual or acoustic alerts) by electronic systems which can indicate the presence of dangerous situations or adverse conditions. The systems installed on level 1 cars are ABS (prevents the wheels from locking when braking), Cruise Control (regulates speed), Park Assist and all those technologies capable of detecting the lane.
Level 2	Partial automation: The driver takes care of driving, but the car is able to intervene on acceleration and braking through safety systems, such as assisted braking and anti-collision emergency braking. Traffic direction and control remain under the control of the driver, although the steering can be managed in a partially automated way in certain scenarios with clearly visible road markings (systems called Lane Keeping Assist and, in the most complete versions, Traffic Jam Assist, Autosteer, Highway Assist, Driver Assist depending on the vehicle manufacturer). In fact, the car is able to stay inside the lane thanks to the detection of the lane limits and to adapt the speed according to the traffic density encountered.
Level 3	Conditioned automation: the car is able to manage driving in ordinary environmental conditions, while the driver intervenes in dangerous situations in the event of a request from the system or if he himself encounters adverse conditions.
Level 4	Conditioned automation: the car is able to manage driving in ordinary environmental conditions, while the driver intervenes in dangerous situations in the event of a request from the system or if he himself encounters adverse conditions.
Level 5	Complete automation. The vehicle is able to independently choose the route, adjusting its speed, braking and direction in any scenario, processing complicated and complex situations without ever requiring the intervention of a human being.

Table 19-Self-driven cars levels

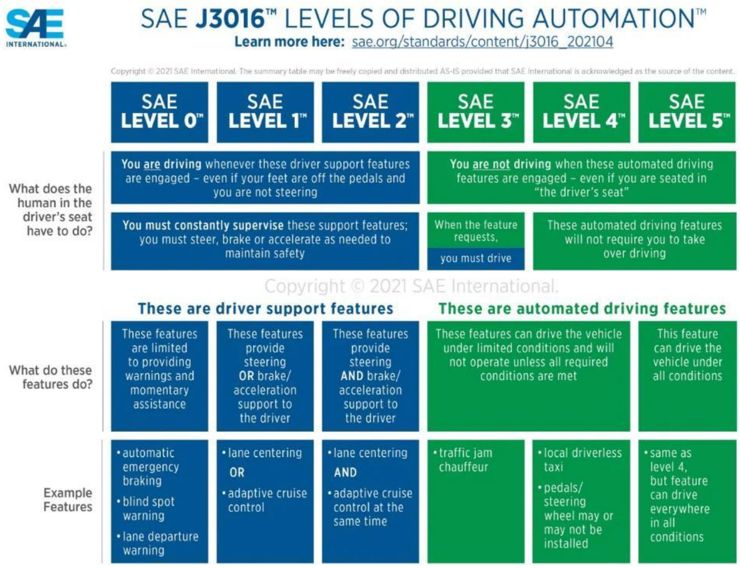


Figure 58-Scheme of self-driven cars levels

Actually, in Italy, only level 1 and 2 self-driving vehicles are allowed to be sold on the market, which provide partial assistance and require the active presence of a driver.

In fact, despite some recent openings by the Italian legislator concerning the possibility of the advent of self-driving cars (as examples are the issue of [R46] and the authorization to test self-driving vehicles), the [R47], which constitutes the reference regulatory apparatus, was drawn up in an era prior to the digital one and, in its Article 46, defines the vehicle as a "machine circulating on the road driven by man", thus excluding a priori the possibility of a car capable of moving independently.

As far as the European regulatory framework is concerned, it is still very light, and consists of a report on autonomous driving by the Dutch Euro-Deputy Mr. Wim Van De Camp-PPE, approved by the European Parliament on 15 January 2018.

From the comparison between the self-driving car and the hybrid rope-motor-wheel system (in its monorail section) the discordant aspects of the two systems emerged the most, first of all the type of location where the vehicles circulate, which is promiscuous for cars and protected for the hybrid system.

Since the application environment of the hybrid system is much more protected than that typical of automobiles, as it operates in an exclusive raceway, the regulatory apparatus described above valid for self-driven cars appears to be very restrictive and binding, and it is unnecessarily binding for the hybrid system object of this PhD thesis.

5.5 Overview about railways and subways regulation

The evolution of the legislation for the railway and underground systems has evolved with the aim of guaranteeing the achievement of a level of safety to minimize the risk of an accident (defined as the product between the impact and the probability of occurrence) by reducing the probability vehicle collision.

While in the section on the end of the hybrid system, in order to maintain the distance between the vehicles it is sufficient to guarantee the correct clamping of the vehicles to the carrying-hauling rope which defines the kinematic quantities of all the vehicles clamped to it, in the section on rail there is no physical constraint that links the kinematic quantities of a vehicle to those of the other vehicles in the system. The knowledge of kinematic parameters such as the position, speed and acceleration of individual vehicles therefore requires the adoption of sensors and localization devices positioned on the vehicle and along the line, whose data must be processed by an advanced control system of gear.

The requirements described about the rail sections of the hybrid system are traditionally related to the development of signalling systems adopted in the railway and metropolitan areas. In this context, in fact, the high masses of the vehicles and the low safety coefficient between wheel and rail (steel-steel contact) define a stopping distance of around 500÷2000 m, higher than the driver's visibility distance (100÷2000 m), and therefore are not consistent with walking on sight.

Since the information that the driver collects through direct sight is not sufficient for safe travel in the railway and underground environments, the signalling system allows the transmission of information to the driver (or to the automation system, in the case in which it is not foreseen the presence of a driver on board the vehicle) about the possibility to enter in a stretch of road, and the maximum speed allowed. In particular, safety in the railway sector is based on the concept of block section, a segment of the line which can be occupied by a maximum of one vehicle. Each block section is preceded by a protection signal which sets at danger if it is already occupied by another vehicle. To ensure that the train stops safely at a certain point (EMA), the signalling system must include an Indication Point (IP) where the driver is notified of the need to initiate braking.

Block sections are used in several rail-based system (railways, subway and light rail), defined in [R48], and they can find application also in the rail section of the hybrid system, that have similar needs and requirements. Of course, considering the total automation of the CableSmart vehicles, the block sections can be of limited length, as the extra braking distance caused by the driver's reaction time is eliminated.

Chapter 6

6. Transportation analysis

This chapter provide a quantitative analysis about the calculus of the main transportation parameters of the CableSmart system.

6.1 Capacity of the system

As the hybrid CableSmart system is a mono-directional continuous transport system, the line capacity C [passengers per hours per direction] is calculable as per the following formula:

$$C = \frac{3{,}600 \cdot p}{i}$$

Where:

Variable	**Meaning**	**Unit of measurement**
C	Line capacity	Passengers per hour per direction
p	Payload	Passengers per vehicle
i	Headway	seconds

Table 20-Comments about the variable of the formula of the line capacity in function of payload and headway

The minimum value of the headway i is limited by the fact that the vehicles must keep a safety distance in order to avoid collision in the station in case one of the them fails.

Another parameter essential in the line capacity calculation (from which the headway i depends) is the vehicle station stop time ts. In order to estimate the stop time of the vehicles in the station the following empirical equation can be considered:

$$t_{s,min} \sim \frac{1{,}5 * p + t_{doors}}{N_{doors}}$$

Variable	*Meaning*	*Unit of measurement*
$t_{s,\,min}$	Minimum stop time in the stations	seconds
p	Payload	passengers per vehicle
t_{doors}	Time for opening and closing of the doors of the vehicle	seconds
N_{doors}	Number of doors of the vehicle used for the entry and for the exit of the passengers	/

Table 21-Comments about the variable of the formula of the minimum time of stop of vehicle in station in function of payload, time of opening and closing of the doors, and number of doors

6.2 Secondary station

Unlike to the traditional gondola, the hybrid CableSmart system can be moved in station by motorized wheels, that allow the complete stop of each vehicle in the station, permitting the comfortable loading and unloading of passengers from the vehicle.

In this configuration, it is calculated the minimum value of the headway i that prevents the vehicles from overcoming the safety distance in the station, as shown in the Figure 59, that represents the time-space chart of the vehicles approaching the stations: each line exhibits the motion of a vehicle that has constant speed (strength oblique line), decelerates, completely stops in station (space is constant in function of the time), accelerates and continues its motion to constant speed.

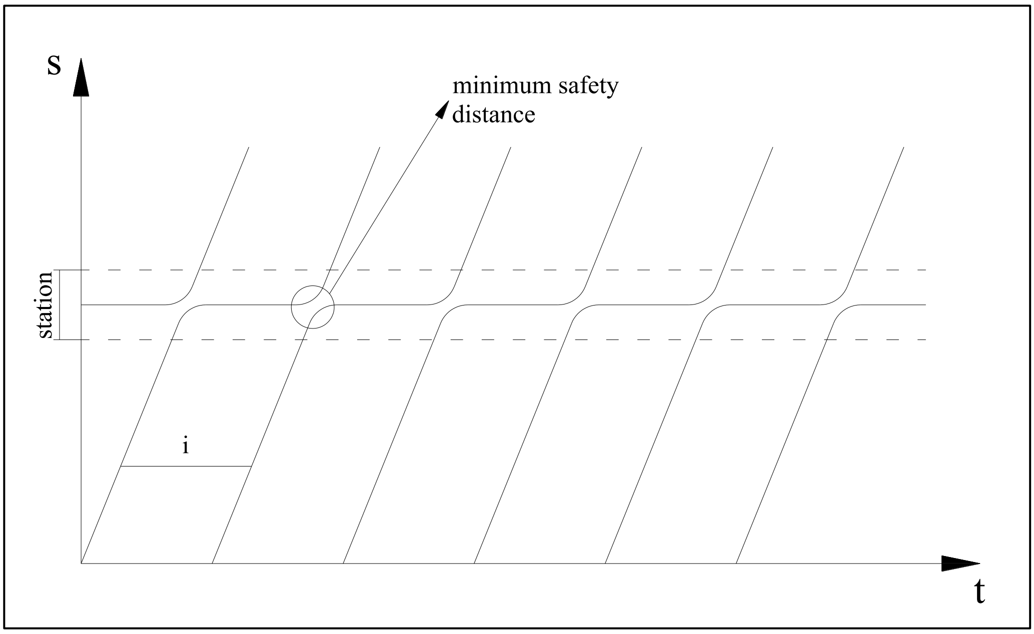


Figure 59-Time-space graph of the vehicles approaching the station

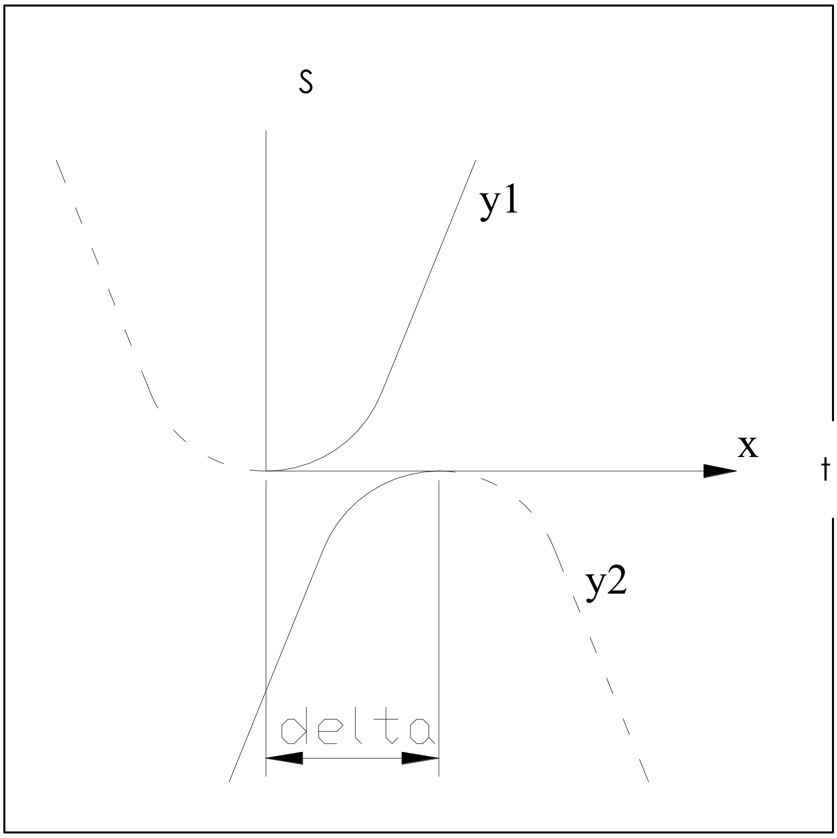


Figure 60-Time-space graph of two vehicles in station, during them acceleration (y1) and deceleration (y2) phase

$$y_1 = \frac{1}{2} a t^2$$

$$y_2 = -\frac{1}{2} a (t - \Delta)^2$$

The distance between the centres of the two vehicles is then:

$$d = y_1 - y_2 =$$

$$= \frac{1}{2} a t^2 + \frac{1}{2} a (t - \Delta)^2 =$$

$$= \frac{1}{2} a (2t^2 - 2t\Delta + \Delta^2)$$

Variable	***Meaning***	***Unit of measure (or equivalent unit: e.g. inch instead of m)***
d	Distance between the centers of the two vehicles	m
y_1	Position of the center of the vehicle 1, e.g. from the entrance in station	m
y_2	Position of the center of the vehicle 2, from the same origin point that defines y_1	m
a	Acceleration of the vehicles	m/s^2
t	Time, e.g. from the moment of entering of the vehicle in the station	s
Δ	Security time between two consecutive vehicles	s

Table 22 *Comments about the variables in the cinematic model representing the behaviour of two vehicles in a station*

For a given Δ, in order to evaluate the minimum distance between the centres of the vehicles, it is necessary to evaluate the null point of the first derivative of the distance d between the centres of the two vehicles:

$$min(d) \rightarrow \frac{\partial d}{dt} = 0$$

$$\frac{\partial}{dt}[\frac{1}{2}a(2t^2 - 2t\Delta + \Delta^2)] = 0$$

$$\frac{1}{2}a(4t - 2\Delta) = 0$$

$$\rightarrow t = \frac{\Delta}{2}$$

The distance d between the centres of the two consecutives vehicles corresponding to the point of minimum $t = \frac{\Delta}{2}$ is

$$d_{min} = \frac{1}{2}\ a\ (2 * \frac{\Delta^2}{4} - 2\ \frac{\Delta}{2}\ \Delta +\ \Delta^2)$$

$$d_{min} = \frac{a\Delta^2}{4}$$

The minimum distance d_{min} must be such as to contain the length of a vehicle (id est the distance between the centre and the rear edge of the preceding vehicle added to the distance between the centre and the front edge of the following vehicle) and a safe distance d_S

$$\frac{a\Delta^2}{4} = l_{veh} + d_S$$

$$\Delta = \sqrt{\frac{4(l_{veh} + d_S)}{a}}$$

So, the minimum headway i between vehicles is:

$$i_{min} = t_{s,min} + \Delta$$

$$i_{min} = \frac{1.5 * p + t_{doors}}{N_{doors}} + \sqrt{\frac{4(l_{veh} + d_S)}{a}}$$

Variable	*Meaning*	*Unit of measurement*	*Typical value*
p	Payload	Passengers per vehicle	8
t_{doors}	Time for opening and closing of the doors of the vehicle	seconds	4 s
N_{doors}	Number of doors of the vehicle used for the entry and for the exit of the passengers	/	1
l_{veh}	Length of a vehicle	m	2 m
d_S	Safe distance	m	1 m
a	Acceleration of the vehicle	m/s^2	1 m/s^2

Table 23-Comments about variables and their typical values of the formula to find the minimum headway i_{min}

With the values reported in the previous Table 23, the typical value of the minimum headway is i_{min}= 20 s, and the correspondent maximum capacity is:

$$C\left[\frac{passengers}{hour}\right] = \frac{3{,}600 \cdot p\left[\frac{passengers}{vehicle}\right]}{i\left[\frac{s}{vehicle}\right]} = 1{,}440\ \frac{passengers}{hour}$$

Vehicles' compliance with the safety distances in the station and along the line in the rail stretches is guaranteed by railway derivation control devices (block sections).

6.3 Primary station

The limit calculated in the previous chapter, due to the fact of having the line capacity limited from the station capacity can be overcame defining stations with a layout using a bypass that allows some vehicle to overcome an idle one without having to stop, as reported the Figure 61: in this case: the stopping vehicle use the b' segment, while the bypassing one travels in the b'' segment not stopping.

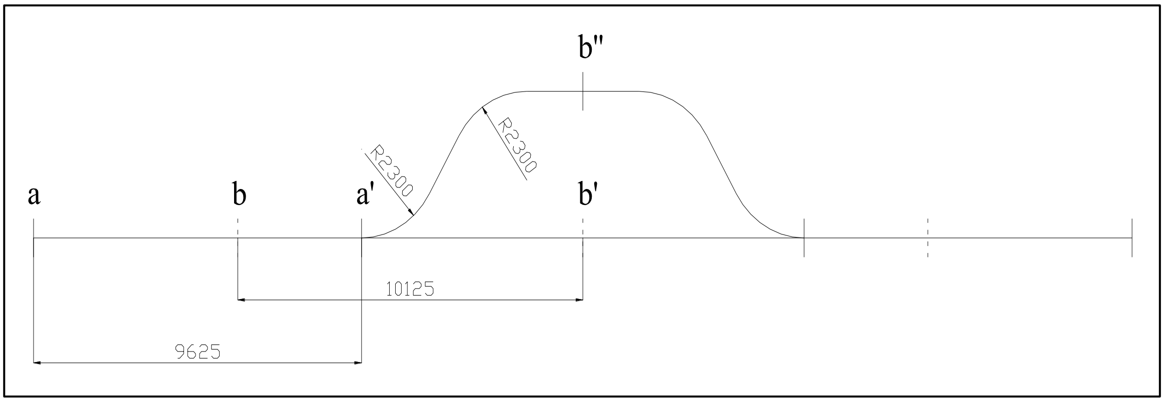


Figure 61-Layout of a station allowing the bypass of an idle vehicle by a non-stopping one

The vehicle which stops in the station starts to decelerate in b and stops in b', while the vehicle with bypasses on the station starts to decelerate in b and in a reaches a speed of around 1m/s, in order to provide comfort during the curved path and to the passengers and then limiting the centripetal acceleration:

$$t_{dec} = \frac{|v_f - v_0|}{a}$$

$$s_{dec} = v_0 t_{dec} - \frac{1}{2} a \cdot {t_{dec}}^2$$

Variable	*Meaning*	*Unit of measurement*	*Typical value- Idle segment*	*Typical value- bypass segment*
t_{dec}	Time of deceleration	s	4.5 s	3.5 s
v_f	Initial speed, measured in the point b	m/s	0 m/s	1 m/s
v_0	Final speed, measured in point b' or a'	m/s	4.5 m/s	4.5 m/s
a	Acceleration (or absolute value of the deceleration) of the vehicle	m/s^2	1 m/s^2	1 m/s^2
s_{dec}	Space travelled by the vehicle during the acceleration / deceleration phase	m	10.125 m	9.625 m

Table 24-Comments about variables and their typical values of the formulas to find the time and space of deceleration, in case of vehicle approaching the idle segment, and approaching the bypass segment

It is necessary to analyses the vehicle flows in order to avoid collisions between bypassing and stopping vehicles. In particular, it is necessary to provide a buffer position after the embarking position in order to avoid collision, as shown in Figure 62, where the considered headway i, and so the time granularity of the simulation, is 7s:

i) In the initial time t=0, the vehicle A is approaching the station;

ii) In the time t=7s, the vehicle A is stopped in the station and the vehicle B is approaching;

iii) In the time t= 14s, the vehicle A is yet stopped in the station, the vehicle B is in the bypass segment and the vehicle C is approaching;

iv) In the time t=21s, the vehicle A is leaving the embarking position while the vehicle B is leaving the bypass segment. In the meantime, the vehicle C is in the bypass segment and the vehicle D is approaching;

v) In the time t=28s, in order to avoid collision between the vehicles A (leaving the embarking position) and B (leaving the bypass segment), the vehicle A stops in the buffer position and the vehicle B has the right to leave the station and return to the line. In the meantime, vehicle C is leaving the bypass segment, vehicle D is stopping and vehicle E is approaching;

vi) In the time t=35s, in order to avoid collision between the vehicles A (leaving the embarking position) and C (leaving the bypass segment), the vehicle A remain stopped in the buffer position and the vehicle C has the right to leave the station and return to the line, while vehicle D continues to stop in the embarking position. In the meantime, vehicle E is entering in the bypass segment and vehicle F is approaching;

vii) In the time t=42s, the vehicle A leaves the buffer position and enters into the line, as no vehicle is leaving the bypass segment, and the vehicle D is leaving the embarking position. In the meantime, vehicles E and F are in the bypass segment and vehicle G is approaching;

viii) In the time t=49s, in order to avoid collision between the vehicles D (leaving the embarking position) and E (leaving the bypass segment), the vehicle D stops in the buffer position and the vehicle E has the right to leave the station and return to the line. In the meantime, vehicle G is stopped in the embarking position, and vehicle H is approaching.

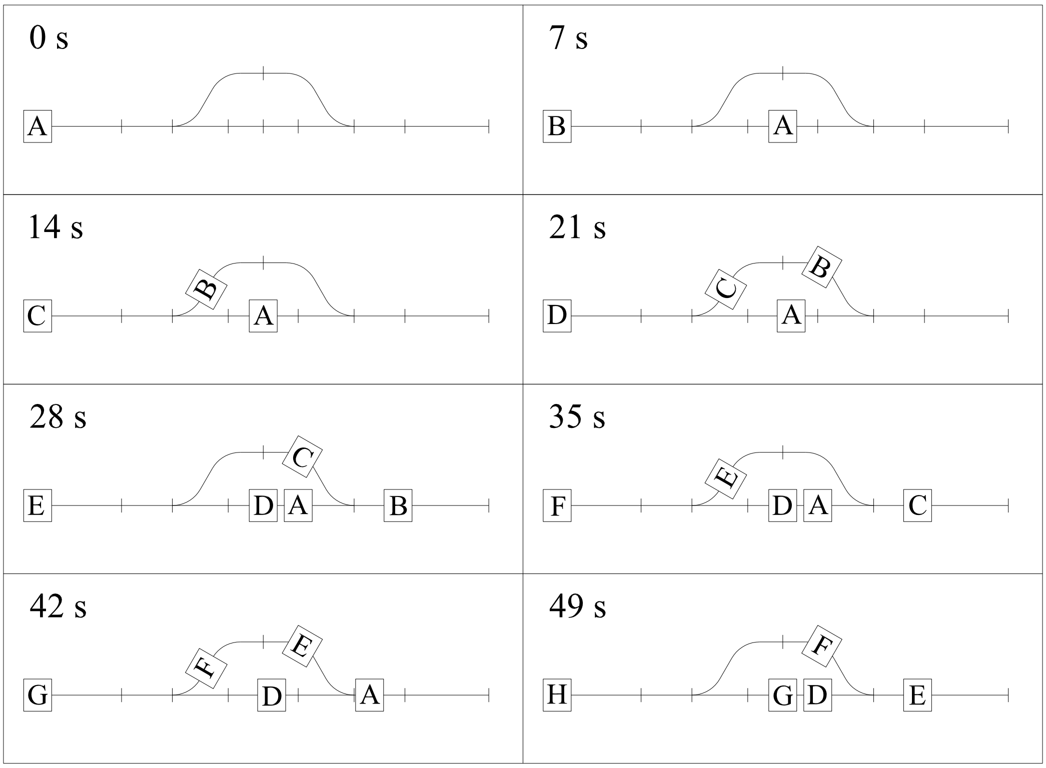


Figure 62-Schematic simulation of the vehicles flows in a station where the vehicle can stop (strength segment) and bypass the embarking position (curved path)

The headway i=7s was calculated in order to have the possibility of intersecting a 1,440 p/h line with a high capacity one. In this case it is necessary that the high-capacity line is a multiple of the low-capacity line; So, the resulting headway is:

$$i_{low} = i_{high} \cdot n \text{ , where } n \in N, i_{low} > i_{low,\min} = 19.46 \text{ s}$$

Variable	*Meaning*	*Unit of measurement*	*Typical value*
i_{low}	headway of the low-capacity station	seconds	21 s
i_{high}	Headway of the high-capacity line	seconds	7 s
n	Multiplier	/	3

Table 25-Comments about variables and their typical values of the formulas connecting the headways of the line and of the station with by passable stops

In this way, a compact station with a capacity (i = 21 s) of:

$$C_{station}[\frac{passengers}{hour}] = \frac{3{,}600 \cdot p\ [\frac{passengers}{vehicle}]}{i\ [\frac{s}{vehicle}]} = \frac{3{,}600 \cdot 8\ \frac{passengers}{vehicle}}{21\ \frac{s}{vehicle}} = 1{,}370\,\frac{passengers}{h}$$

Can serve a line of (i = 7 s):

$$C_{line}[\frac{passengers}{hour}] = \frac{3{,}600 \cdot p[\frac{passengers}{vehicle}]}{i\ [\frac{s}{vehicle}]} = \frac{3{,}600 \cdot 8\ \frac{passengers}{vehicle}}{7\ \frac{s}{vehicle}} = 4{,}110\,\frac{passengers}{h}$$

6.4 Primary station with high capacity

A station able to completely serve a high-capacity line can be designed considering a double bypass for each branch with two stop slots for each bypass.

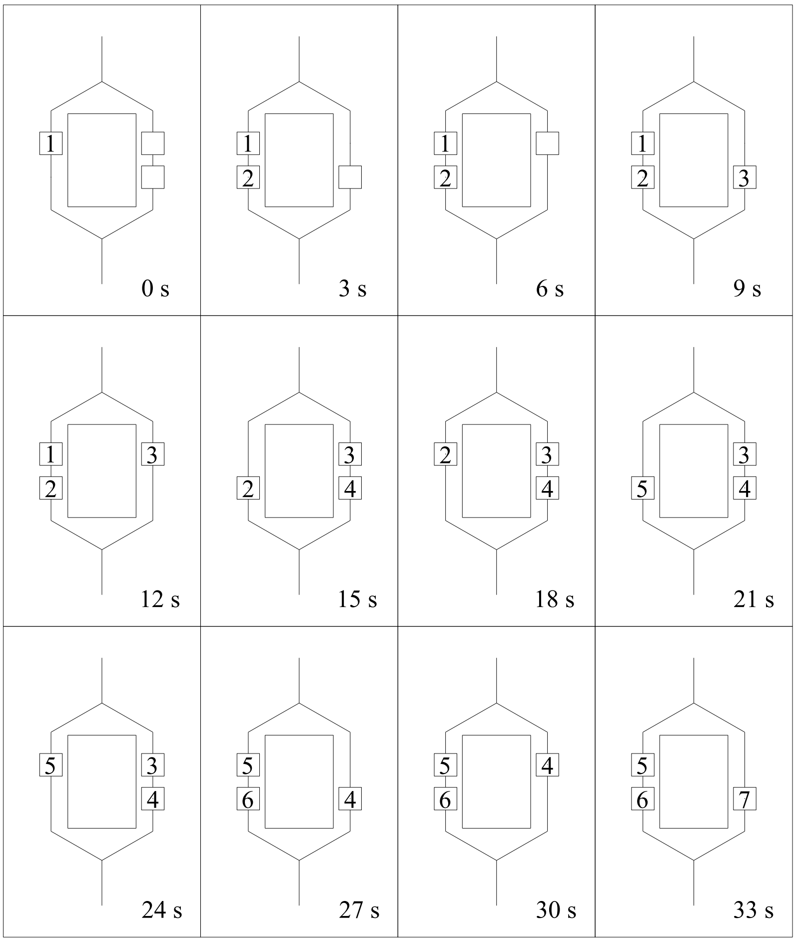


Figure 63-Functional schema of a high-capacity primary station, with a double bypass for each branch and with a double buffer slot for each bypass

In the above-shown configuration the station capacity is equal to line capacity and it is:

$$C\ [\frac{passengers}{hour}] = \frac{3{,}600 \cdot p\ [\frac{passengers}{vehicle}]}{i\ [\frac{s}{vehicle}]} = \frac{3{,}600 \cdot 8\ \frac{passengers}{vehicle}}{6\ s}$$
$$= 4{,}800\,\frac{passengers}{h}$$

In case of intersecting a low-capacity line with a high-capacity one, the minimum common headway of the two lines, in order to guarantee the minimum station, stop time for the system would be:

i = 8 s

And the corresponding station stop time would be:

ts = 16 s

The high line capacity:

$$C\,[\frac{passengers}{hour}] = \frac{3{,}600\ \cdot p\,[\frac{passengers}{vehicle}]}{i\,[\frac{s}{vehicle}]} = \frac{3{,}600 \cdot 8\ \frac{passengers}{vehicle}}{8\,s}$$
$$= 3{,}600\,\frac{passengers}{h}$$

6.5 Transport network and hub stations

In urban installations it is very useful to design a transport network, in order to satisfy a spread mobility demand. This condition entails that intersection stations, or hubs, have to be provided for. In these hubs the vehicles must have the possibility to load/unload passengers and to choose to follow different cableway lines. The most effective way to do this is to emulate the highway roundabouts. In the following Figure 64 is shown a hub for intersecting two lines (AC and BD) with a capacity of 1,440 passengers per hour.

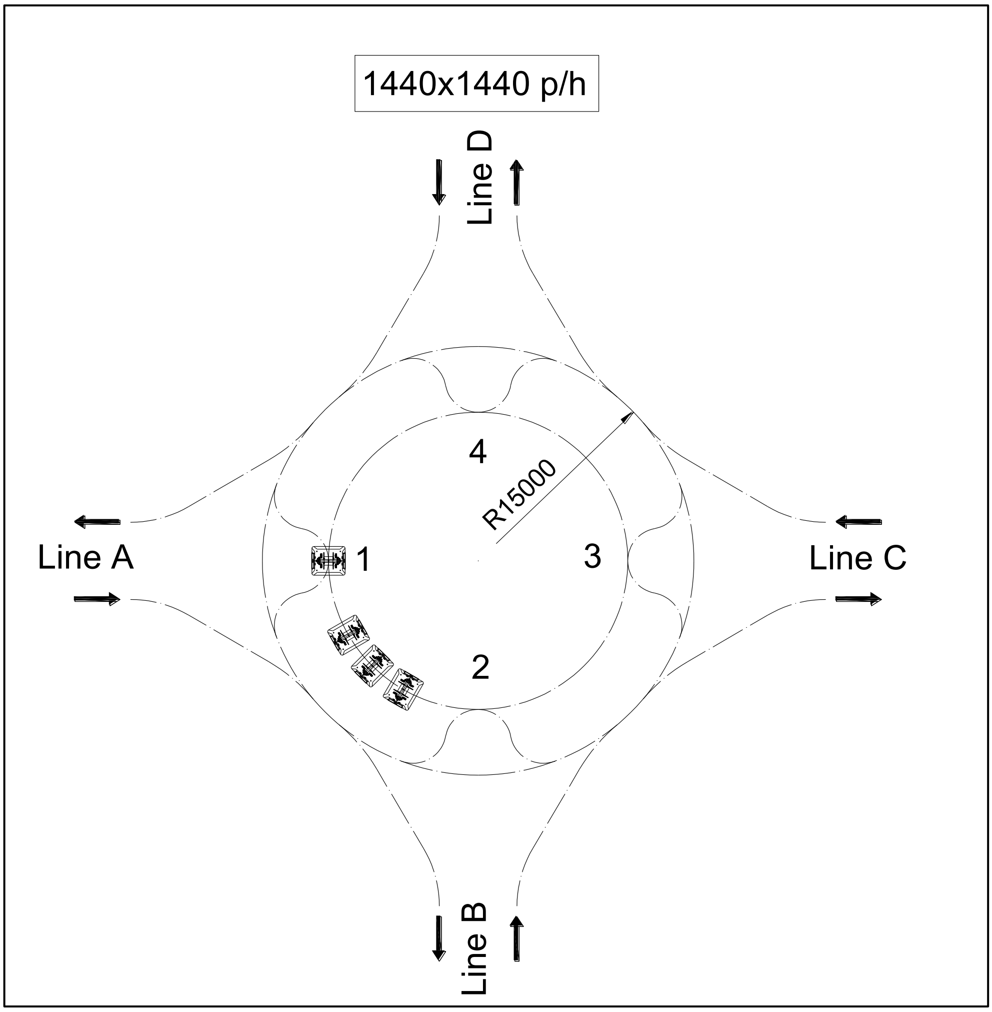


Figure 64-Hub intersecting two lines with a capacity of 1.440 passengers per hours per direction each

As reported in the previous chapters, 1,440 passengers per hour is a line capacity that allows the sequential station stop of every vehicle, without the need to have a bypass of the embarking segment. Then, in this case, the vehicles coming from Line A will be hosted in bypass 2, the ones coming from Line B in bypass 3 etc. After the unloading/loading of the passengers the vehicles can choose to follow any of the lines using the external circle and overcoming the idle vehicles in the slots. Additional slots can be provided for in the inner circle for storing vehicles.

For intersecting lines with different capacities, it is enough to increase the diameter of the hub in order to add station stop slot as shown in the Figure 65

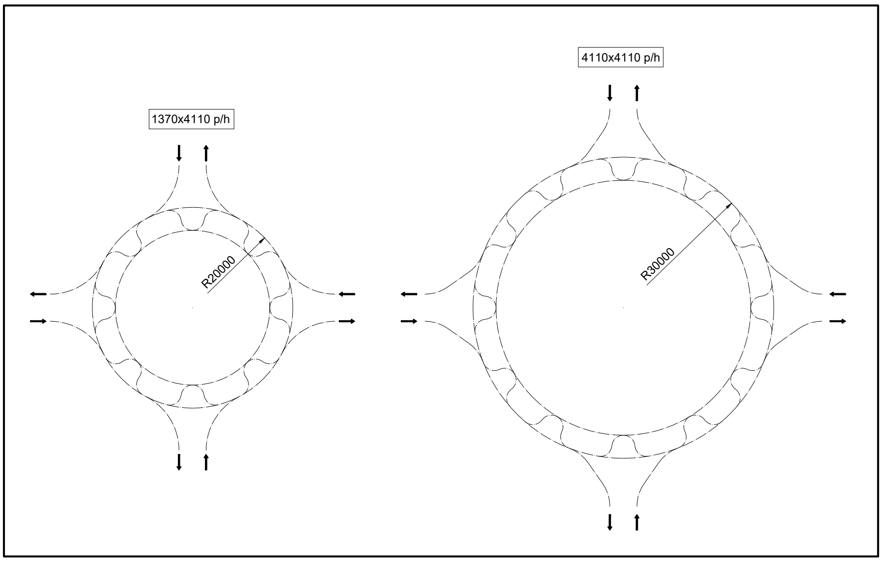


Figure 65-Hub intersecting lines with different capacities

A simple example of a complete transport network is shown in Figure 66, where here is a central high-capacity line with low-capacity ones crossing it.

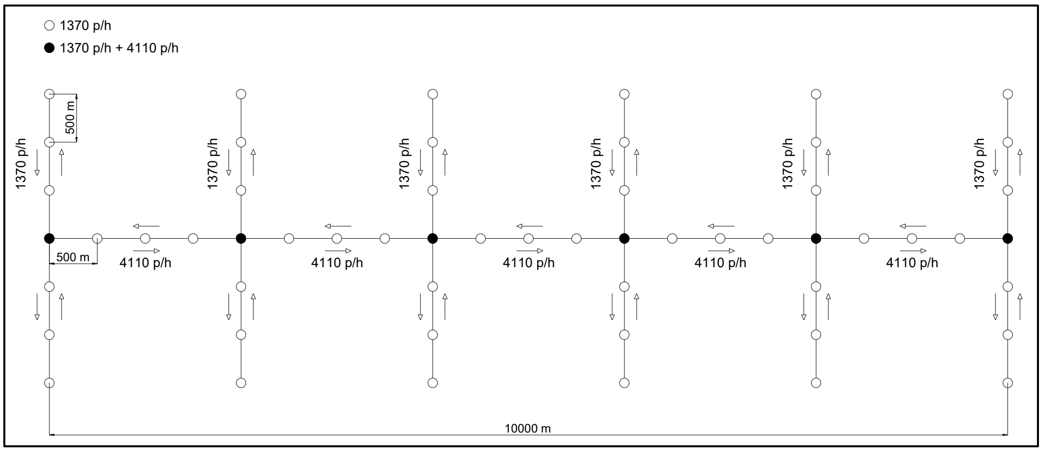


Figure 66-Simple of transport network

Chapter 7

7. Structural analysis

7.1 Structural design of the bogie connection bridge

The bogie connection bridge is an element necessary for preventing the two semi-bogies from rotating one respect the other around the two hinges of connection of the main dampening to which they are linked and also for several other purposes. In case one of the two rope of the cableway stops while the other keeps on moving one of them starts to slide within the respective grip. It is essential that in such situation the bridge could stand the torque generated from this relative sliding without yielding. In the it is shown the geometry of the bridge.

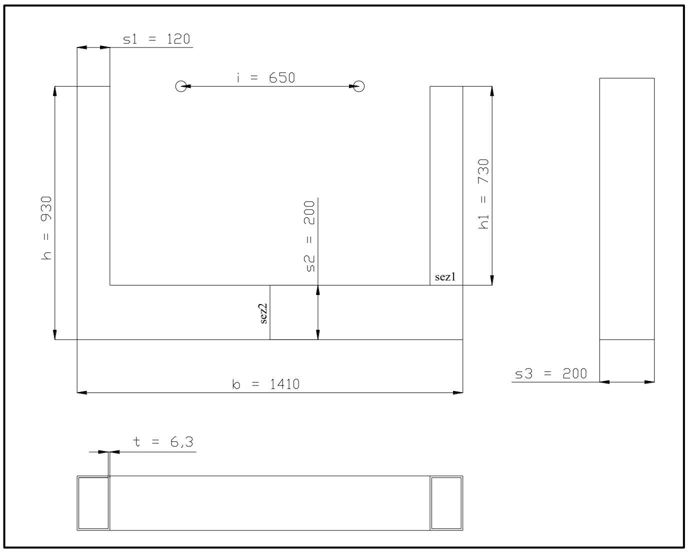


Figure 67-Geometry of the bridge

The most critical sections of the body are:

i) Section 1: the bending moment of the load on the right rope is at its maximum;
ii) Section 2: the torque of the load on the right rope is at its maximum.

First of all, the load on the grip due to the sliding of the rope has to be calculated. According to the norm, the minimum resistance for rope sliding against the grip has to be:

$$F_s = 3 \cdot W \cdot g \cdot sen\alpha$$

Variable	*Meaning*	*Unit of measurement*	*Typical value*
F_s	Sliding resistance force	N	22,700 N
W	Gross vehicle weight	kg	1,200 kg The gross vehicle weight is 2,400 kg but there are two grips (and two ropes) and then the load for each of them is halved
g	Gravitational acceleration	m/s^2	9.81 m/s^2
α	Maximum grade of the ropeway	deg	40^O

Table 26-Comments about variables and their typical values of the formula to find the sliding resistance force of the rope.

Section 1

The following Figure 68 reports the loads acting on the section 1

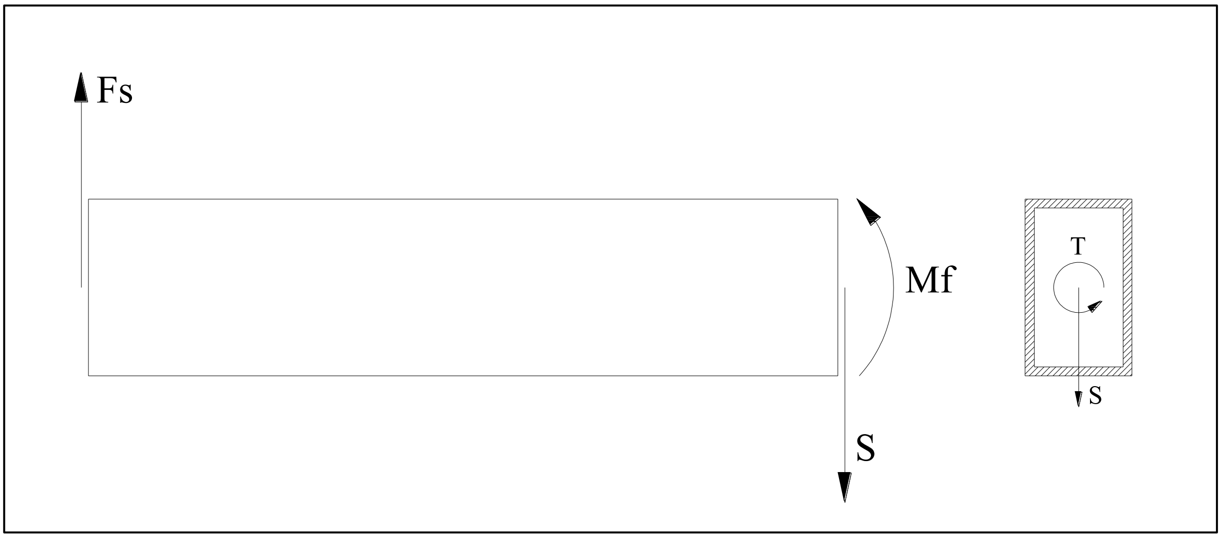


Figure 68-Loads acting on the section 1 of the bridge

$$\begin{cases} Bending\ momentum:\ M_f = F_s \cdot h_1 \\ Torque: T = F_s \cdot \left(\frac{b}{2} - \frac{i}{2} - \frac{s1}{2}\right) \\ Shear\ load: S = F_s \end{cases}$$

Variable	*Meaning*	*Unit of measurement*
M_f	Bending momentum	N*m
F_S	Shear force	N
h_1	Length of the section 1- y axes	m
T	Torque	N*m
b	Length of the bogie- x axes	m
i	Distance between the ropes- x axes	m
s1	Lenght of the section 1- x axes	m

Table 27-Comments about variables in the equilibrium formulas in section 1

There is not any compression/traction load.

In order to evaluate the maximum normal stress due to bending momentum the second moment of area has to be calculated, considering the geometrical dimensions of the section 1 collected in the Figure 69

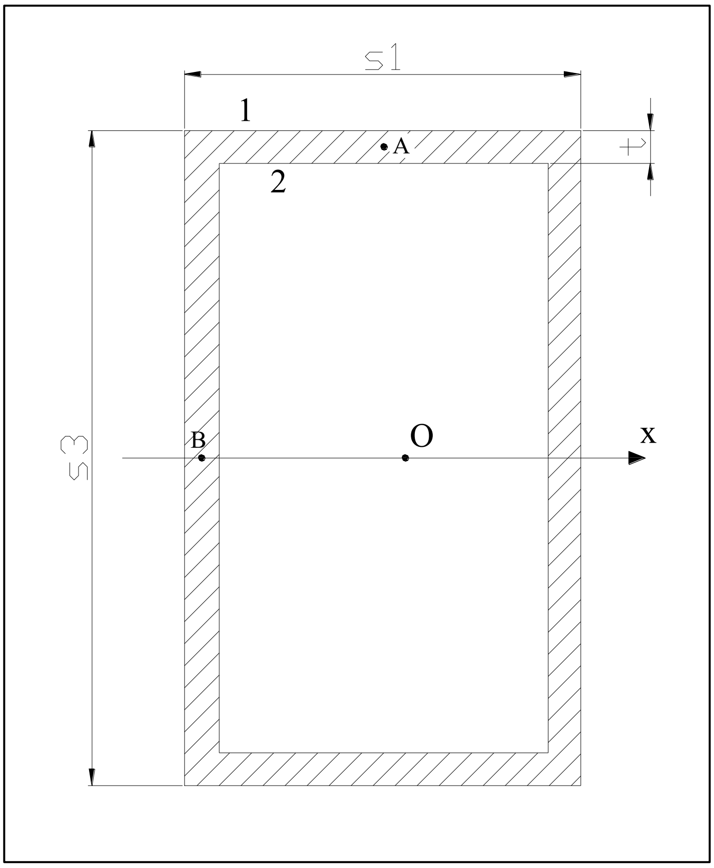


Figure 69-Geometry of the section 1 of the bridge

$$I_x = I_{x1} - I_{x2} = \frac{s_1 \cdot s_3^3}{12} - \frac{(s_1 - 2t) \cdot (s_3 - 2t)^3}{12}$$

Variable	*Meaning*	*Unit of measurement*
I_X	Moment of inertia of the section 1 in the rotation around x axes	m^4
s_1	Lengh of the section 1- x axes	m
s_2	Lengh of the section 1- z axes	m
t	Thickness of the section 1- x axes	m

Table 28-Comments about variables in formula of the momentum of inertia of the section 1

The maximum normal stress is then:

$\sigma_{\mathrm{f,max}} = \frac{M_f * y_{max}}{I_x}$, with $y_{max} = \frac{s3}{2}$

The maximum shear stress caused by torque can be evaluated, in this case, thanks to Bredt's formula:

$$\tau_{\ T,max} = \frac{M_t}{2\Omega t}$$

Where Ω is the area enclosed by the mean line of the section:

$$\Omega = (s1 - t)(s3 - t)$$

The maximum shear stress due to shear load can be calculated considering the area of the vertical rectangle of the section without considering the top and the bottom ones which contribute to shear resistance is negligible:

$$\tau_{\ S,max} = 1.5 * \frac{S}{A} =$$

$$= 1.5 * \frac{S}{2 \cdot t \cdot (s3 - 2t)}$$

The most critical point for the equivalent stress according Von Mises could be A or B, with reference to the Figure 69:

Point A: $\sigma_{\mathrm{f,max}}$ and $\tau_{\ T,max}$

Point B: $\tau_{\ S,max}$ and $\tau_{\ T,max}$

The equivalent stress according Von Mises is:

$$\sigma_{id} = \sqrt{\sigma^2 + 3\tau^2}$$

And the results are:

$\sigma_{id,A}$ = 90.7 MPa

$\sigma_{id,B}$ = 64.4 MPa

Supposing the connection bridge made of steel 355 with a yield point R_s of 355 MPa the minimum safety factor is:

$$SF = \frac{R_s}{\sigma_{id}} = 3.9$$

Section 2

The following Figure 70reports the loads acting on the section 2

Figure 70-Loads acting on the section 2 of the bridge

$$\begin{cases} Bending\ momentum:\ \ M_f = F_s \cdot i \\ Torque: T = F_s \cdot \left(h - \frac{s2}{2}\right) \\ Shear\ load: S = F_s \end{cases}$$

There is not any compression/traction load.

In order to evaluate the maximum normal stress due to bending momentum the second moment of area has to be calculated, considering the geometrical dimensions of the section 1 collected in the

Where Ω is the area enclosed by the mean line of the section:

$$\Omega = (s2 - t)(s3 - t)$$

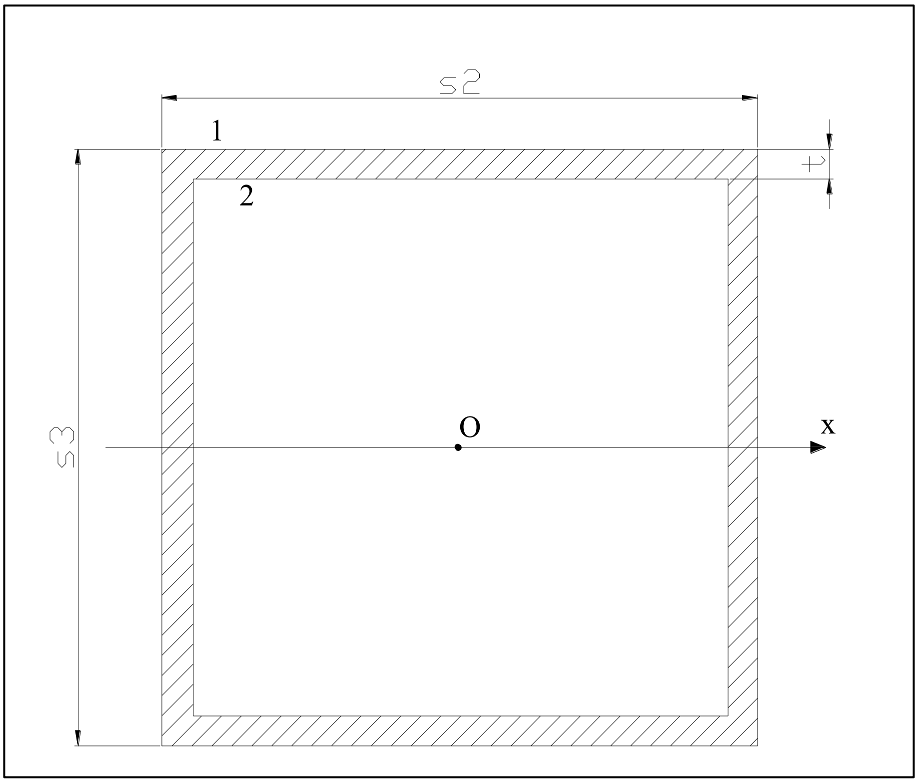


Figure 71-Geometry of the section 2 of the bridge

$$I_x = I_{x1} - I_{x2} = \frac{s_2 \cdot s_3^3}{12} - \frac{(s_2 - 2t) \cdot (s_3 - 2t)^3}{12}$$

The maximum normal stress is then:

$\sigma_{\mathrm{f,max}} = \frac{M_f * y_{max}}{I_x}$, with $y_{max=} \frac{s3}{2}$

The maximum shear stress caused by torque can be evaluated, in this case, thanks to Bredt's formula:

$$\tau_{\ T,max} = \frac{M_t}{2\Omega t}$$

Where Ω is the area enclosed by the mean line of the section:

$$\Omega = (s2 - t)(s3 - t)$$

The maximum shear stress due to shear load, likewise the previous section, is:

$$\tau_{\ S,max} = 1.5 * \frac{S}{A} =$$

$$= 1.5 * \frac{S}{2 \cdot t \cdot (s3 - 2t)}$$

The values of the most critic equivalent stresses are in this case:

$\sigma_{id,A}$ = 84.3 MPa

$\sigma_{id,B}$ = 87.1 MPa

The minimum safety factor is:

$$SF = \frac{R_s}{\sigma_{id}} = 4.1$$

Once the most critical sections are checked, it is possible to evaluate the weight of the bridge, essential for calculating the vehicle weight and for checking the ropeway. In order to do this, it was considered the middle perimeter of the bridge as shown in Figure 72

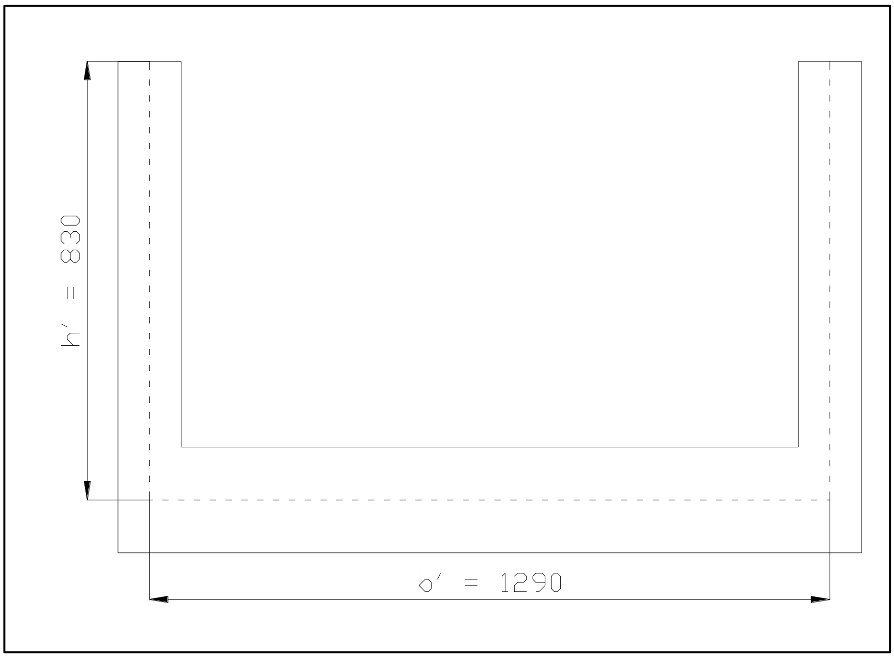


Figure 72-Body sectioning for bridge weight calculation

For the two vertical parts it was considered the area of the section 1 (Figure 69), whereas for the horizontal one it was considered the area of section 2 (Figure 71):

$$A_{sez1} = 2 \cdot s_1 \cdot t + 2(s_3 - 2t)t$$

$$A_{sez2} = 2 \cdot s_2 \cdot t + 2(s_3 - 2t)t$$

And the volumes are:

$$V_1 = A_{sez1} \cdot h'$$

$$V_2 = A_{sez2} \cdot b'$$

The approximate volume of the bogie connection bridge is then:

$$V_{tot} = 2 \cdot V_1 + V_2$$

Then, considering the density of the material ρ, the mass of the bridge is:

$$W = V_{tot} \cdot \rho$$

Considering the density of the steel (ρ = 7,800 kg/m3) the resulting approximate mass is 100 kg.

7.2 Suspension design

The suspension has to stand the load of the weight of the cabin and the passengers and the force of the wind that press it against the bogie connection bridge. In case of absence of the bogie contact against the bogie connection bridge the configuration is shown in *Figure 73*

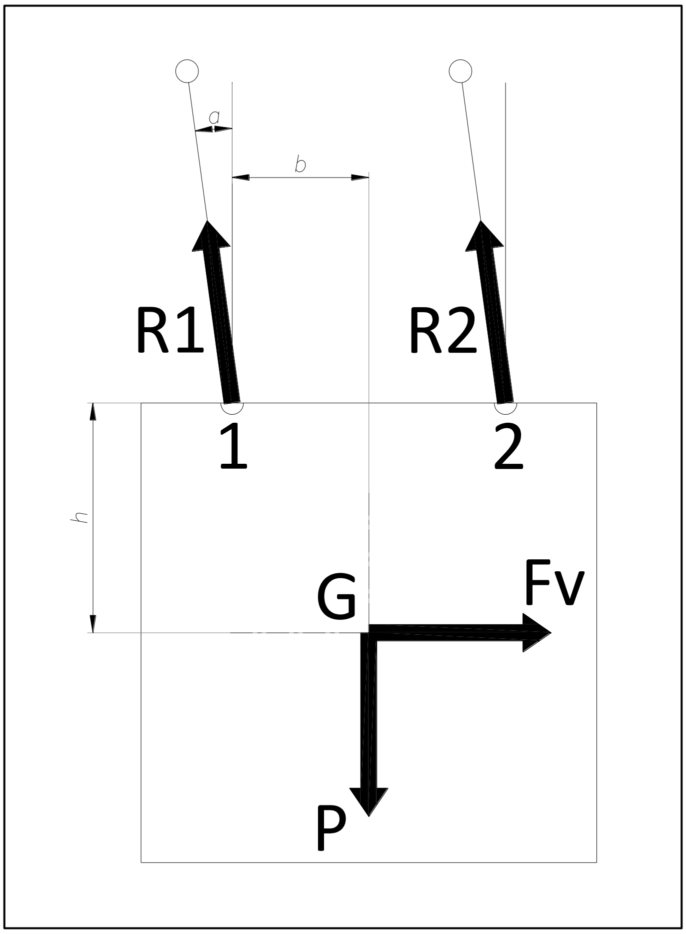


Figure 73-Suspension configuration in case of absence of the bogie contact against the bogie connection bridge

$$\begin{cases} Vertical\ component\ of\ the\ resultant\ force\ acting\ on\ the\ first\ clamp: R_{1v} = \dfrac{F_v h}{2b} + \dfrac{P}{2} \\ Vertical\ component\ of\ the\ resultant\ force\ acting\ on\ the\ second\ clamp: R_{2v} = P - R_{1v} \\ Angle\ between\ vertical\ and\ horizantal\ components\ of\ the\ resultant\ forces: \alpha = arctan\left(\dfrac{F_v}{P}\right) \\ Horizontal\ component\ of\ the\ resultant\ force\ acting\ on\ the\ first\ clamp: R_{1H} = R_{1v} \cdot tan\,\alpha \\ Horizontal\ component\ of\ the\ resultant\ force\ acting\ on\ the\ second\ clamp: R_{2H} = R_{2v} \cdot tan\,\alpha \end{cases}$$

$$\begin{cases} \alpha = 11 \text{ deg} \\ R_1 = 11{,}489\ N \\ R_2 = 6{,}500\ N \end{cases}$$

If the bogie connection bridge is considered, the angle of inclination of the arm of the suspension is limited to α* = 7.8°. The configuration is then the one reported in the following Figure 74:

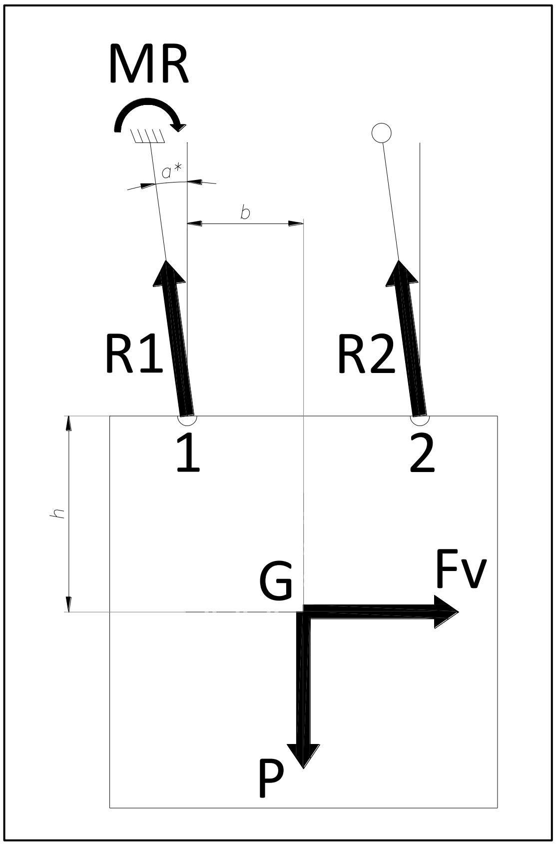


Figure 74-Suspension configuration in case of presence of the bogie contact against the bogie connection bridge

$$\begin{cases} Vertical\ component\ of\ the\ resultant\ force\ acting\ on\ the\ second\ clamp: R_{2v} = \dfrac{P}{2} - \dfrac{F_v h}{2b} \\ Vertical\ component\ of\ the\ resultant\ force\ acting\ on\ the\ first\ clamp: R_{1v} = P - R_{2v} \\ Horizontal\ component\ of\ the\ resultant\ force\ acting\ on\ the\ second\ clamp: R_{2o} = R_{2v} \cdot \tan\alpha^{*} \\ Horizontal\ component\ of\ the\ resultant\ force\ acting\ on\ the\ first\ clamp:\ R_{1o} = F_v - R_{2o} \\ Angle\ between\ vertical\ and\ horizantal\ components\ of\ the\ resultant\ forces\ \alpha_R = arctan\left(\dfrac{R_{1o}}{R_{1v}}\right) \\ M_R = R_1 \cdot b_R \\ R_{1n} = R_1 \cdot \cos\delta \\ \delta = \alpha_R - \alpha^{*} \\ b_R = L \cdot \sin\delta \end{cases}$$

$$\begin{cases} \alpha_R = 12{,}8\ \text{deg} \\ \delta = 5\ deg \\ L = 1{,}66 m \\ b_R = 0{,}145\ m \\ M_R = 1.679\ Nm \\ R_{1n} = 11.521\ N \end{cases}$$

Once defined the dynamical values above calculated; it is possible to check the load resistance of the arm of the suspension, whose geometry is shown in the Figure 75 and in the Figure 76.

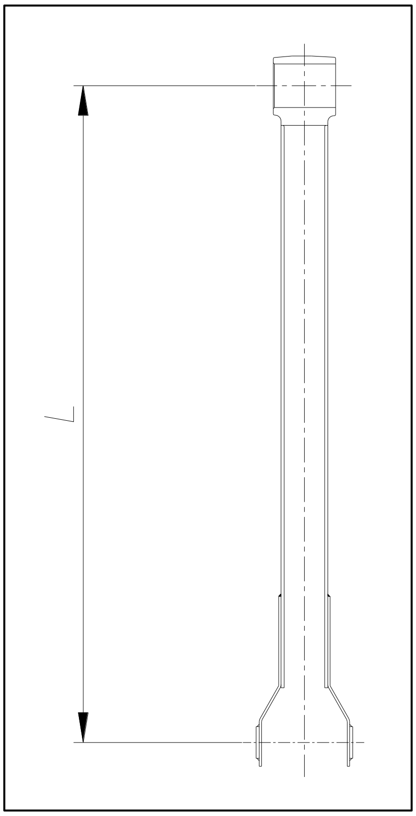


Figure 75-Geometry of the suspension (1)

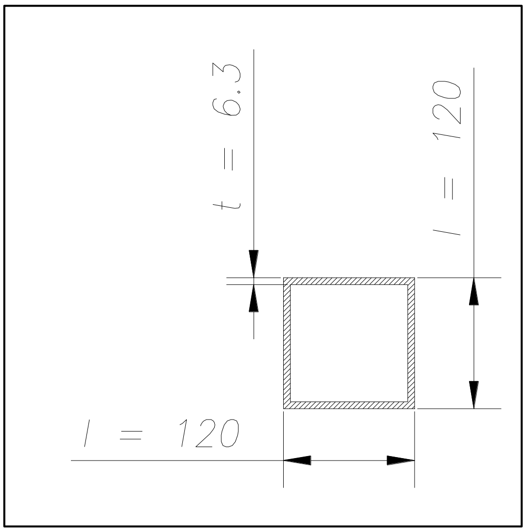


Figure 76-Geometry of the suspension (2)

$$\boldsymbol{\sigma_{eq}} = \boldsymbol{\sigma_f} + \boldsymbol{\sigma_n} =$$

$$\boldsymbol{\sigma_{eq}} = \frac{\boldsymbol{M_R}}{\boldsymbol{W_f}} + \frac{\boldsymbol{R_{1n}}}{\boldsymbol{A}} =$$

$$\boldsymbol{\sigma_{eq}} = \frac{1{,}679\ Nm}{103{,}207\ mm^3} + \frac{11{,}521\ N}{2{,}865\ mm^2} = 20.3\ \mathrm{MPa}$$

$$\boldsymbol{CS} = \frac{\mathrm{R_s}}{\sigma_{\mathrm{eq}}} = 17.5$$

Chapter 8

8. Cable car analysis

In order to evaluate the main values related to an urban plant through the fully automated hybrid CableSmart public transport system, an installation was simulated.

8.1 Calculation methodology

In its cable segments, the hybrid CableSmart system works as a traditional gondola, so it is possible to analyse its line through the traditional tools used in ropeway sector. In particular, the line calculations object of this chapter is performed by using the software SIF designed by Eng. Vitali, in its version 2022.

SIF is a procedure realized using Excel and the VBA development environment (Macro instrument). The program is released through an excel file and can be used after entering a license password which enables the procedures and, therefore, the functions of the software [R38]. SIF software is traditionally used by Politecnico di Torino in the academic course “Sistemi di trasporto ferroviari, metropolitan e a fune” (prof. Dalla Chiara), and the license is sold on the market and also used by numerous companies operating in the ropeway design sector.

In this section, it is described the calculation software for the definition of the variables that make up the results of the line testing calculation.

Calculation of the rope tensions

The software takes into consideration every i[th] span of the cableway, as reported in the following Figure 77 and Table 29.

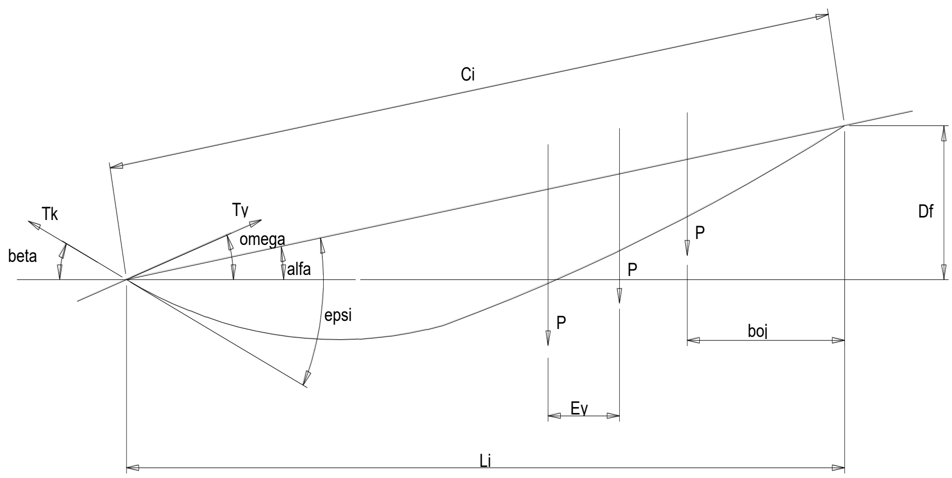


Figure 77-Scheme of the cable car generic span, with the relevant variables for the line calculation by SIF software

Variable	*Meaning*	*Unit of measurement*
D_f	Difference on altitude in the span	m
L_i	Horizontal length of the span	m
C_i	Oblique length of the span	m
alpha	Tilt of the oblique length above the horizontal plan	deg
q	Unitary weight of the rope	daN/m
p	Weight of a vehicle	daN
N_g	Number of casters of vehicle in each rope segment	/

N_{vg}	Number of vehicles in each cluster	/
E_V	Distance between vehicles in the same cluster	m
E_g	Distance between clusters of vehicles	m
n	Number of vehicles traveling in the span	/
b_{oj}	Horizontal distance between the j^{th} vehicle and the upstream end of the span	m
T_k	Rope tension at the downstream end of the span	N
Epsi	Angle between the rope tension at the downstream of the rope T_K and the oblique length C_i	deg
Omega	Tilt of the rope tension at the downstream end of the rope T_K above the horizontal plan	deg
N_k	Vertical component of the rope tension at the downstream of the rope T_K	N
H_k	Horizontal component of the rope tension at the downstream of the rope T_K	N
T_y	Rope tension at the upstream end of the span	N
N_y	Normal component of the tension at the upstream end of the span T_y	N
beta	Tilt of the rope tension at the upstream end of the rope Ty above the horizontal plan	deg

Table 29-Relevant variables for the line calculation by SIF software

Assuming that the value of downstream tension of the span is know, and applying the rotation balancing equation around the upstream end of the span, the following results are defined:

$$alpha = \arctan \frac{D_i}{L_i}$$

$$T_k \cdot C_i \cdot sen(epsi) = q \cdot C_i \cdot \frac{L_i}{2} + \sum_{j=1}^{n} (P \cdot b_{oj}),$$

Then

$$epsi = arcsen\left(\frac{q \cdot Ci \cdot \frac{L_i}{2} + \sum_{j=1}^{n} P \cdot b_{oj}}{T_k \cdot C_i}\right)$$

$beta = \text{epsi} - \text{alpha}$

$N_y = qC_i + \text{nP} + N_k$

$T_y = \sqrt{H_k^2 + N_y^2}$

$omega = \text{arctan}\frac{N_y}{H_k}$

The automatic calculation starts from the downstream span, and consider that the value of the rope tension in known. This assumpsion is true only if the counterweight of the rope is located in the downstream station; if it is located elsewhere, the software applies the iterative procedure reported in the Figure 78:

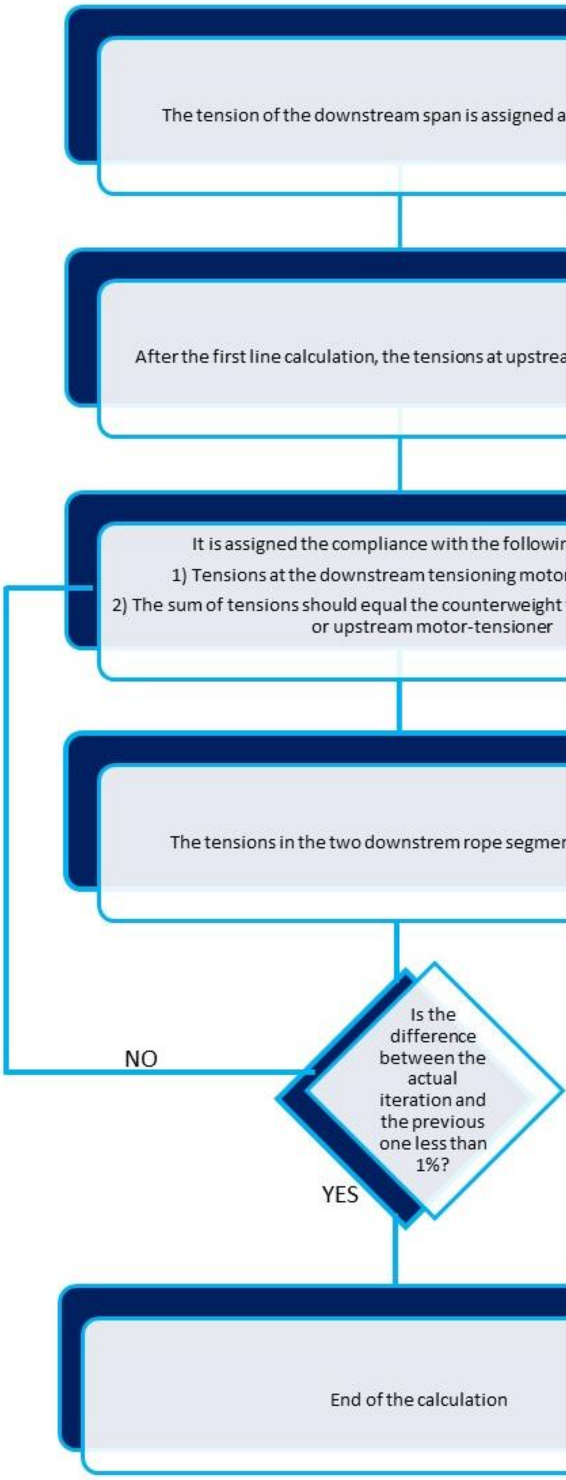


Figure 78-Scheme SIF line calculation in terms of calculations of the tensions for each span if the counterweight is not located in the downstream station

Calculation of the deflection in the spans

Once the downstream and upstream tensions (Tk and Ty, respectively) and their horizontal component (Hk) are known, the middle-span deflection is calculated through the overlap effects principle.

The deflection will therefore result from the sum of bare rope deflection (distributed load) and the components of deflections at concentrated loads:

Bare rope deflection: $F_f = \frac{q * C_i^2}{8 * \frac{T_k + T_y}{2}}$

Deflection under load j: $F_{Pj} = \frac{P\ (L_i - b_{oi}) b_{oi}}{L_i * H_k}$

$$\begin{cases} if\ b_{oi} < \frac{L_i}{2}, than\ F_{gjm} = F_{gj} * \frac{\frac{L_i}{2}}{L_i - b_{oj}} \\ if\ b_{oi} > \frac{L_i}{2}, than\ F_{gjm} = F_{pj} * \frac{\frac{L_i}{2}}{b_{oj}} \end{cases}$$

Overlap effects principle: $Fm = Ff + \sum_{j=l}^{n}(Fpjm)$

Calculation of the catenary development

Once the values of span deflections have been obtained, the actual geometric configuration of the rope is determined by calculating the coordinates of the points where loads concentrate. The total development of the entire span results from the sum of the chords between such point and the development of the bare rope at every considered chord.

$$S_{vc} = \sum_{j=1}^{n+1} (C_j + \frac{8}{3} * \frac{F_{cj}^2 * \cos^2(\,alpha_j)}{C_j})$$

being

S_{vc} = development of ith span

C_j = chord between the vertex of concentrated loads

F_{cj} = deflection of the bare rope at the middle of chord j

$alpha_j$= chord j inclination angle as to the horizontal plan

$$F_{cj} = q * \frac{C_j^2}{8\,H_k * \cos(alpha_j)}$$

The coordinates of the vertexes of the concentrated loads along the span result from the exact sum of the lowering caused due to individual deflection, the component of other loads in the span, and the bare rope itself.

Please note that calculating how much the bare rope affects the lowering of loads required finding the coefficients of its function ($y = A\ x^2 + B\ x + C$) by establishing the boundary conditions.

8.2 Simulation of an urban line

It is simulated an urban line of the hybrid CableSmart system installation, in a cable car segment, with the input data shown in the Table 30:

Variable	*Unit of measurement*	*Input value*
Line capacity	Passengers per hour per direction	1,480
Counterweight	daN	
Line horizontal length	m	1,500
Line difference in altitude	m	0

Table 30-Input data of the urban line simulation

The simulation is performed considering a bicable installation, so, as the weight of the vehicle is equally supported between the two ropes, the value of the vehicle weight is halved in the SIF software input, that simulates a mono cable system.

About the line geometry, it is considered a 25m high tower every 150m, with exception for the first and the last towers, with reduced high and which the distance with the borders of the stations is lower. Every tower has 6 rolls for each rope both in ascend and in descend direction, except the first two and the last two towers, having 12 rolls for each rope, as they should manage the incremented pressure due to the difference in height of the rope altitude. The geometry of the line is reported in the Table 31

Tower	*Horizontal distance from AV [m]*	*Altitude of the terrain [m]*	*Vertical high of the tower [m]*	*Altitude of the rope [m]*	*Number of rolls for each rope in ascent direction*	*Number of rolls for each rope in descent direction*
AV	0	0	4.00	4.00		
C1	20.00	0	8.00	8.00	12	12
C2	170.00	0	25.00	25.00	12	12
C3	320.00	0	25.00	25.00	6	6
…						
Ci	O[i-1] +150.00m	0	25.00	25.00	6	6
…						
C10	1,220.00	0	25.00	25.00	6	6
C11	1,370.00	0	25.00	25.00	12	12
C12	1,480.00	0	8.00	8.00	12	12
AM	1,500.00	0	4.00	4.00		

Table 31 Geometry of the simulated line

The line testing calculation is performed for each dynamic scenario (stopped plant, motion with constant speed, acceleration phase and deceleration phase) and for each utilization scenario (full ascent and descent, empty ascent and descent, full ascent and empty descent, empty ascent and full descent, and rope without any clamped vehicle), and it is verified that all the constrains defined by the Italian normative

Topic	*Italian norms reference*	*Italian norms prescription*	*verification*
Minimum load of support rollers	DM 172-2021, art 15.6.4.6	Minimum load ≥ 50 daN	158 daN (C12)
Minimum load of compression rollers	DM 172-2021, art 15.6.4.6	Minimum load ≥ 50 daN	The line does not include compression rollers
Maximum load of rollers	/	/	629 daN (C10)
Load of roller assemblies	DM 172-2021, art 15.6.4.3	Minimum load of the subjacent support rollers should be > 0 in case of tension increase of 40%	The line does not subjacent rollers

Load of roller assemblies	DM 172-2021, art 15.6.4.4	Minimum load of the compression rollers should be < 0 in case of minimum tension of the rope and load increase of 25%	The line does not include compression rollers
Minimum safety degree	DM 192-2021 art 15.6.2.1	Safety degree>4	4.01
Maximum safety degree	DM 172-2021, art 15.6.2.3	Safety degree<20	4.53
Adhesion	DM 172-2021, art 15.11.1	$\frac{T}{t} < e^{f*\alpha}$	$\frac{333,633}{295,625} < e^{0,2*\frac{170\pi}{180}}$ 1.12<1.81
Maximum number of passengers in the line	DM 172-2021, art 3.1.3.4	Maximum number of passengers in the line<500	192
Minimum vertical clearance	DM 172-2021, art 3.3.5	- Distance between the vehicle and the snowed ground of unreachable areas> 1,5m - Distance between the vehicle and the snowed ground of reachable areas> 2,5m - Distance between the vehicle and the roads or ski runs> 4,0m	As the line is completely horizontal and with constant spans, the minimum clearances are related to middle point of the span. Its value is the difference between the high of the rope in the middle point of the span (22,63m) and the high of the vehicle (4m), id est 18,63m
Maximum vertical clearance	DM 172-2021, art 3.4.2.1.	In case of evacuation of the passengers through lowered to the ground, the maximum distance between the vehicle and the ground should not overcame 60m. This value can be locally increased until 100m	As the line is completely horizontal, the maximum clearances are related to the tower position. Its value is the difference between the high of the towers (25m) and the high of the vehicle (4m), id est 21m
Maximum speed in line	DM 172-2021, art 3.5.2.4	Speed < 7m/s (Enclosed vehicles with two carrying- hauling ropes)	5 m/s

Maximum speed in station	DM 172-2021, art 3.5.2.6	Speed < 1.3 m/s (transportation of pedestrians)	0 m/s The hybrid technology allows the complete stop of the vehicle in front of the embarking pad
Minimum headway	DM 172-2021, art 3.5.3.2	Headway>5s	24,2 s

Table 32-Verification of compliance with the Italian cable car norms. Norms references and prescriptions are related to a cable car with two carrying- hauling ropes and with enclosed vehicles

Regarding the power needed by the simulated installation, the fully-operational power requested from the engine is 314.7kW (each of the two ropes need to a power of 157.35W), while the power requested during the acceleration phase is 497.38kW. The above-mentioned values are obtained with an overall yield of $\eta=0.92$.

8.3 Perturbation analysis

In order to understand how sensitive the results described in the previous chapter are in function of the input data variations, a perturbation analysis was carried out, varying one input data at a time and, therefore, defining the impact that a particular input data has on the line calculation.

Line capacity

The base scenario was defined with a line capacity of 1,480 passengers per hour per direction. Increasing this value without variation in the other variables value, the safety degree falls below the limit value of 4.00 imposed by the Italian norms [R39] during the perturbation analysis, to intervene, jointly with the variation of the line capacity, also changing another parameter. In order not to decrease the counterweigh, and so avoiding the reduction of the pressures on the rollers, that can have unwanted effect on the line (e.g., rope derailment) it was decided to consider a bigger rope (and so, with higher actual breaking load, that is the numerator in the calculation of the safety degree) when the safety degree decreases under its normative limit of 4.00. Moreover, increasing the line capacity maintaining constant the speed of the vehicles, the number of vehicles increases. So, also the load on the towers (and on the rollers) raises, and, in particular, the value of the unitary load on each roller P_U increase. So, in order to avoid that the value of the unitary load on the rollers P_u reach too high values, the number of rollers for each tower is increased. Despite the Italian norms do not cite an upper limit for the unitary load on the rolls $P_{u,}$ its value is constrained by the manufacturers of rollers. Typically, the upper limit is between 800 daN and 900daN, and in this calculation it was considered the average value of 850daN.

The below-reported Table 33 summarizes the main output data in function of the hourly capacity of the line. The column “full operation power” is calculated as the average value in the maximum capacity scenario, so in the hypothesis that both the branches of the plant are fully loaded, when the plant is operating in steady state. It is underlined that, as the plant considered in this simulation is derived from a bicable gondola, the correct values of the “full operated power” inserted in the Table 33 are calculated by doubling the output value of the SIF software (that simulate the line testing calculation for a mono-cable gondola, and in which the input values regarding the weight of the empty vehicle and of the passengers ware halved).

Capacity [passengers per hour per direction]	*Number of vehicles*	*Rope*	*Safety degree*	*Full-operation power [kW]*
1,480	30	Warrington φ=47	4.01	287
1,500	30	Warrington φ=48	4.16	292
1,750	35	Warrington φ=48	4.13	313
2,000	41	Warrington φ=48	4.12	334
2,250	46	Warrington φ=48	4.08	360
2,500	51	Warrington φ=48	4.06	372
2,750	56	Warrington φ=48	4.04	397
3,000	61	Warrington φ=48	4.03	421
3,250	66	Warrington φ=48	4.03	442
3,500	71	Warrington φ=49	4.14	471
3,750	76	Warrington φ=49	4.14	486
4,000	81	Warrington φ=49	4.09	508
4,250	85	Warrington φ=49	4.09	528
4,500	91	Warrington φ=49	4.07	559
4,750	96	Warrington φ=49	4.02	581
5,000	101	Warrington φ=49	4.02	600

Table 33-Results of the perturbation analysis of the variable "hourly capacity"

With the aim to quantify the energy impact of the simulated line, it is calculated the specific consumption associated to the made simulation, as per the following formula:

$$e = \frac{P}{C * L * \mu}$$

Variable	*Meaning*	*Unit of measurement*	*Input value*
P	Fully operational power	kW	Depending by the line capacity.
C	Line capacity	Passengers per hour	
L	Line horizontal length	km	1.5
μ	Average filling factor of the line		100%
e	Specific consumption	kWh/passenger/km	

Table 34-Variables and their input values in the formula for the calculation of the specific consumption e

About the hourly line capacity C, its value is obtained considering the full load situation, in coherence with the power P, that is related to the same load scenario. In fact, contrary to what happens in traditional mountain application of cable cars, in urban contexts the maximum load value can be reached in both the directions, so doubling the passengers transported in the unit of time.

Capacity [passengers per hour]	**Specific consumption [kWh/pass/km]**
2,960	0.065
3,000	0.065
3,500	0.060
4,000	0.056
4,500	0.053
5,000	0.050
5,500	0.048
6,000	0.047
6,500	0.045
7,000	0.045
7,500	0.043
8,000	0.042
8,500	0.041
9,000	0.041
9,500	0.041
10,000	0.040

Table 35-Specific consumption and hourly capacity of the line

The punctual value of the specific consumption e calculated in this simulation are consistent with the ones cited in [R33], that shown a value of 0,05 kwh/passenger/km for the rope segment of the hybrid CableSmart system.

Regarding the correlation between the capacity as independent variable and the specific production as dependent variable, the Figure 79 shows a decrescent correlation: higher is the hourly capacity of the line, lower is the unitary energy needed to transport a passenger for one kilometre, as in high-capacity scenarios the fixed consumption in terms of energy is allocated in more passengers. Nevertheless, the graph reported in the Figure 79 shows that the correlation is not mathematically perfect, but it suffers the presence of a background noise, due to the heaviness of the line (bigger rope with higher weight, and more numerous rolls). Furthermore, as the friction of the rope on the rolls depends by the unitary load on each roll P_U, in turn directly linked to the number of vehicles and, so, to the hourly capacity, the reverse dependence between hourly capacity and specific consumption is muffled.

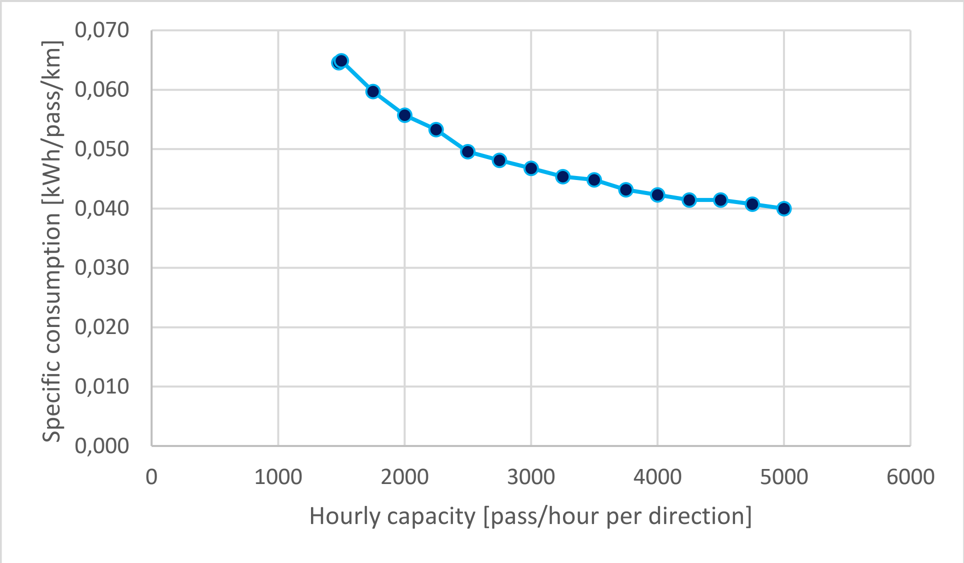


Figure 79-Graph linking the hourly capacity and the specific consumption

In order to mathematically quantify the dependence of the specific production in function of the hourly capacity, the linear regression model between the inverse of the hourly capacity and the specific consumption is used.

$$C \sim \frac{1}{e}$$

$$e \sim \frac{1}{C}$$

$$e = \beta_0 + \beta_1 \frac{1}{C}$$

To find the coefficients β_0 and β_1 associated to the linear regression model means to define the line which best approximates, in terms of least squares methodology, the mathematical correlation between inverse of the hourly capacity and the specific consumption

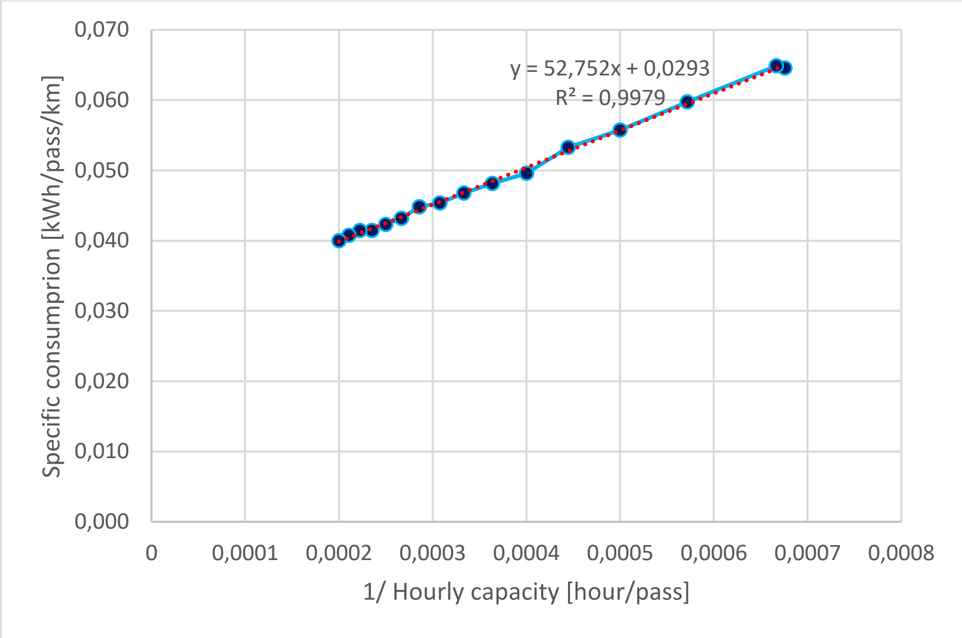


Figure 80-Graph linking the inverse of the hourly capacity and the specific consumption

The linear regression line can model very well the empirical curve, as it is shown by the high value of R^2 parameter: the 99.8% of the variability of the empirical data can be explained by the linear regression model.

The following Table 36 collects the output parameters of the linear regression, and consider for each parameter the expected values and the lower and upper limits of the confidence interval with confidence degree of 95%.

Coefficient	*Expected value*	*Confidence interval*
β_0 $[\frac{kWh}{pass*km}]$	0.0293	(0.0287; 0.0298)
β_1 $[\frac{kWh}{h*km}]$	52.7518	(51.3813; 54.1225)

Table 36-Coefficient of the linear regression line that quantifies the correlation between the inverse of the hourly capacity and the specific consumption

Considering the average values of the regression parameters, the above-mentioned formula linking the hourly capacity and the specific consumption is:

$$e = \beta_0 + \beta_1 \frac{1}{C}$$

$$e = 0.0293 + 52.7518 \frac{1}{C}$$

The above-mentioned results were calculated considering envelope of all the load scenarios

Load scenarios with horizontal line

The above-mentioned results are obtained considering a line completely loaded in the both travel directions. Of course, this is a very peculiar and non-common situation; even if, in the urban contexts, the passengers flow direction is not univocal, as in the case in mountain transportation of skiers, where, normally, the plant is loaded in the rise branch and unladed in the descent branch, also in urban environment the mobility demand typically follows models with vectorial sum non null.

In this chapter, the results of an analysis about the energy impact of the plant with load scenarios are described.

In addition to the “classical” load scenarios (one branch loaded and the other one unladen, both branches loaded, both branches unladen and empty rope), an analysis considering different passengers load in the two cable-car branches was performed. The intermediate load scenarios between the completely unlading and the complete loading of the branches were defined with granularity 10%; so, 11 situations for the loading of one branch and 11 situations for the loading of the other branch were analysed, defining a total of 121 load scenarios. The simulated line was the base one, so completely horizontal, with a distance between the two stations of 1,500m and with an hourly maximum capacity of 1,480 passengers per hour per direction.

The below-reported *Table 37* shows the power requested for the simulated line in the different load scenarios, in steady state condition; The *Table 38* reports the hourly capacity for each load scenario, and the *Table 39* collects the data regarding the specific consumption of the line, calculated for each load scenario (so, for each cell of the matrix) as per the following formula:

$$e_{ad} = \frac{P_{ad}}{C_{ad} * L}$$

Where:

- A [%] is the load scenario of one branch;
- d [%] is the load scenario of the other branch;
- e_{ad} $[\frac{kWh}{pass*km}]$is the unitary energy consumption of the ad scenario;

- P_{ad} $[kW]$ is the power associated to the ad scenario, calculated by doubling the output data of the SIF software, as the simulated line is derived from a bicable gondola;
- C_{ad} $[\frac{pass}{h}]$is the actual hourly capacity of the line, calculated summing the hourly capacity of the two branches, each of them included between 0 and 1,480 passengers per hour

d: loading of the branch between the tension station and the drive station	a: load of the branch between the drive station and the tension station										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%	260	261	262	264	265	266	268	269	270	272	273
10%	261	262	264	265	266	268	269	270	272	273	274
20%	262	264	265	266	268	269	270	272	273	274	276
30%	264	265	266	268	269	270	272	273	274	276	277
40%	265	266	268	269	270	272	273	274	276	277	278
50%	267	268	269	270	272	273	274	276	277	278	280
60%	268	269	271	272	273	275	276	277	278	280	281
70%	269	271	272	273	275	276	277	279	280	281	283
80%	271	272	273	275	276	277	279	280	281	283	284
90%	272	273	275	276	277	279	280	281	283	284	285
100%	273	275	276	277	279	280	281	283	284	285	287

Table 37-Power [kW] required by the simulated plant in steady state condition, for each load scenario

As the simulated line is completely flat and symmetrical, also the matrix reported in the previous Table 37 is symmetric: in fact, in a complete horizontal line, it is not possible to define a rise and a descent branch.

d: loading of the branch between the tension station and the drive station	a: load of the branch between the drive station and the tension station										
	0%	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
0%	0	148	296	444	592	740	888	1,036	1,184	1,332	1,480
10%	148	296	444	592	740	888	1,036	1,184	1,332	1,480	1,628
20%	296	444	592	740	888	1,036	1,184	1,332	1,480	1,628	1,776
30%	444	592	740	888	1,036	1,184	1,332	1,480	1,628	1,776	1,924
40%	592	740	888	1,036	1,184	1,332	1,480	1,628	1,776	1,924	2,072
50%	740	888	1,036	1,184	1,332	1,480	1,628	1,776	1,924	2,072	2,220
60%	888	1,036	1,184	1,332	1,480	1,628	1,776	1,924	2,072	2,220	2,368
70%	1,036	1,184	1,332	1,480	1,628	1,776	1,924	2,072	2,220	2,368	2,516
80%	1,184	1,332	1,480	1,628	1,776	1,924	2,072	2,220	2,368	2,516	2,664
90%	1,332	1,480	1,628	1,776	1,924	2,072	2,220	2,368	2,516	2,664	2,812
100%	1,480	1,628	1,776	1,924	2,072	2,220	2,368	2,516	2,664	2,812	2,960

Table 38-Actual hourly capacity [passengers/hour] of the simulated plant in steady state condition, for each load scenario

d: loading of the branch between the tension station and the drive station	a: load of the branch between the drive station and the tension station										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%	/	1.176	0.591	0.396	0.298	0.240	0.201	0.173	0.152	0.136	0.123
10%	1.176	0.591	0.396	0.299	0.240	0.201	0.173	0.152	0.136	0.123	0.112
20%	0.591	0.396	0.299	0.240	0.201	0.173	0.152	0.136	0.123	0.112	0.104
30%	0.396	0.299	0.240	0.201	0.173	0.152	0.136	0.123	0.112	0.104	0.096
40%	0.299	0.240	0.201	0.173	0.152	0.136	0.123	0.112	0.104	0.096	0.090
50%	0.240	0.201	0.173	0.152	0.136	0.123	0.112	0.104	0.096	0.090	0.084
60%	0.201	0.173	0.152	0.136	0.123	0.112	0.104	0.096	0.090	0.084	0.079
70%	0.173	0.152	0.136	0.123	0.112	0.104	0.096	0.090	0.084	0.079	0.075
80%	0.152	0.136	0.123	0.112	0.104	0.096	0.090	0.084	0.079	0.075	0.071
90%	0.136	0.123	0.112	0.104	0.096	0.090	0.084	0.079	0.075	0.071	0.068
100%	0.123	0.112	0.104	0.096	0.090	0.084	0.079	0.075	0.071	0.068	0.065

Table 39-Unitary energy consumption [kWh/passenger/km] of the simulated plant in steady state condition, for each load scenario

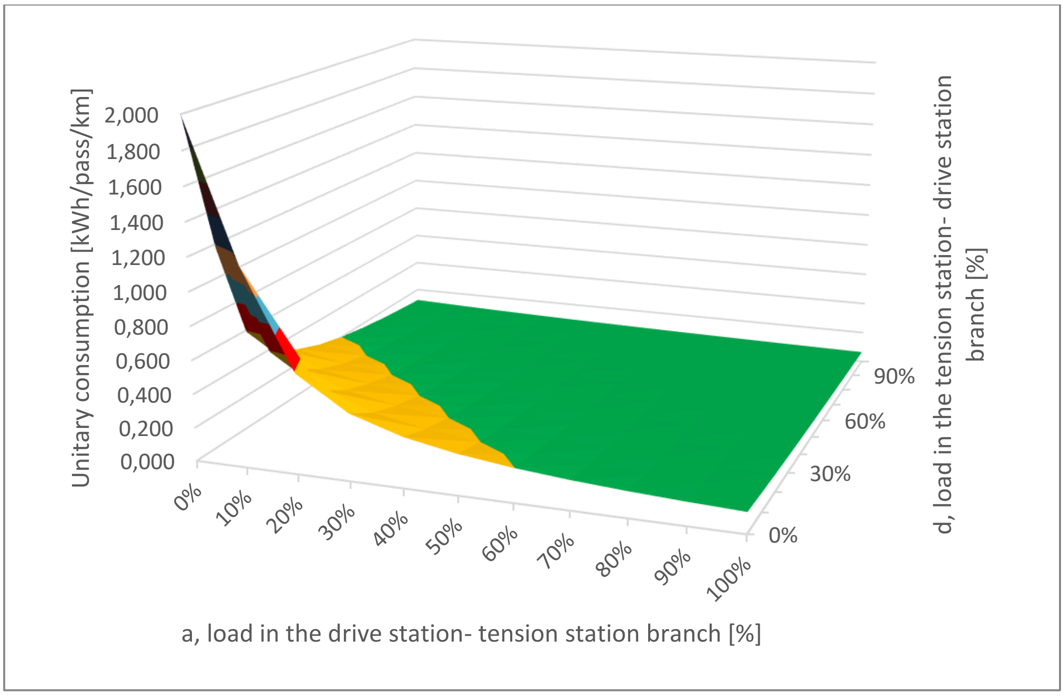


Figure 81-Unitary consumption in function of the load in the two branches of the simulated line. Simulations were made through MATLAB and Excel software

As reported in the Table 39 and graphically shown in the Figure 81, the unitary consumption does not depend by the way in which the line is loaded, but solely by the total load value. It follows that equal hourly capacities correspond to equal specific consumption, without the individual values of the load in the two opposite branches a and d.

$$e = f\ (a + d), \text{ not } \ e = f(a, d)$$

So, it is possible to reduce the matrix reported in the Table 39 in the one-dimension Table 40, that collect the values of the energy consumption in function of the hourly capacity:

- The column "load" represents the average percentage fill of the vehicles, so the actual hourly capacity compared with the nominal one. For instance, the 200% value corresponds to the load scenario where both the branches are completely loaded, while the 100% value can correspond to the scenario where one branch is completely load and the other one is completely unloaded (a=100% and d=0%) or to the scenario where both the branches are half-loaded (a=50% and d=50%), or to the all-intermediate scenario as, as previously reported, the value of the unitary consumption is only function of the actual capacity of the line, and it is not linked to the mode through which the value is reached.

- The column C represents the hourly capacity;
- The column e represents the energy unitary consumption;
- The column $e_{HYPERBOLA}$ represents the theoretical value of the energy specific consumption calculated as the hyperbolic mathematical function with the constrain to pass in the point ($C_{200\%}$, $e_{C=200\%}$). So, the $e_{HYPERBOLA}$ value represents the specific consumption calculated not through SIF punctual simulation, but by mathematical way, as proportion of the maximum capacity energy specific consumption.

$$e = \frac{\beta}{C}$$

With β=191, deduced imposing the hyperbola by the point ($C_{200\%}$, $e_{C=200\%}$) = (2,960 passengers per hour; 0,065 kWh/pass/km)

- The column Δe represent the percentual difference between the specific consumption mathematically calculated and the specific consumption obtained through SIF simulation.

$$\Delta e = \frac{e_{HYPERBOLA} - e}{e_{HYPERBOLA}}$$

Load [%]	C [passenger/hour]	e [kWh/pass/km]	$e_{HYPERBOLA}$ [kWh/pass/km]	Δe [%]
0%	0	/	/	/
10%	148	1.176	1.291	8.9%
20%	296	0.591	0.646	8.4%
30%	444	0.396	0.430	8.0%
40%	592	0.299	0.323	7.5%
50%	740	0.240	0.258	7.0%
60%	888	0.201	0.215	6.5%
70%	1,036	0.173	0.184	6.1%
80%	1,184	0.152	0.161	5.6%
90%	1,332	0.136	0.143	5.1%
100%	1,480	0.123	0.129	4.6%
110%	1,628	0.112	0.117	4.3%
120%	1,776	0.104	0.108	3.8%
130%	1,924	0.096	0.099	3.3%
140%	2,072	0.090	0.092	2.8%
150%	2,220	0.084	0.086	2.4%
160%	2,368	0.079	0.081	1.9%
170%	2,516	0.075	0.076	1.4%
180%	2,664	0.071	0.072	1.0%
190%	2,812	0.068	0.068	0.5%
200%	2,960	0.065	0.065	0.0%

Table 40-Specific consumption in function of the actual capacity

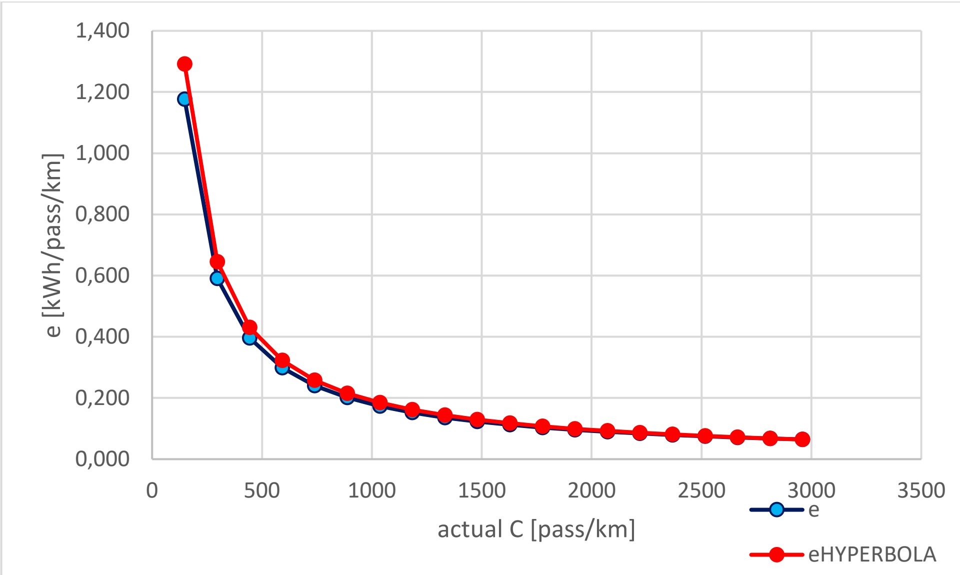


Figure 82-Specific consumption in function of the actual capacity

As reported in the **Table 40** and in the **Figure 82**, the hyperbolic function is able to model the simulated behaviour of the energy specific consumption when the actual C is close to the maximum one (through the hyperbolic function is defined), while it tends to overestimate the energy impact when for low actual hourly capacities (until 8,9% in the scenario with actual capacity equal to the 5% of the total maximum one).

This happens because, in ropeway plants and in plants derived by gondolas, the weight of the passengers is not negligible compared with the weight of the vehicle, and so, the friction due to the contact between the rope and the rollers (that in a growing function of the weight of the vehicles), increase with the actual hourly capacity and with the transported load. In other words, with low actual capacity also the requested total power is lower, and this causes the fact that the simulated function is lower than the hyperbolic one.

In the simulated case, the ratio between the weight of the passengers in a fully loaded vehicle (640 kg) and the weight of the empty vehicle (1,977 kg) is more than 32%. The effect of the actual payload that makes sub-hyperbolic the function of the specific consumption is even higher in the traditional gondolas' plants, where the absence of batteries, supercapacitors and electric devices in the vehicle makes it even lighter, and increase the ratio between the weight of the passengers and the weight of the empty vehicle.

Slope

The base scenario is defined as a line with null slope, where the difference in height between the upstream station and the downstream one is zero. This can be a good model for a high number of urban installations, but, as the hybrid CableSmart system is derived from cable car technology and it has as strength the efficient overcoming of differences in high, the slope parameter was perturbed in order to find the correlation between the average inclination of the line and other output parameters.

In this perturbation analysis, the slope of the line is maintained constant along all the line, but it is changed. It is underlined that, considering a non-null difference in height between the two stations, the location of the engine and of the counterweight become relevant; and in all the perturbation scenarios it is assumed that the power station is the upstream one, and the tension station is the downstream one, in order to optimize the line in terms of rope tensions and motor power.

The horizontal length of the line was kept constantly equal to 1,500m. The hourly capacity is maintained the same of the base scenario, id est 1,480 passengers per hour per direction, while the type of the rope was changed, choosing ropes with higher maximum load, in order to ensure the compliance with the in-force Italian norms; similarly, also the number of rollers per roller assembly was increased, in order to maintain the compliance of the line with maximum values of unitary pressure on the rollers.

The results, with emphasis on the energy performance of the line, are collected in the following Table 41, where the results are related to the load scenario of maximum load, when both the rise branch and the ascent one are fully loaded.

Slope [%]	*Difference in height between the two stations [m]*	*Inclined length of the plant [m]*	*Full-operation power [kW]*	*Specific consumption [kWh/pass/km]*
0%	0	1,500.0	290	0.065
5%	75	1,501.9	290	0.065
10%	150	1,507.5	295	0.066
15%	225	1,516.8	304	0.068
20%	300	1,529.7	304	0.067
25%	375	1,546.2	314	0.069
30%	450	1,566.0	312	0.067
35%	525	1,589.2	323	0.069
40%	600	1,615.5	324	0.068
45%	675	1,644.9	329	0.068
50%	750	1,677.1	336	0.068
55%	825	1,711.9	336	0.066
60%	900	1,749.3	324	0.063

Table 41-Energy performance output of the 1,480 passengers per hours per direction / 1,500-meters line in function of the slope of the terrain

In order to define and quantify the statistical relationship between the slope of the line, assumed constant, and the specific consumption, a linear regression model was defined, and the results are reported in the following *Figure 83* and *Table* ***42***.

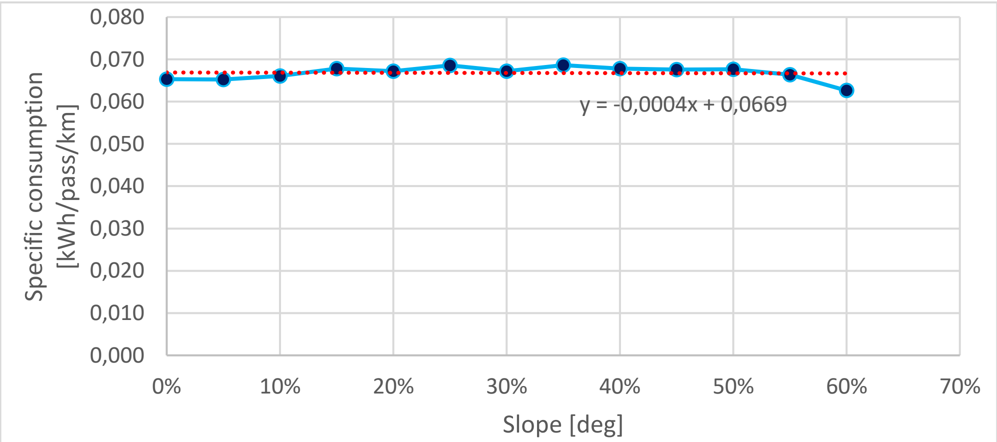


Figure 83-Graph linking the slope of the line to its specific consumption, with the assumption that both branches are fully loaded

Coefficient	Expected value	Confidence interval
$\boldsymbol{\beta_0}\ [\frac{kWh}{pass*km}]$	0.0669	(0.065; 0.069)
$\boldsymbol{\beta_1}\ [\frac{\frac{kWh}{pass*km}}{\%}]$	-0.004	(-0.006; 0.005)

Table 42-Coefficient of the linear regression line that quantifies the correlation between the slope and the specific consumption

$$e = \beta_0 + \beta_1 s$$

$$e\left[\frac{kWh}{pass * km}\right] = 0.0669\,\frac{kWh}{pass * km} - 0.004\,\frac{\frac{kWh}{pass * km}}{\%}\,s\ [\%]$$

As the confidence interval of the coefficient of the slope in the equation of the linear regression line (-0.006; 0.005) contains the null value, it is possible to assert, with an interval of confidence of 95%, that there is not dependence between the slope of the line and the energy specific consumption, considering the scenario where the line is completely loaded both in rise branch, and in descent one.

Load scenarios with sloped line

In the horizontal-line cases the load scenario intervened in marginal way in the calculation of the energy and power output of the line. As previously demonstrate, indeed, there is also in the horizonal line a crescent dependency between the load scenario and the power requested by the plant, and this caused a sub-hyperbolic link between the actual capacity and the specific consumption of the line, due to the fact that, increasing the hourly actual capacity, the power to be allocated to more passengers was strictly higher. Quantifying the phenomenon, it was in the order of less than 20% (data obtained in *Table **40*** as percentual difference between the hyperbolic and the simulated energy consumption), and anyway it was dependent only by the quantity of passengers on the line, not by the way in which they are distributed on the two branches.

On the other hand, in the sloped scenario the potential energy lost by the vehicle in descend branch is used to increase the potential energy of the vehicle in the rise branch, acting as a counterweight and reducing the energy needs of the plant.

This type of effect was the basis of the water funiculars, transport systems that did not require electricity or engines, in which the motion of the carriages was guaranteed by the gravitational balance of the two vehicles, joined by an upper half-loop of rope:

i) When the carriage on the rise branch was empty and the carriage on the descent branch was loaded, the system naturally moved the loaded and heavier carriage in the descent branch toward the downstream station, and the empty and lighter carriage toward the upstream station.

ii) When the carriage on the rise branch was loaded and the carriage on the descent branch was empty, a tank in the empty carriage in the upstream station was fulfilled with water, increasing its weight and making it heavier than the loaded vehicle in the downstream station. In this way, the system moved the unloaded, but heavier as its tank was fulfilled by water, carriage in the descent branch toward the downstream station, and the loaded carriage toward the upstream station.
When the heavy water-fulfilled carriage arrived in the downstream station, its tank was emptied.

In general, the energy ΔU exchanged, net of the losses due to the friction, by the two carriages was

$$\Delta U = \Delta m * g * h$$

Where:

-g $[\frac{m}{s^2}]$is the gravity acceleration;

- h [m] is the difference in height between the two stations;

- Δm [kg] is the difference in the mass of the two carriages. In the (i) situation it is the difference between the mass of the loaded vehicle and the mass of the empty vehicle, id est the mass of the passengers, while in the (ii) situation it is the difference between the mass of the water-fulfilled carriage and the passengers-loaded vehicle.

This physical principle makes the energy calculation of a gondola line very dependent in function not only by the actual hourly capacity, but also by the distribution of the passengers in the ascent and descent branch. Qualitatively:

i) If the gravitational potential energy owned by the vehicles on the descent branch is, gross of the losses due to the friction, higher than the gravitational potential energy owned by the vehicles in the rise branch, the motion of the system is given naturally by the equilibrium laws, and the energy to give to the gondola is negative. Operatively, in traditional gondolas the energy obtained from the rope-vehicle system when it naturally evolves towards motion is converted into electrical energy and transferred to the electricity grid or used to fill energy storage systems; the latter use is very useful in the case of the hybrid CableSmart system, which uses batteries on board the vehicles that can easily be charged by the over-energy of the rope-vehicle system;

ii) If the gravitational potential energy owned by the vehicles on the descent branch is, gross of the losses due to the friction, lower than the gravitational potential energy owned by the vehicles in the rise branch, the motion of the system should be guaranteed by an external engine, and the energy to inject into the system is higher than zero.

By a quantitative point of view, an analysis of the relationship between the slope and energy consumption in different load scenarios is carried out. The results are collected in the following tables and graphs:

Ascent branch	Loaded	Loaded	Empty	Empty	Empty rope
Descent branch	Loaded	Empty	Loaded	Empty	Empty rope
Slope = 0%	290	286	260	259	162
Slope =5%	290	310	239	259	163
Slope =10%	295	337	222	264	170
Slope =15%	304	368	209	272	174
Slope =20%	304	394	184	273	177
Slope =25%	314	429	168	282	185
Slope =30%	312	453	139	280	184
Slope =35%	323	490	123	290	191
Slope =40%	324	518	100	294	198
Slope =45%	329	549	78	298	201
Slope =50%	336	582	58	304	204
Slope =55%	336	608	32	303	202
Slope =60%	324	623	-4	294	200

Table 43-Average power [kW] requested for the 1,480 passengers per hours per direction / 1,500-meters line in function of the slope of the terrain and of the load scenario

The previous *Table 43* collects the data of the average power [kW] requested for the line in the five limit scenarios, while the *Table 44* and the *Figure 84* define, when it is possible (so, when there are passengers transported) the energy unitary consumption as a function of the slope and of the load scenario.

ASCENT BRANCH	Loaded	Loaded	Empty
DISCENT BRANCH	Loaded	Empty	Loaded
Slope= 0%	0.065	0.129	0.117
Slope= 5%	0.065	0.140	0.107
Slope= 10%	0.066	0.151	0.100
Slope= 15%	0.068	0.164	0.093
Slope= 20%	0.067	0.174	0.081
Slope= 25%	0.069	0.187	0.073
Slope= 30%	0.067	0.195	0.060
Slope= 35%	0.069	0.209	0.052
Slope= 40%	0.068	0.217	0.042
Slope= 45%	0.068	0.226	0.032
Slope= 50%	0.068	0.234	0.023
Slope= 55%	0.066	0.240	0.013
Slope= 60%	0.063	0.241	-0.001

Table 44-Specific consumption requested for the 1,480 passengers per hours per direction / 1,500-meters line in function of the slope of the terrain and of the load scenario

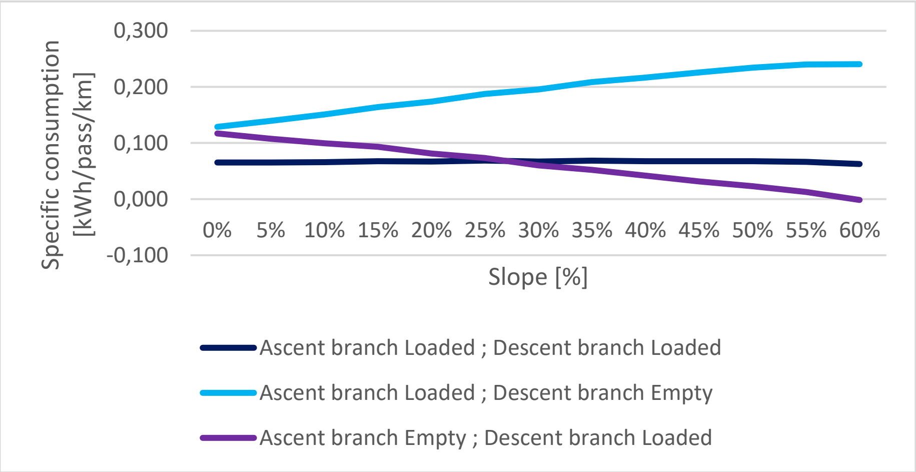


Figure 84-Specific consumption requested for the 1,480 passengers per hours per direction / 1,500-meters line in function of the slope of the terrain and of the load scenario

The above reported *Figure **84*** reports the behaviour of the specific consumption of the line in function of the average slope, considering three extreme load scenarios: ascent branch completely loaded and descent branch completely empty, descent branch completely loaded and ascent branch completely empty, and both the branches completely loaded.

i) When both the branches are completely loaded (scenario analysed and explained in the previous chapter, dark blue line in *Figure **84***), the specific consumption associated to the horizontal line is approximately half than the value found in the other two scenarios, as the hourly capacity is double and the requested power is approximately the same of the other scenario. Then, the curve is almost flat: as demonstrated in the previous chapter, there is not statistical correlation between the specific consumption and the slope of the line when both the branches are loaded. This result can be explained by the fact that, being both the ascent line and the descent, one completely loaded, the two branches are balanced in terms of weight and energy, and this balance does not depend by the slope. So, with all the slope values, the requested energy is the one needed to cover the friction;

ii) When the ascent branch is loaded and the descent one is empty (light blue line in Figure 30) the forward force and the energy consumption are maximum. In this scenario, in fact, the gravitational contribution to the motion of the plant of the empty and lighted vehicles in the descent branch is only minimal. So, an external engine should provide the unbalanced power, in addition to the power to cover the one lost by friction, and the unbalance between the vehicles in the two branches depend in crescent way by the slope

iii) When the ascent branch is empty and the descent one is fully loaded (violet line in Figure 30) the forward force and the energy consumption are minimum. In this scenario, in fact, the gravitational contribution to the motion of the plant of the loaded and heavy vehicles in the descent branch is able to provide the maximum contribute to the motion toward the upstream station of the empty and light vehicle in the ascent branch. Also in this case, the unbalance force given by the weight disequilibrium in the two branches growths with the slope, and, when the slope is over 60%, the energy provided to the imbalance of the weights is able to win all the frictions, and the energy consumption.

The below reported *Table **45*** shows the coefficients of the linear regression line, that more closely approximate the curves of specific consumption in function of the slope in the three extreme scenarios considered.

Coefficient	Ascent branch loaded; descent branch loaded	Ascent branch loaded; descent branch empty	Ascent branch empty; descent branch loaded
$\boldsymbol{\beta_0}\ [\frac{kWh}{pass*km}]$	0.0669	0.1236	0.1292
$\boldsymbol{\beta_1}\ [\frac{\frac{kWh}{pass*km}}{\%}]$	-0.004	0.0099	-0.0097

Table 45-Coefficient of the linear regression line that quantifies the correlation between the slope and the specific consumption in the three different load scenarios

$$e = \beta_0 + \beta_1 s$$

$$e\left[\frac{kWh}{pass*km}\right] = \begin{cases} 0.0669\frac{kWh}{pass*km} - 0.004\frac{\frac{kWh}{pass*km}}{\%}s\,[\%]\ \ if\ asc = loaded; desc = loaded \\ 0.1236\frac{kWh}{pass*km} + 0.1236\frac{\frac{kWh}{pass*km}}{\%}s\,[\%]\ if\ asc = loaded; desc = empty \\ 0.1297\frac{kWh}{pass*km} - 0.0097\frac{\frac{kWh}{pass*km}}{\%}s\,[\%]\ if\ asc = empty; desc = loaded \end{cases}$$

Load scenarios with 60-degree sloped line

In the previous chapter, an analysis on the specific consumption and of the requested power in function of the slope and with some extreme load scenario was described.

In this chapter, always maintaining the characteristics of the line in terms of base-scenario hourly capacity (1,480 passengers per hour per direction) and of horizontal length (1,500 meters) of the line, a detailed analysis about the different load scenario was carried out, considering a line with average and constant slope of 60%

Slope	60% = 30.96 degree
Horizontal length	1,500 meters
Difference in height	900 meters
Inclined length	1,749 meters

Table 46-Geometrical data of the 60%-sloped line

In coherence with the analysis described in the previous chapter regarding the horizontal line, also in this case, in addition to the extreme load scenarios, intermediate load scenarios are studied. The intermediate load scenarios between the completely unlading and the complete loading of the branches were defined with granularity 10%; so, 11 situations for the loading of one branch and 11 situations for the loading of the other branch were analysed, defining a total of 121 load scenarios.

The below-reported Table 47 shows the power requested for the simulated line in the different load scenarios, in steady state condition; The Table 48 reports the hourly capacity for each load scenario, and the Table 38 and the Table 49 collect the data regarding the specific consumption of the line, calculated for each load scenario (so, for each cell of the matrix) as per the following formula:

$$e_{ad} = \frac{P_{ad}}{C_{ad} * L}$$

Where:

- a is the load scenario of the ascent branch;
- d is the load scenario of the descent branch;
- e_{ad} is the unitary energy consumption of the ad scenario;
- P_{ad} is the power associated to the ad scenario, calculated by doubling the output data of the SIF software, as the simulated line is derived from a bicable gondola;
- C_{ad} is the actual hourly capacity of the line, calculated summing the hourly capacity of the two branches, each of them included between 0 and 1,480 passengers per hour.

a: load of the ascent branch (columns); **d: loading of the descent branch** (rows)

d \ a	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%	294	327	360	393	426	458	491	524	557	590	623
10%	264	297	330	363	396	429	461	494	527	560	593
20%	234	267	300	333	366	399	432	464	497	530	563
30%	205	237	270	303	336	369	402	435	467	500	534
40%	175	208	240	273	306	339	372	405	438	470	504
50%	145	178	211	243	276	309	342	375	408	441	474
60%	115	148	181	214	246	279	312	345	378	411	444
70%	85	118	151	184	217	249	282	315	348	381	414
80%	55	88	121	154	187	220	252	285	318	351	384
90%	25	58	91	124	157	190	223	256	288	321	355
100%	-4	33	66	99	132	165	198	231	263	296	324

Table 47-Power [kW] required by the simulated plant in steady state condition, for each load scenario

a: load of the ascent branch (columns); **d: loading of the descent branch** (rows)

d \ a	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%	0	148	296	444	592	740	888	1,036	1,184	1,332	1,480
10%	148	296	444	592	740	888	1,036	1,184	1,332	1,480	1,628
20%	296	444	592	740	888	1,036	1,184	1,332	1,480	1,628	1,776
30%	444	592	740	888	1,036	1,184	1,332	1,480	1,628	1,776	1,924
40%	592	740	888	1,036	1,184	1,332	1,480	1,628	1,776	1,924	2,072
50%	740	888	1,036	1,184	1,332	1,480	1,628	1,776	1,924	2,072	2,220
60%	888	1,036	1,184	1,332	1,480	1,628	1,776	1,924	2,072	2,220	2,368
70%	1,036	1,184	1,332	1,480	1,628	1,776	1,924	2,072	2,220	2,368	2,516
80%	1,184	1,332	1,480	1,628	1,776	1,924	2,072	2,220	2,368	2,516	2,664
90%	1,332	1,480	1,628	1,776	1,924	2,072	2,220	2,368	2,516	2,664	2,812
100%	1,480	1,628	1,776	1,924	2,072	2,220	2,368	2,516	2,664	2,812	2,960

Table 48-Actual hourly capacity [passengers/hour] of the simulated plant in steady state condition, for each load scenario

d: loading of the descent branch	a: load of the ascent branch 0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%		1.263	0.695	0.506	0.411	0.354	0.316	0.289	0.269	0.253	0.241
10%	1.020	0.574	0.425	0.350	0.306	0.276	0.255	0.239	0.226	0.216	0.208
20%	0.453	0.344	0.290	0.257	0.235	0.220	0.208	0.199	0.192	0.186	0.181
30%	0.263	0.229	0.209	0.195	0.185	0.178	0.172	0.168	0.164	0.161	0.159
40%	0.169	0.160	0.155	0.151	0.148	0.145	0.144	0.142	0.141	0.140	0.139
50%	0.112	0.114	0.116	0.118	0.119	0.119	0.120	0.121	0.121	0.122	0.122
60%	0.074	0.082	0.087	0.092	0.095	0.098	0.100	0.103	0.104	0.106	0.107
70%	0.047	0.057	0.065	0.071	0.076	0.080	0.084	0.087	0.090	0.092	0.094
80%	0.027	0.038	0.047	0.054	0.060	0.065	0.070	0.073	0.077	0.080	0.082
90%	0.011	0.023	0.032	0.040	0.047	0.052	0.057	0.062	0.066	0.069	0.072
100%	-0.002	0.012	0.021	0.029	0.036	0.042	0.048	0.052	0.057	0.060	0.063

Table 49-Unitary energy consumption [kWh/passenger/km] of the simulated plant in steady state condition, for each load scenario

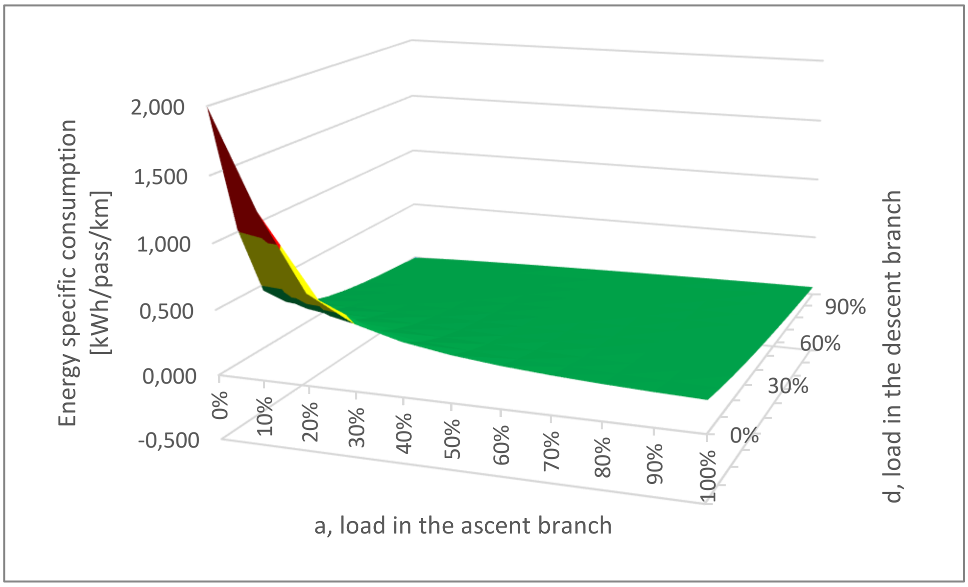


Figure 85-Unitary consumption in function of the load in the two branches of the simulated line

Contrary to what was stated in the previous chapters regarding the case of a horizontal line, with an inclined line the overall hourly capacity of the two branches is not sufficient to uniquely determine the specific energy consumption of the line, which instead is a function of the two independent variables a and d.

$e = f\ (a; d)$, not $e = f(a + d)$

This result can be explained by the fact that the ascent and the descendent branches' loads give a different contribution in the calculus of the energy consumption:

- Ascent branch load gives a positive contribution in terms of energy consumption, as the greater the load in rise branch, the greater the energy required by the system for its motion;
- Descendent branch load gives a negative contribution in terms of energy consumption, as the greater the load in descendent branch, the greater the energy produced internally by the system (through the loss of the gravitational potential energy of the descending vehicles which, since they are loaded, are heavier than the ascending vehicles) and which should not be fed into the system from the outside.

In particular, the case in which the actual capacity is the half of the sum of the maximum hourly currying capacity of each branch of the line.

The following *Table **50*** and *Figure **86*** show the values of energy specific consumption related to an actual capacity equal to 1,480 passengers per hours (a+d=100%), in function of the a and d value with which this currying capacity is achieved. While in the previously faced case of the horizontal line the value of the energy consumption was constant in function of the load distribution on the hourly capacity in the two branches, with a sloped line the lower energy specific consumption the descent branch is loaded.

Scenario	Energy specific consumption [kWh/pass/km]
d=0%; a=100%	0.241
d=10%; a=90%	0.216
d=20%; a=80%	0.192
d=30%; a=70%	0.168
d=40%; a=60%	0.144
d=50%; a=50%	0.119
d=60%; a=40%	0.095
d=70%; a=30%	0.071
d=80%; a=20%	0.047
d=90%; a=10%	0.023
d=100%; a=0%	-0.002

Table 50-Energy specific consumption [kWh/pass/km] in function of the load scenario, with the constrain to have an actual currying capacity of 1,480 (id est the half of the sum of the maximum hourly capacity of the two branches)

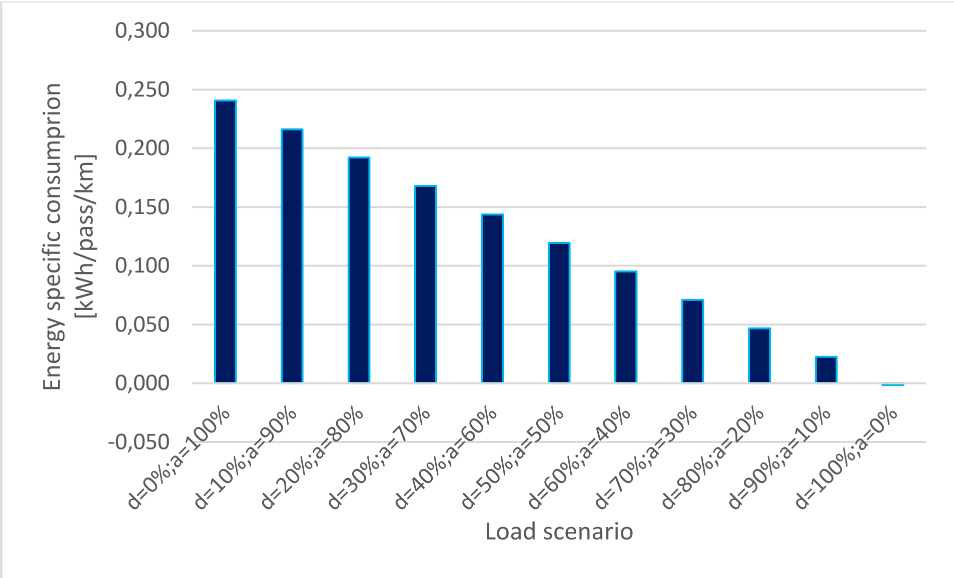


Figure 86-Energy specific consumption [kWh/pass/km] in function of the load scenario, with the constrain to have an actual currying capacity of 1,480 (id est the half of the sum of the maximum hourly capacity of the two branches)

On the other hand, if a whole cycle is considered, so if the constraint that every passenger traveling the line upstream should also travel it downstream and vice versa is inserted in the model, the dependence of the specific energy on the distribution of the load on the two branches is eliminated. The following Table 51 and Figure 87 report the energy consumption of a downstream-upstream cycle (or vice versa), and show that the sum of the energy specific consumption of the two branches is the same for all the load distribution scenario. In particular, in the "cycle scenario" column, the first vector represents the load distribution along the line of the first part of the cycle, and the second vector represent the load distribution along the line of the second part of the cycle; inside every vector, the first percentage is the loading in the descent branch (d) and second percentage is the loading in the rise branch (a).

Cycle scenario	***e1*** [kWh/pass/km]	***e2*** [kWh/pass/km]	$\sum e$ [kWh/pass/2km]	AVG (e) [kWh/pass/km]
(0%;100%) + (100%;0%)	-0.002	0.241	**0.239**	**0.120**
(10%;90%) + (90%;10%)	0.023	0.216	**0.239**	**0.120**
(20%;80%) + (80%;20%)	0.047	0.192	**0.239**	**0.120**
(30%;70%) + (70%;30%)	0.071	0.168	**0.239**	**0.120**
(40%;60%) + (60%;40%)	0.095	0.144	**0.239**	**0.120**
(50%;50%) + (50%;50%)	0.119	0.119	**0.239**	**0.120**

Table 51-Energy specific consumption related to a cycle in different load distribution scenarios (actual hourly carrying capacity equal to 1,480 passengers per hour)

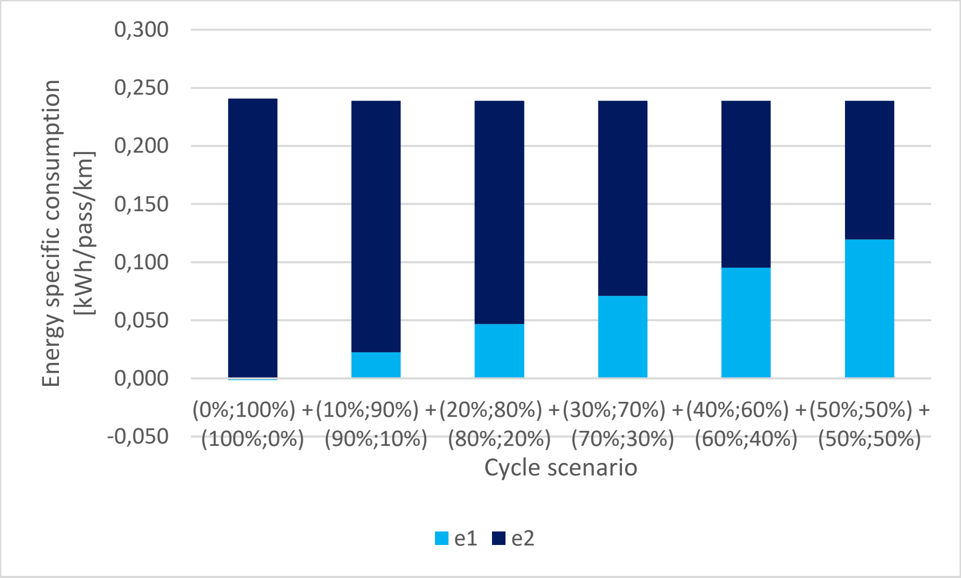


Figure 87-Energy specific consumption related to a cycle in different load distribution scenarios (actual hourly carrying capacity equal to 1,480 passengers per hour)

Chapter 9

9. Energy analysis

9.1 Cable-car energy analysis

The energy analysis of the stretch in cable-car motion mode was reported in the previous chapters. In particular, in the previous chapter, the energy specific consumption related to motion of the hybrid CableSmart system was defined for several scenarios. The results of a subset of analysed scenarios in terms of specific consumption [kWh/passenger/km] and of specific emissions [gCO2/pass/km] are collected in the following Table 52.The conversion between the consumption and emissions was made by considering a conversion factor of 415gCO2/kWh, which is equal to the mean value of the carbon dioxide emissions per kWh of electricity in Italy [R49]

Scenario	*Description of the scenario*	*Specific energy consumption [kWh/pass/km]*	*Specific emissions [gCO₂/pass/km]*
1	Hourly carrying capacity=1,480 pass/h/direction; Flat line; Actual used capacity= 200%[3]	0.065	27.0
2	Hourly carrying capacity=2,500 pass/h/direction; Flat line; Actual used capacity= 200%	0.050	20.8
3	Hourly carrying capacity=5,000 pass/h/direction; Flat line; Actual used capacity= 200%	0.040	16.6

[3] 100% in the rise branch, plus 100% in the descent branch

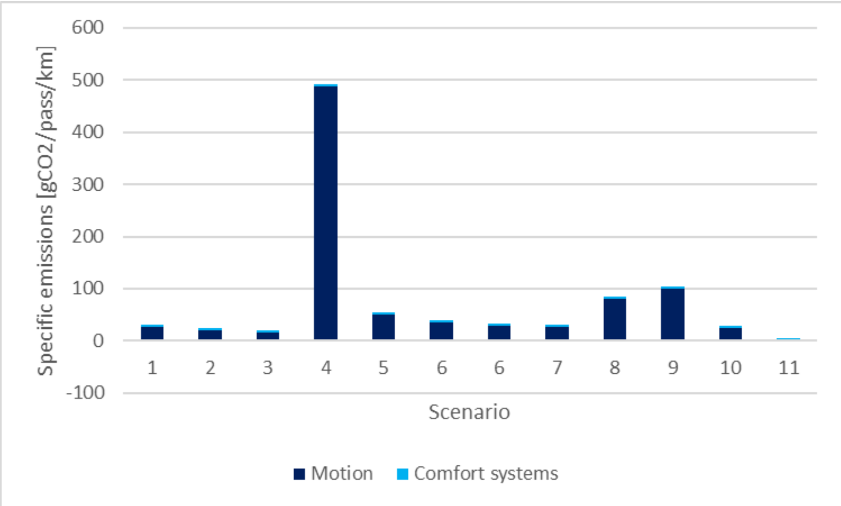
4	Hourly carrying capacity=1,480 pass/h/direction; Flat line; Actual used capacity= 10%	1.176	488.0
5	Hourly carrying capacity=1,480 pass/h/direction; Flat line; Actual used capacity= 100%	0.123	51.0
6	Hourly carrying capacity=1,480 pass/h/direction; Flat line; Actual used capacity= 150%	0.084	34.9
7	Hourly carrying capacity=1,480 pass/h/direction; Slope = 30%; Actual used capacity= 200%; Load distribution load: a=100%; d=100%	0.067	27.8
8	Hourly carrying capacity=1,480 pass/h/direction; Slope = 60%; Actual used capacity= 200%; Load distribution load: a=100%; d=100%	0.063	26.1
9	Hourly carrying capacity=1,480 pass/h/direction; Slope = 30%; Actual used capacity= 100%; Load distribution load: a=100%; d=0%	0.195	80.9
10	Hourly carrying capacity=1,480 pass/h/direction; Slope = 60%; Actual used capacity= 100%; Load distribution load: a=100%; d=0%	0.241	100.0
11	Hourly carrying capacity=1,480 pass/h/direction; Slope = 30%; Actual used capacity= 100%; Load distribution load: a=0%; d=100%	0.060	24.9
12	Hourly carrying capacity=1,480 pass/h/direction; Slope = 60%; Actual used capacity= 100%; Load distribution load: a=0%; d=100%	-0.001	-0.4

Table 52-Summary of the energy and environmental impact, in terms of kWh/pass/km and gCO2/pass/km of a subset of the analysed scenarios for the motion of the plant

One of the strengths of the hybrid CableSmart system that distinguishes it from a traditional gondola system and makes it particularly suitable for urban application is that its vehicles are electrified, and this allows, in addition to the concede self-motion to the vehicles and the consequent definition of segment on rail and of simplified stations, the installation inside the vehicle of system for its ventilation, security, lighting and info-tainment.

Of course, the presence inside the vehicle of the above-mentioned systems causes an increase of the energy requested by the plant. Their impact was analysed in detail in [R34], that provides information to calculate the impact of the comfort system on the energetic and environmental performance of the plant for installation in different cities worldwide. It is possible to define an average value of the energy impact of the comfort system of the hybrid CableSmart system in 0.01076 kWh per passenger per kilometre, that implies an environmental impact, in terms of specific emissions, of 4,5 gCO_2 per passenger per kilometre.

The below reported *Figure 88*-A and *Figure 88*-B show the specific emissions of the system in the different scenarios defined as per Table 52



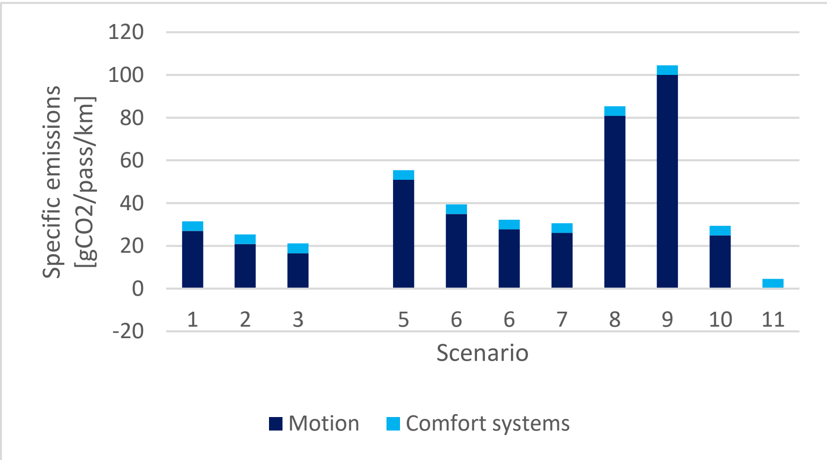


Figure 88-Specific emissions for the motion (dark blue) and the comfort and ancillary systems (light blue) of the hybrid cable- motorized wheels transport system in different scenarios. In the second image the 4th scenario was eliminated, in order to make the other columns of the histogram more readable

9.2 Mono-rail energy analysis

The detailed energy analysis of the energy consumption of the hybrid CableSmart system in the mono-rail stretch was reported in [R34], where the authors defined in 0.0269 kWh/pass/km its average specific consumption. In a tempered area-located plant (e.g., Torino), the 40% of the energy is used for comfort and ancillary systems, while the remaining 60% is used for the motion of the vehicle. The Figure 89 reports the splitting of the energy consumption of the mono-rail stretch of the hybrid CableSmart system.

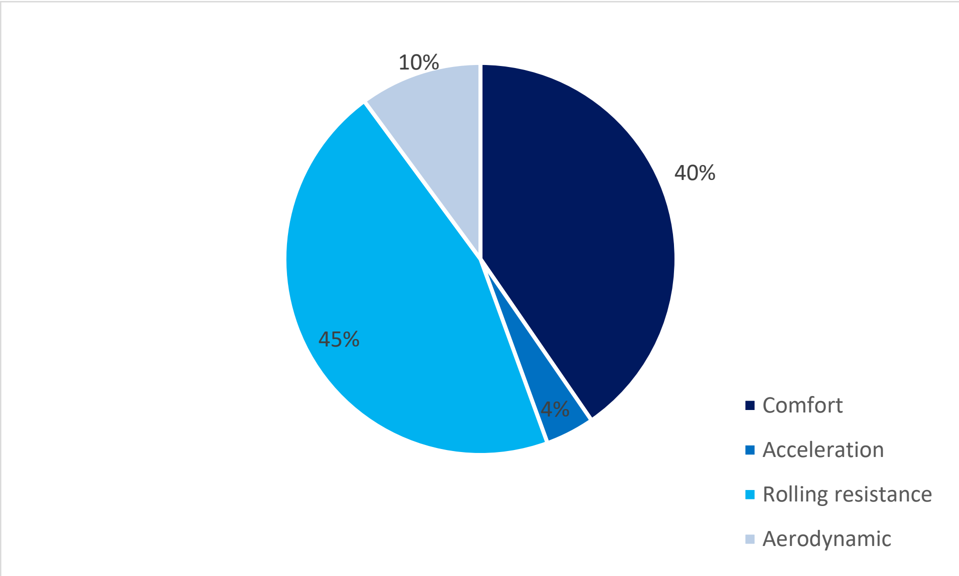


Figure 89-Splitting of the energy consumption of the mono-rail stretch of the hybrid system, as issued in [R34]

Sloped path

Authors of [R34] calculated the above-mentioned results simulating a line of rail stretch of the hybrid system CableSmart without considering any accidental resistance, so considering a linear and horizontal path.

In this paragraph, a calculation of the resistances due to the slope and of their energy impact is provided, considering a rail stretch of hybrid system with the parameters collected in the *Table 53*

Parameter	Symbol	Unit of measurement	Value
Mass of the empty cabin	M_0	[kg]	1,977
Mean mass of the cabin, calculated considering a mean load of 8 passengers per cabin (Mean filling factor equal to 100%, in that each cabin can host a maximum of 8 passengers) of 80 kg each	M_{TOT}	[kg]	2,617
Constant slope	i	[%]	From 0% to 7%, with granularity 0.5%
Constant speed	v	[m/s]	4
Hourly carrying capacity of the line	C	[passengers per hour per direction]	1,480
Hourly carrying capacity of a vehicle	p	[passengers per vehicle]	8
Headway	$h = \frac{3{,}600 * p}{C}$	[s]	= 19.46
Inclined Length of the line	L	[m]	1,500
Cycle time, calculated adding to the time of the cruising phase also the time in the acceleration and deceleration phases	T_c	[s]	450
Number of vehicles	$n = \frac{C * \frac{T_C}{3{,}600}}{p}$	/	84

Table 53-Parameters of the simulated line in rail stretch

When a vehicle moves in a sloped path, the resultant force of the sum between the weight of the vehicle and the normal force (established by the contact between the wheels of the vehicle and the plane of the rail) is non null, but it’s a vector having:

i. Direction: parallel to the plan of the trajectory of the vehicle

ii. Way: opposite to the force injected by the motorized wheels if the vehicle is moving downhill, concordant to the force injected by the motorized wheels if the vehicle is moving uphill

iii. Module:

The weight Q, in vertical direction, decomposed in its components in relation to the cartesian plan defined by the sloped trajectory (Nsin(γ); Ncos(γ)). While the component perpendicular to the plan Ncos(γ) is equilibrated by the normal force, the component of the weight force parallel to the trajectory Qsin(γ) is responsible of the additional resistance:

$R_S = Q_{TOT} * \sin(\gamma)$, if the gradient of the trajectory γ is small, then sin(γ) ~ tan (γ) ~ γ. In the simulated case, the maximum slope considered is $= \tan(\gamma) = 7\%$. For this angle sin(γ)=0.0698, tan(γ)=0.07 and γ=0.0699, so the difference (0.3%) is negligible

$R_S = Q_{TOT} * \tan(\gamma)$

$\boldsymbol{R_S = M_{TOT} * g * i}$

Where:

-R_S [N] is the resistance caused by the gradient per each vehicle;

-M_{TOT} [kg] is the mass of the loaded vehicle;

-g=9.81m/s^2 is the gravity acceleration;

-i [%] is the slope of the path

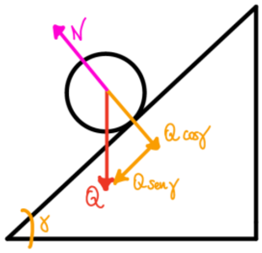


Figure 90-Diagram of the forces of a massive body on a sloped plan

So, the force loss due to the gradient is, per each vehicle $R_S = M_{TOT} * g * i$, and the power loss due to the gradient is, per each vehicle, $P_S = M_{TOT} * g * i * v$. In order to calculate the power requested in each instant by the system, it is enough to multiplicate the power per vehicle for the number of vehicles travelling in the ascent span, id est roughly (considering negligible the number of the vehicle traveling in station) the half of the total number of vehicles n: $P_{S,tot} = M_{TOT} * g * i * v * \frac{n}{2}$. Finally, the energy specific consumption is calculated as per the following formula:

$$e = \frac{P_{S,tot}}{L * C}$$

$$e_S = \frac{M_{TOT} * g * i * v * \frac{n}{2}}{L * C}$$

Considering the parameters collected in the *Table* ***53*** and varying the slope i from 0% to 7% (limits of the values accepted by the system, that must guarantee the adhesion between the metallic rail and the tire-made motorized wheels), the values of the specific energy consumption due to the positive gradient are reported in the *Figure 91*

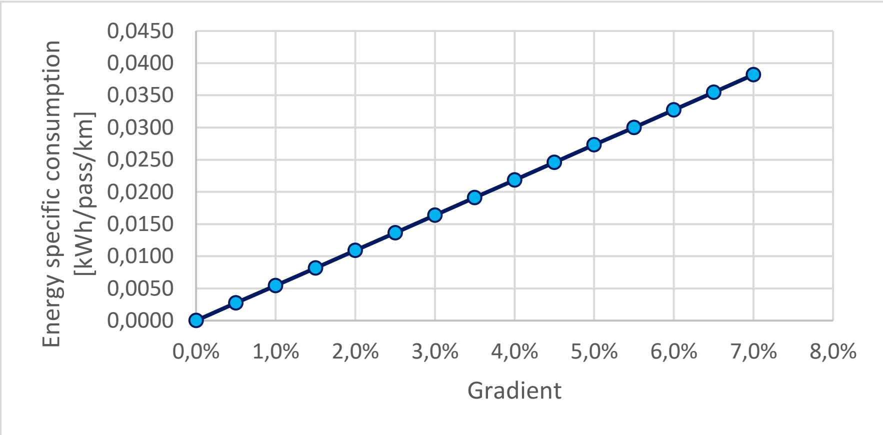


Figure 91-Specific energy consumption due to the gradient in function of the slope, considering only the ascent branch

The value collected in the previous *Figure 91* are calculated considered only the rise branch, so with the unrealistic hypothesis that the energy that the system can provide due to the negative gradient in the descent branch cannot be recovered and it is completely lost. Operatively, it is possible to recover the energy coming from the descent branch of the line, with a yield that is supposed to be η=0.8. Whit this assumption, and considering a time interval long enough so that the load distribution is uniform between the two branches[4], the energy specific consumption due to the gradient of a symmetric line is reported in the following Table 54 and *Figure 92*, that represents both the energy consumed in the ascent branch, id est the energy impact of the plant with the hypothesis that it is not possible to recover the energy provided by the vehicle in the descendent branch, and the energy consumption of the equilibrated system. The tilt angle of the red line in the *Figure*

[4] It is considered a maximum hourly carrying capacity of 1,480 passengers per hour per direction, and it is supposed that both the ascent branch and the descent one has a utilization of 100%, defining a total hourly carrying capacity of 2,960 passengers per hour.

92 depends by the yield η of the energy recovery system: if its value was 100%, the energy impact of the line would be null and the red line would be constantly equal to the abscissa axes, while if the value of the yield η of the energy recovery system was 0%, the energy impact of the line would be maximum and the red line would be constantly equal to the blue one.

Slope	**Energy consumed in the ascent branch [kWh/pass/km]**	**Energy recovered in the descent branch [kWh/pass/km]**	**e [kWh/pass/km]**
0.0%	0.0000	0.0000	0.0000
0.5%	0.0027	-0.0022	0.0005
1.0%	0.0055	-0.0044	0.0011
1.5%	0.0082	-0.0066	0.0016
2.0%	0.0109	-0.0087	0.0022
2.5%	0.0136	-0.0109	0.0027
3.0%	0.0164	-0.0131	0.0033
3.5%	0.0191	-0.0153	0.0038
4.0%	0.0218	-0.0175	0.0044
4.5%	0.0246	-0.0197	0.0049
5.0%	0.0273	-0.0218	0.0055
5.5%	0.0300	-0.0240	0.0060
6.0%	0.0328	-0.0262	0.0066
6.5%	0.0355	-0.0284	0.0071
7.0%	0.0382	-0.0306	0.0076

Table 54-Energy impact, in terms of kWh/passenger/km, of the ascent branch, of the descendent branch, and of the whole system in the simulated line

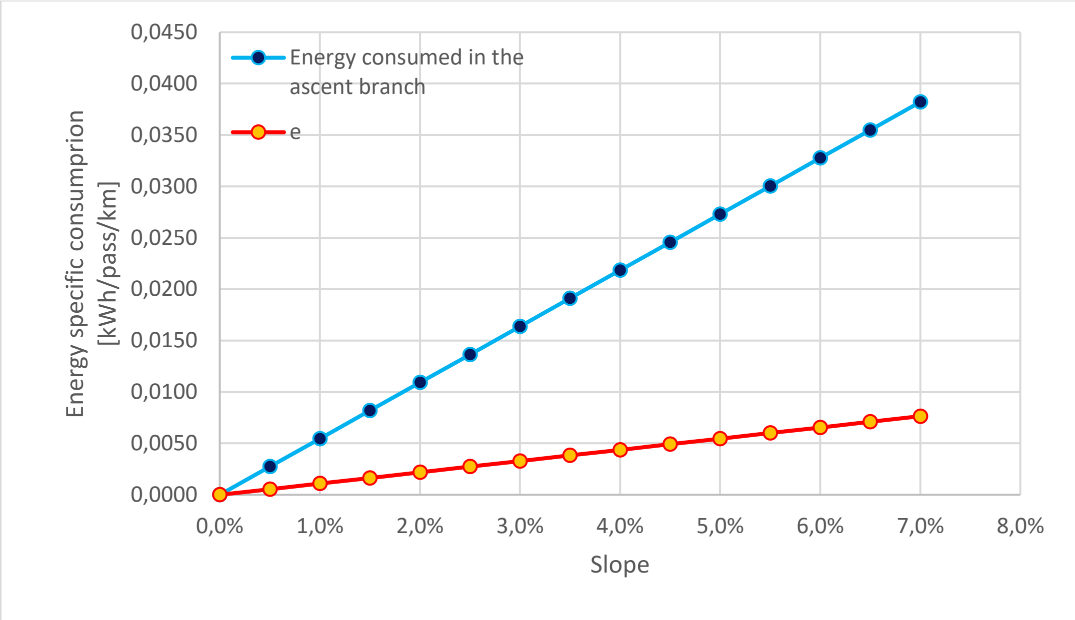


Figure 92-Specific energy consumption due to the gradient as a function of the slope in the scenarios where the yield η energy recovery system is 0% (blue line) and where the yield η energy recovery system is 80%.3

The results previously described was found with the hypothesis that both the branches of the line are fully loaded, and every vehicle is completely fulfilled with 8 passengers. Considering a more realistic situation, this constrain is relaxed, and all the load permutation are considered; so, a matrix collecting the energy specific consumption for each average filling of the ascent and descent branches is defined and reported in the *Table 55*, where:

- a is the average number of passengers in the ascent branch
- d is the average number of passengers in the descent branch
- every cell of the matrix reports the value of the specific consumption due to the slope in function of the load distribution (a,d):

$$e_{S(a,d)} = \frac{(M_{TOT,a} * g * i * v * \frac{n}{2}) - \eta * ((M_{TOT,d} * g * i * v * \frac{n}{2})}{(L * 2) * C * (\frac{a + d}{2})}$$

d: number of passengers in the descent branch	a: number of passengers in the ascent branch								
	0	1	2	3	4	5	6	7	8
0	/	0.1112	0.0649	0.0495	0.0418	0.0372	0.0341	0.0319	0.0303
1	0.0775	0.0481	0.0383	0.0334	0.0305	0.0285	0.0271	0.0261	0.0252
2	0.0313	0.0271	0.0250	0.0237	0.0229	0.0223	0.0218	0.0215	0.0212
3	0.0159	0.0166	0.0170	0.0173	0.0175	0.0176	0.0178	0.0179	0.0179
4	0.0081	0.0103	0.0117	0.0127	0.0134	0.0140	0.0145	0.0149	0.0152
5	0.0035	0.0061	0.0079	0.0092	0.0103	0.0111	0.0118	0.0124	0.0129
6	0.0004	0.0031	0.0050	0.0065	0.0077	0.0087	0.0096	0.0103	0.0109
7	-0.0018	0.0008	0.0028	0.0044	0.0057	0.0068	0.0077	0.0085	0.0092
8	-0.0034	-0.0010	0.0010	0.0026	0.0040	0.0051	0.0061	0.0069	0.0076

Table 55-Energy impact. in terms of kWh/passenger/km. of the simulated system as a function of the average number of passengers in the ascent branch (a. in the columns) and in the descend one (d. in the rows)

Curvilinear path

In the traditional railway technology, the carriages have not differential gear, and there is an additional resistance due to the curves in the path. caused by the friction due to the contact between the border of the rail and the side of the wheel, as reported in Figure 93 [R50]. Since, when the vehicle goes around a curve, the distance to be covered by the external wheels is greater than one that internal wheels should travel, the transversal displacement of the carriage wheels and its conicity only partially compensate the difference in path. and this entails an increase in traction effort with a consequent increase in energy consumption.

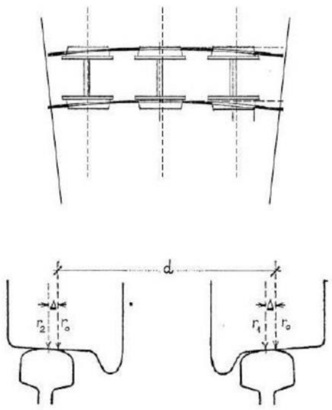


Figure 93 Contact between rail and wheels in the railway traditional technology

On the other hand, in road case vehicles have differential gear, and so there is not difference of travelled path between the wheels internal to the curve and the external ones.

In the hybrid CableSmart system, the reduced speed of the vehicle during the curves and the material of the wheels, covered by a rubber layer, make the additional resistance due to the curves negligible.

Tunnels

While traditional cableway technology is hardly compatible with the definition of tunnel stretch. due to the high transverse oscillation angles around the rope-clamp constraint that the traditional cableway vehicle has which would require very large tunnel sections with very high excavation costs. the CableSmart hybrid system. in its rail segments. efficiently accepts tunnel stretches.

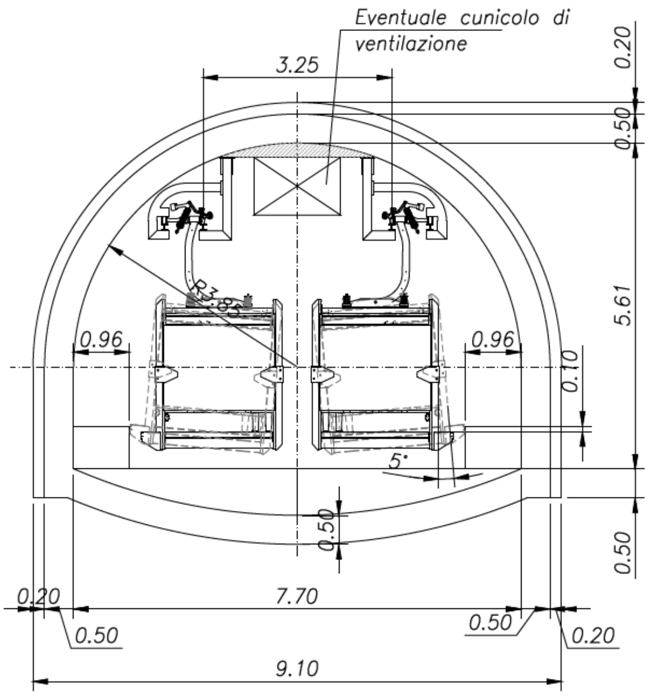


Figure 94-Example of tunnel section to host a CableSmart installation. in its rail stretch

While. due to the high heterogeneity of the vehicles. road tunnels normally have a much larger section than the cars passing through, and therefore the effect of the tunnel in terms of resistance to the motion is negligible, in railway tunnels the sections are comparable to the frontal surface of the train and so the convoy, when pass through the tunnel, undergoes an increase in aerodynamic resistance which has been quantified in the literature as:

- 10% in tunnels with double track;
- 20% in tunnels with single track.

As. as drawn in *Figure 94*. in the rail stretch of CableSmart installation the frontal surface of the tunnel is not hugely bigger than the frontal area of the vehicle, it is not possible to neglect the increase in the aerodynamic resistance due to the passage of the line in tunnels. In [R34], authors defined in 0.0031 kWh/passenger/km the specific consumption due to the aerodynamical resistance of a line without stretches in tunnel, so it is possible to calculate the aerodynamical resistance of a line installed totally in tunnel as:

$$e_{aer.tot} = e_{aer} + e_{tunnel}$$

$$e_{aer.tot} = \begin{cases} e_{aer} + e_{aer} * 10\% & if\ the\ tunnel\ hosts\ two\ tracks \\ e_{aer} + e_{aer} * 20\% & if\ the\ tunnel\ hosts\ one\ track \end{cases}$$

$$e_{aer.tot} = \begin{cases} 110\% * e_{aer} & if\ the\ tunnel\ hosts\ two\ tracks \\ 120\% * e_{aer} & if\ the\ tunnel\ hosts\ one\ track \end{cases}$$

Tunnel	e_{aer} [kWh/pass/km]	e_{tunnel} [kWh/pass/km]	$e_{aer.tot}$ [kWh/pass/km]
Single track	0.0031	0.0003	0.0034
Double track	0.0031	0.0006	0.0037

Table 56-Specific consumption due to the increase of aerodynamic resistance in tunnel stretches

Chapter 10

10. Case studies

This chapter aims to summarize how the CableSmart hybrid system is able to intercept needs and requirements of the transport demand and to be compliant with the urban and geological constraints that the territory presents, referring to three case studies, designed in collaboration with Dimensione Ingenierie.

10.1 Sorrento- Sant'Agata

This project was designed as a feasibility study of the connection between the Municipalities of Sorrento and Massa Lubrense (Napoli). The definitive project will be performed in 2023.

The scope of works of the project is to design a public transport system that connects the centre of the coastal town of Sorrento, in particular the station of the Circumvesuviana railway, that provide an existing link with Napoli, with the village of Sant'Agata sui due Golfi (hamlet in the Municipality of Massa Lubrense), rising on the hilly area in the centre of the Sorrentine Peninsula, at an altitude of 390 m above the sea level.

Currently, the mobility offer between the two towns is guaranteed by a bus service. In non-touristic season the duration of the journey is approximately 20 minutes, but the whole area, and in particular the roads in the bus path, is affected by traffic and congestion during the touristic seasons, hugely increasing the duration of the bus journey. Likewise, also the journey by private car along the road SS145 has an ideal duration of 19 minutes, but it is normally increased during touristic seasons due to traffic and congestion.

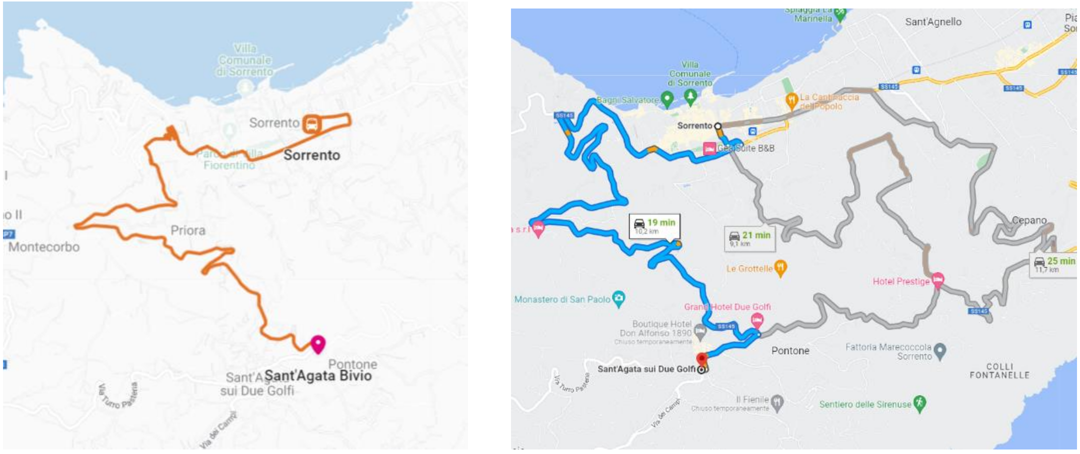


Figure 95-Current connection between Sorrento and Sant'Agata sui due Golfi, through bus (left) and through private car (right)

The plant object of this project will allow to reduce the travel time between the two towns, making it insensitive to traffic conditions and road congestion. Moreover, satisfying part of the transport demand through the new system will reduce the pressure on the road network and will allow an increase in demand itself, making it faster and easier for tourists staying in Sorrento to reach Sant'Agata sui due Golfi.

The main challenging and constrains in the definition of the new plant have been the following:

i) Since the downstream end station is foreseen in the Sorrento city centre, close to the existing railway station, the line should pass across the urban fabric that, in addition to be densely built, has a high landscape value;

ii) The city of Sorrento has its historical roots thousands of years ago (the first evidences of its existence dates back to 600 b.C.). The great historical and cultural heritage and the numerous archaeological sites located in the area constituted one of the challenges of the project;

iii) The non-urban stretch of the line is located on a hillside, with stringent geological constraints.

The project workflow involved the definition of three dimensions: route, technological alternative and entity of the demand. From the envelope of these dimensions, 42 preliminary scenarios were defined; therefore, non-possible scenarios have been eliminated (in which, for example, the route is not compatible with the technological constraints of the means of transport), the remaining scenarios were in depth analysed and, for each of them, an ordinary score was given. Then, the three scenarios with higher scores were presented to the contractor authority.

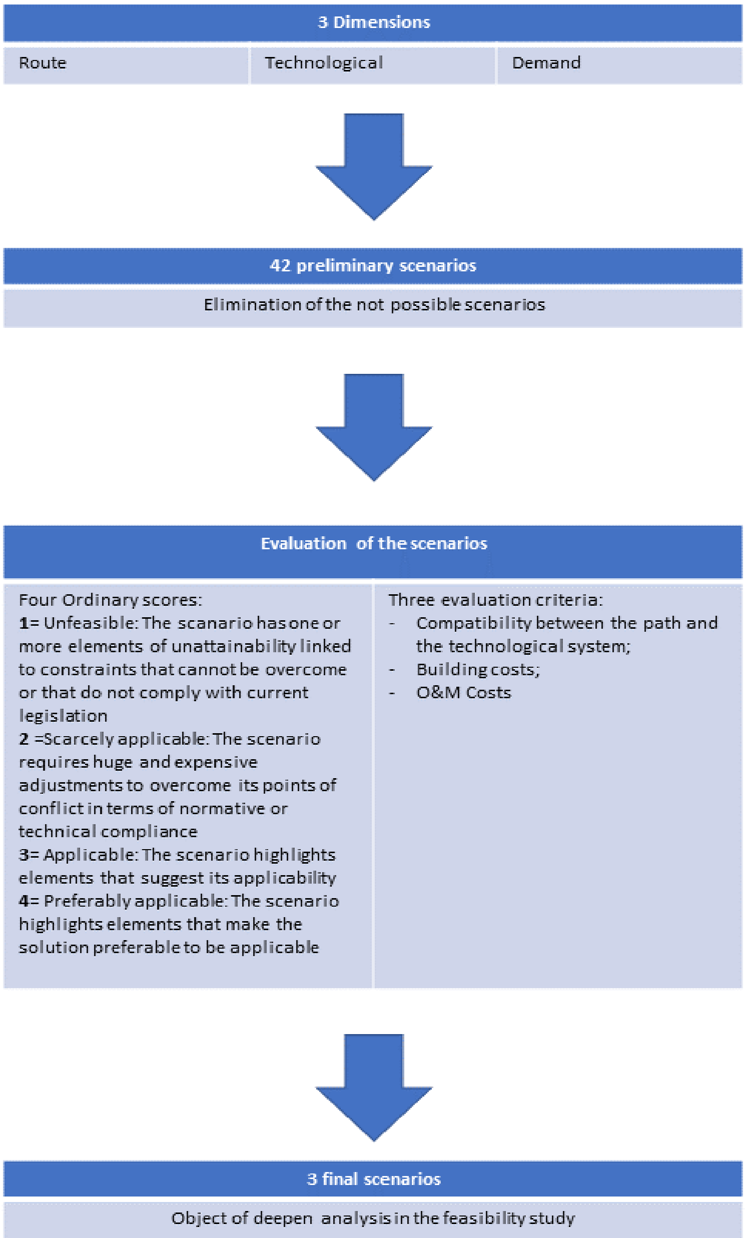


Figure 96-Workflow scheme about the choice of the scenarios to be deepen

Downstream to the evaluation phase described in the Figure 96, three plant alternatives were designed, all of them have the hybrid system as technology, since (as often reiterated in the previous chapters) it is able to efficiently manage the issues related to the urban integration.

The following *Table 57* shown the evaluation of the transport systems for the overcoming of differences in high, as described in the previous chapter declined in the Sorrento- Sant'Agata project. In particular, it underlines the reasons why the traditional systems are not able to match the needs and the be compliant with the constrains of the project object of this chapter.

Traditional transport systems for the overcoming of differences in high	Reason for incompatibility in the Sorrento-Sant'Agata project
Inclined lift	The distance separating Sorrento and Sant'Agata, around 1,800m as the crow flies, is not compatible with the utilization domain of the inclined lift. Moreover, the slope of an inclined lift line should be constant, while the Sorrento-Sant'Agata line has a fist urban stretch almost constant, and a second hilly stretch with an average slope close to 30%
Cog railway	In order to reduce its impact in the densely-built urban area of Sorrento and in the hillside, the plant should be totally in tunnel, with consequent very high costs
APM- Perugia style	In order to reduce its impact in the densely-built urban area of Sorrento and in the hillside, the plant should be totally in tunnel, with consequent very high costs
To-and-fro ropeway	It would be hardly to integrate the voluminous stations, which should be built in the urban centres of Sorrento and Sant'Agata. Furthermore, the length of the line would hardly be compatible with the desired hourly capacity (in a to-and-fro system, the hourly capacity is inversely proportional to the length of the line)
Funicular railway	In order to reduce its impact in the densely-built urban area of Sorrento and in the hillside, the plant should be totally in tunnel, with consequent very high costs
Monocable traditional gondola	Although the gondola system is particularly suitable for the stretch on the hillside, outside the Sorrento city centre area, this system would have integration difficulty within the urban fabric, which could only be overcome by installing very high towers to define a line that passes over the buildings, with a consequent increase in terms of costs and of visual and environmental impact of the plant
Bicable traditional gondola	Beyond the weaknesses typical of a monocable traditional gondola, the bicable traditional gondola presents higher cost that can be legitimate only in case of critical whether conditions in terms of wind, that this project has not

Table 57-Reason for incompatibility of traditional transport system for the overcoming of differences in hight in the Sorrento-Sant'Agata project

The *Table 57* shows how the traditional transport systems for overcoming difference in high fail to match the peculiar needs of the case study subject of this chapter. The hybrid system is able to overcome the limits and the weakness of the traditional transport systems for the overcoming differences in high summarized in the Table 57 , and it is able to match the needs and the requirement of the project.

In general, so considering not only the case of study described in this chapters, but the three cases of studies reported in the Ph.D. thesis, the hybrid system is able to better match the needs of the urban transport due to:

i) Unlike all to-and-fro or automated-detachment systems, which involve slowing down all vehicles at the station, in the hybrid system each vehicle is kinematically independent from the others at the station. In this way, it is still possible to make a vehicle enter the station, make it slow down and stop without any impact on the others, and this involves a significant increase in commercial speed.

ii) The user interface is similar to that of an elevator. The traveller can thus decide the destination of his trip in a simple and intuitive way.

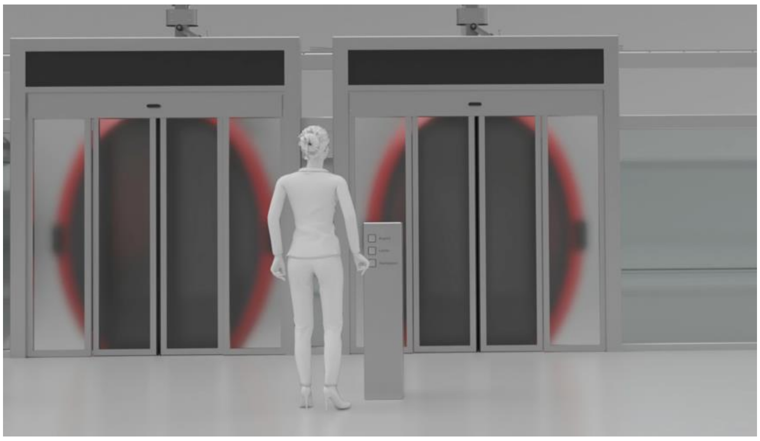


Figure 97- Draft of the interface

In particular, thanks to the hybrid system, is it possible to define stretches in rope, suitable for the sloped segment between Sorrento and Sant'Agata, and rail stretches, that can be integrate efficiently in the urban context inside the town of Sorrento.

In order to further minimize the impact of the work in the urban centre of Sorrento, the first part of the route is planned in underground tunnel, whose section is represented in Figure 98.

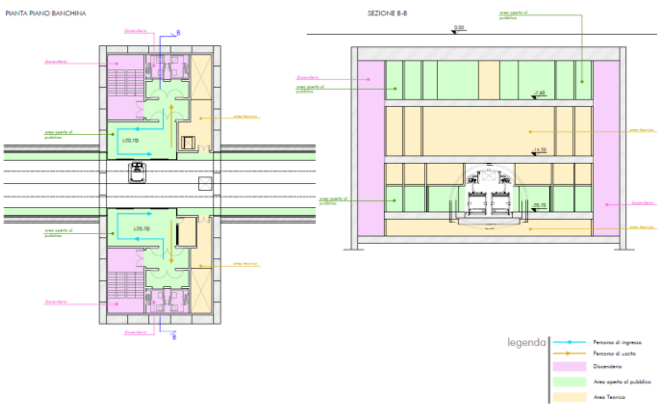


Figure 98- View from above and frontal view of the tunnel stretches

First scenario

Downstream station	Sorrento- EAV railway station
Upstream Station	Sant'Agata- Church
Vehicle deposit	Sant'Agata- Church
Stretch on cable	1,649 m From the downstream station to the technological change site
Stretch on rail	210 m From the technological change site to the upstream station (totally on tunnel)
Rail- cable stretches modality change	Ramp

Table 58-Main info about the first scenario

Figure 99-Planimetry of the line in the first scenario

The emersion of the plant from the underground tunnel stretch to the elevated one is foreseen through a ramp located in the nearby to the Sorrento city centre. The cable car line would have a downstream station inside the underground tunnel, and the line would exit via cable towards the elevated section. To allow the transition of the plant from the underground to the elevated section, the excavation of an inclined ramp in the tunnel is envisaged.

The cableway norms

[R37], Dalla Chiara B., Alberto D., Zannotti G., “Impianti a fune per trasporto persone e materiali - Evoluzione, elementi costitutivi, progettazione ed esercizio, I edizione”, EGAF, 2022

[R38] Vitali, C.D.P. Software per verifica linea monofuni (tipologie : morsa fissa, automatica, pulsè e telemix), realize 0110, giugno 2017

[R39] allow a maximum slope of 45 degrees = 100%, but to reduce the pressure on the rollers of the first line support, it was decided to incline the ramp by 30 degrees.

As in the ramp that allows it to emerge from the tunnel, the vehicle is clamped to the rope and so it has higher transversal oscillation around its clamp, the front section of the ramp (*Figure 100* shows the design hypothesis of the front section of the ramp, in accordance with current cableway legislation

[R37], Dalla Chiara B., Alberto D., Zannotti G., “Impianti a fune per trasporto persone e materiali - Evoluzione, elementi costitutivi, progettazione ed esercizio, I edizione”, EGAF, 2022

[R38] Vitali, C.D.P. Software per verifica linea monofuni (tipologie : morsa fissa, automatica, pulsè e telemix), realize 0110, giugno 2017

[R39]) is significantly higher than that section of the horizontal segment of the tunnel, where the vehicle proceeds driven by its motorized wheels.

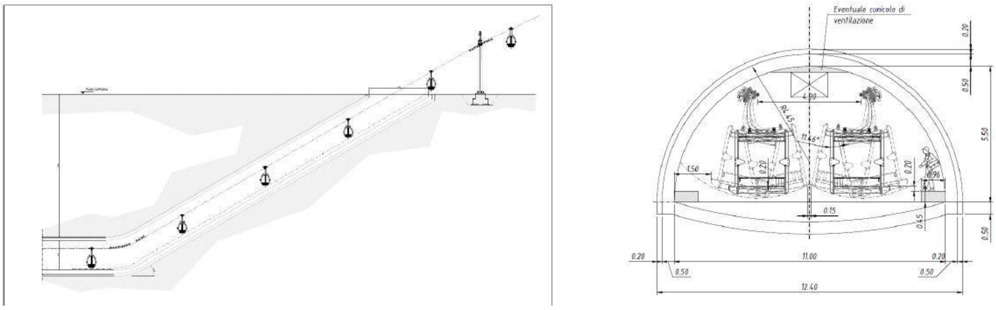


Figure 100-Lateral view and frontal view of the ramp through which the system, in its cable stretch, passes from tunnel to the elevated segment

Second scenario

Downstream station	Sorrento- EAV railway station
Upstream Station	Sant’Agata- Nastro Azzurro
Vehicle deposit	Sant’Agata- Nastro Azzurro
Stretch on cable	1,702 m From the downstream station to the technological change site
Stretch on rail	220 m From the technological change site to the upstream station (totally on tunnel)
Rail- cable stretches modality change	Ramp

Table 59-Main info about the second scenario

Figure 101-Planimetry of the line in the second scenario

The path related to the second scenario is almost the same of the first one, with the only difference to have the upstream station located in slightly back position. Also in this case, the emersion of the line from its tunnel stretch happens through a tilted ramp.

Third scenario

Downstream station	Sorrento- EAV railway station
Upstream Station	Sant'Agata- Church
Intermediate station	Sorrento- Torquato Tasso
Vehicle deposit	Sorrento- Torquato Tasso
Stretch on cable	1,751 m From the downstream station to the technological change site
Stretch on rail	403 m From the technological change site to the upstream station (totally on tunnel)
Rail- cable stretches modality change	Vehicles lift

Table 60-Main info about the third scenario

Figure 102-Planimetry of the in third the second scenario

In order to better intercept the mobility demand nodes, in the third scenario an intermediate station sited in Piazzale Tasso, that is a bus station node and that can act as an intermodal hub is foreseen.

Particularly innovative is the method of emersion of the system from the section in the tunnel to the elevated one, which takes place in a position immediately before the intermediate station located in Piazzale Tasso. The installation of four vertical lifts is foreseen, two to serve the ascent branch and two for the descent branch, in order to avoid "bottleneck" issues due to the lift technology.

In the wake of similar design solutions (e.g., the system that combines lift technology and funicular technology installed in Genoa in 2004 and which connects the Castello d'Albertis to Montegalletto), the present hypothesis envisages that the vehicle located in the underground section proceeding at reduced speed in rail stretch, enters in an elevator (lifting platform) and is thus moved up to the raised floor where the downstream station of the cableway stretch is located. Obviously, the same procedure is carried out in reverse by vehicles moving from upstream (Sorrento-Piazzale Tasso station) to downstream (Sorrento-Eav station).

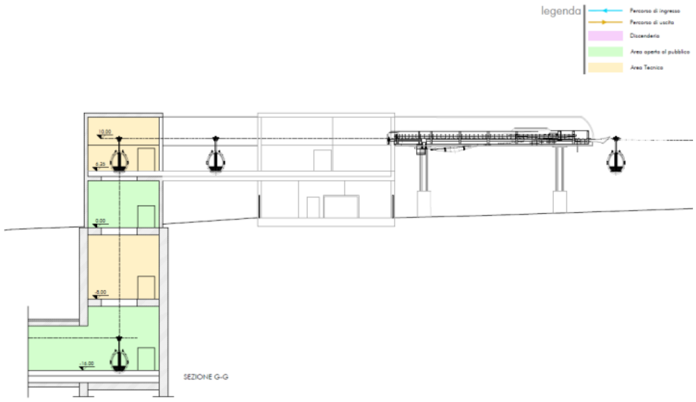


Figure 103-Side view of the vehicles-lift, modality of the emersion from the tunnel stretch to the elevated one. In the image the cable-car station sited in Piazzale Tasso (on the right) is represented.

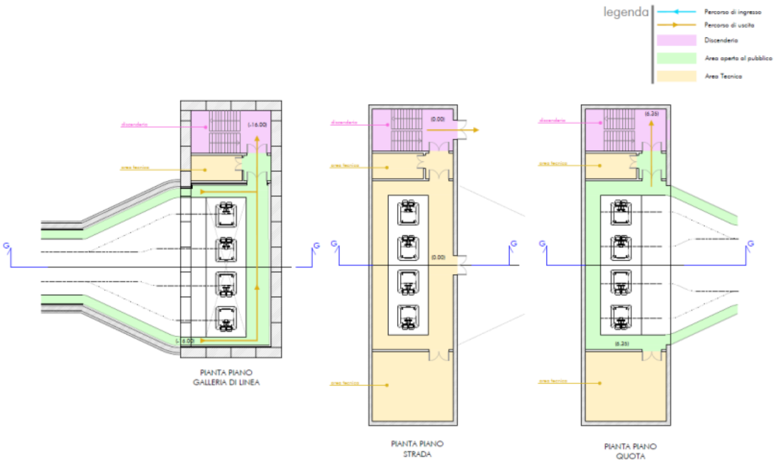


Figure 104-View from above of the vehicles-lift, modality of the emersion from the tunnel stretch to the elevated one

10.2 Angri- Tramonti- Maiori

This project was designed as a feasibility study of the connection between the Municipalities of Angri, Corbara, Tramonti and Maiori (Salerno). The definitive project will be performed in 2023.

The scope of works of the project is to design a public transport system to connect the city of Angri, an almost 35,000-inhabitants city in the hinterland of Naples, to the town of Maiori, a touristic town in the Amalfi Coast, passing through the Municipalities of Corbara and Tramonti, and crossing the mountain range of the Monti Lattari. Since a station of the Naples-Salerno railway line is located in Angri, close to the foreseen terminal station for this plant's line, the project not only makes it possible to connect Angri to Maiori, but allows to unite two of the most popular and famous touristic poles in the world: the Amalfi coast and the cultural and archaeological poles of Pompeii and Naples.

Currently, the faster and more effective way to reach Maiori from Angri is the private car, with a journey almost 1-hour long in the road SP2, which crosses the Lattari Mountains and has characteristics, in terms of reduced width of the roadway and the presence of hairpin bends, typical of a mountain road. Moreover, the whole area is affected by traffic and congestion during the touristic seasons, (the above-mentioned road is not an exception) and the entire Amalfi coast is suffering from a chronic lack of car parking lots.

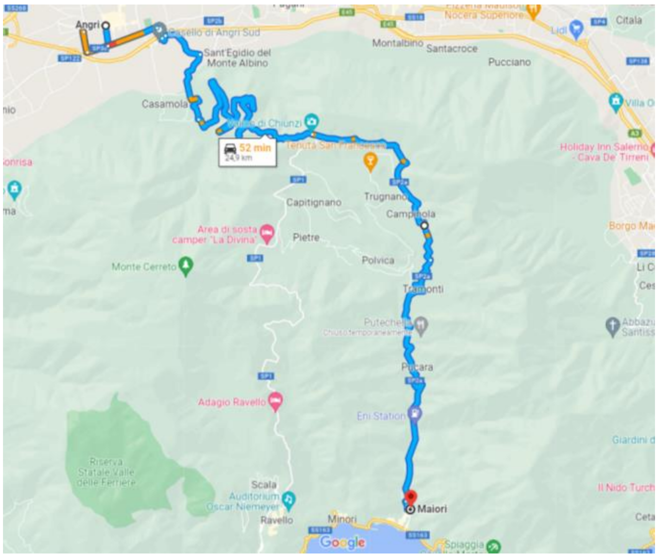


Figure 105-Current connection between Angri and Maiori private car

There are two major points of technical challenge associated with this project. Firstly, the layout of the line should provide for the integration of the plant into the urban fabric of Angri and Maiori, and should effectively be able to cross the Lattari Mountains (the maximum altitude, corresponding to the Chiunzi pass, is 665m). Secondly, the distance between the two terminal nodes is almost 15 km, much higher than the typical domain of use of traditional systems for overcoming differences in high.

In terms of mobility needs and opportunity, the following objectives are pursued during the design phase:

- To promote the territorial integration of the Amalfi coast into the regional context, giving Angri the function of hinge between the different areas. It would become a relevant park & ride point to drain the road flows between the municipalities interested by the plant (Corbara, Tramonti, Maiori);
- Enhance and integrate the regional transport system (road, railway, maritime) with particular reference to the Angri train station located on the railway line Naples-Salerno and the wider SMR (Regional Metro System) of the Campania Region, that consists of a complex and articulated system of railway networks (regional and urban) interconnected through service and interchange nodes.
- To enhance the landscape and naturalistic aspects, through the use of intermediate stations and the Maiori node to facilitate access to areas otherwise difficult to access with public transport systems.

The operative workflow of the design phase was the same followed for the above-described Sorrento- Sant'Agata project and summarized in the Figure 96. Through the definition of three dimensions: route, technological alternative (the following *Table 61-* shown the evaluation of the transport systems for the overcoming of differences in high, as described in the previous chapter declined in the Angri-Maiori project.) and entity of the demand, 42 preliminary scenarios were defined; therefore, non-possible scenarios have been eliminated, the remaining ones were in depth analysed and, for each of them, an ordinary score was given. Then, the three scenarios with higher scores were presented to the contractor authority.

Transport systems for the overcoming of differences in high	Reason for incompatibility in the Angri-Maiori project
Inclined lift	The distance separating the two terminal stations, around 15 km as the crow flies, is absolutely incompatible with the application domain that is limited to some hundreds of meters
Cog railway	The impact on the ground of the railway-type line can be inserted with extreme difficulty within the densely anthropic centres of Angri and of Maiori
APM Perugia style	The impact on the ground of the railway-type line can be inserted with extreme difficulty within the densely anthropic centres of Angri and of Maiori
To-and-fro ropeway	It would be hardly to integrate the voluminous stations, which should be built in the urban centres of Angri and Maiori. Furthermore, the length of the line would not be compatible with the desired hourly capacity (in a to-and-fro system, the hourly capacity is inversely proportional to the length of the line). Furthermore, the length, in terms of journey duration, of the connection is incompatible with vehicles without air conditioning and other thermal comfort systems, above all in consideration of the extreme conditions, in terms of maximum temperature, which are reached in the area in the summer months
Funicular railway	The funicular system needs to define two different segments (one for the uphill section and one for the downhill one) for overcoming the Lattari Mountains. Furthermore, since the terrestrial funicular is a to-and-fro system, the length of the planned section has a significant impact in terms of reducing its hourly capacity. Finally, the impact on the ground of the railway-type line can be inserted with extreme difficulty within the densely anthropic centre of Angri and Maiori
Monocable traditional gondola	The traditional monocable gondola line, that can be only straight between two stations, is hardly to integrate in the Angri and Maiori city centres. Furthermore, the length, in terms of journey duration, of the connection is incompatible with vehicles without air conditioning and other thermal comfort systems, above all in consideration of the extreme conditions, in terms of maximum temperature, which are reached in the area in the summer months
Bicable traditional gondola	Beyond the weaknesses typical of a monocable traditional gondola, the bicable traditional gondola presents higher cost that can be legitimate only in case of critical whether conditions in terms of wind, that this project has not

Table 61-Reason for incompatibility of traditional transport system for the overcoming of differences in hight in the Angri-Sant'Agata project

The *Table 61* shows how the traditional transport systems for overcoming difference in high fail to match the peculiar needs of the case study subject of this chapter. So, also in this case of study, the hybrid system is referred to as the optimal system with the actual constrains of the project.

From the analysis of the preliminary scenarios, the three scenarios with the best scores were defined and subjected to in-depth analysis. It should be noted that, of these, two envisage the adoption of hybrid technology.

In fact, the hybrid technology allows the effective integration into the urban fabric of the densely anthropized urban fabrics of Angri and Maiori through its rail sections, and the overcoming of the high difference in height during the crossing of the Lattari Mountains in its section by cable. Furthermore, its vehicles equipped with thermal comfort systems allow passengers to spend the relatively long (about 50 minutes) journey comfortably in the cabin.

The third design scenario, which envisages the adoption of a traditional cable car, renounces crossing the historic centre of Maiori, defining its terminal station in a setback position with respect to the town, in the Regina Maior valley which goes up from Maiori to the Chiunzi pass.

In the following paragraphs, the paths of the two design scenarios that envisage the adoption of the hybrid system are presented.

First scenario

The total length of the line is 14,751 meters, of which around 602 m in rail stretch and 14,150 m in cable segment

In addition to the two terminal stations, the line presents six intermediate stations. In order to reduce the size and the complexity of the cable car stations, as well as reducing the elongation of the rope due to changes in load conditions and sudden changes in temperature (which depends linearly by the length of the rope according to the formula $L = L_0(1 + \lambda * \Delta T)$), the aerial cable-car stretch is split in five rings of rope.

		Length [m]	Difference in height [m] (Average slope)
Angri, Railway station (1)	Terminal station	/	/
Angri, Railway station – Angri MCM factory	Rail stretch, in tunnel	602	8 (1%)
Angri, MCM factory (2)	Intermediate station and emersion of the line through vehicles lift	/	/
Angri, MCM factory- Angri, motorway junction	Cable-car stretch	1,140	40 (4%)
Angri, motorway junction (3)	Intermediate station	/	/
Angri, motorway junction- Corbara	Cable-car stretch	1,943	162 (8)
Corbara (4)	Intermediate station	/	/
Corbara- Chiunzi pass	Cable-car stretch	2,907	393 (14%)
Chiunzi pass (5)	Intermediate station	/	/
Chiunzi pass- Tramonti Polvica	Cable-car stretch	3,018	334 (11%)
Tramonti Polvica (6)	Intermediate station	/	/
Tramonti Polvica- Inland Maiori	Cable-car stretch	1,890	31 (2%)
Inland Maiori (7)	Intermediate station	/	/
Inland Maiori- Port Maiori	Cable-car stretch	3,251	253 (8%)
Port Maiori (10)	Terminal station	/	/

Table 62-Stations and stretches in the first scenario

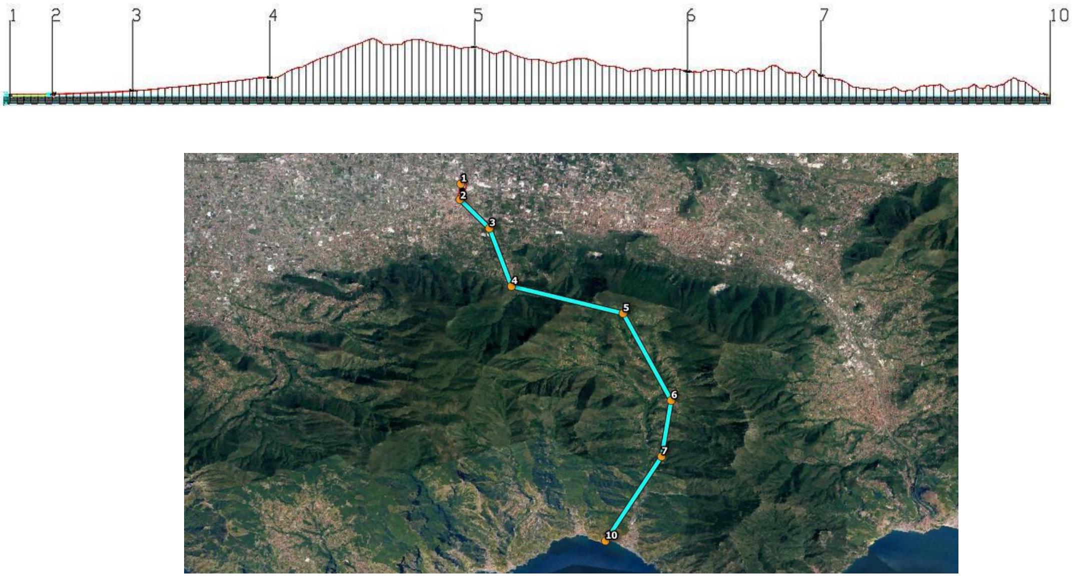


Figure 106-Altimetry and planimetry of the first scenario line

As regards the urban section of the Angri area (*Figure 107*), section 1-2 is allowed by rail technology and would not be possible with a traditional monocable gondola; this path is developed in tunnel, in order to minimize the interference with the town of Angri. At station 2, an emersion artifact of the system via lifts is also planned, similar to the one shown in *Figure 103* and *Figure 104*. However, in this path scenario, the impact of the plant in the Angri urban area is limited, but not eliminated, as the stretch 2-3 is traveled aerially, through cable modality.

Figure 107-Planimetry of the urban part in Angri of the line in the first scenario. With the red/black line the rail stretch is represented, while in light blue line the cable segment is indicated

Second scenario

The total length of the line is 14,816 meters, of which around 1,452 m in rail stretch and 13,364 m in cable segment

In addition to the two terminal stations, the line presents six intermediate stations. In order to reduce the size and the complexity of the cable car stations, as well as reducing the elongation of the rope due to changes in load conditions and sudden changes in temperature (which depends linearly on the length of the rope according to the formula $L = L_0(1 + \lambda * \Delta T)$), the aerial cable-car stretch is split in five rings of rope.

		Length [m]	Difference in height [m] (Average slope)
Angri, Railway station (1)	Terminal station	/	/
Angri, Railway station – Angri MCM factory	Rail stretch, in tunnel	602	8 (1%)
Angri, MCM factory (2)	Intermediate station	/	/
Angri, MCM factory Angri, emersion artifact	Rail stretch, in tunnel	850	34 (4%)
Angri, emersion artifact (2T)	Emersion of the line through ramp	/	/
Angri, emersion artifact Angri, motorway junction	Cable-car stretch	355	28 (8%)
Angri, motorway junction (3)	Intermediate station	/	/
Angri, motorway junction- Corbara	Cable-car stretch	1,943	162 (8)
Corbara (4)	Intermediate station	/	/
Corbara- Chiunzi pass	Cable-car stretch	2,907	393 (14%)
Chiunzi pass (5)	Intermediate station	/	/
Chiunzi pass- Tramonti Polvica	Cable-car stretch	3,018	334 (11%)
Tramonti Polvica (6)	Intermediate station	/	/
Tramonti Polvica- Inland Maiori	Cable-car stretch	1,890	31 (2%)
Inland Maiori (7)	Intermediate station	/	/
Inland Maiori- Port Maiori	Cable-car stretch	3,251	253 (8%)
Port Maiori (10)	Terminal station	/	/

Table 63-Stations and stretches in the second scenario

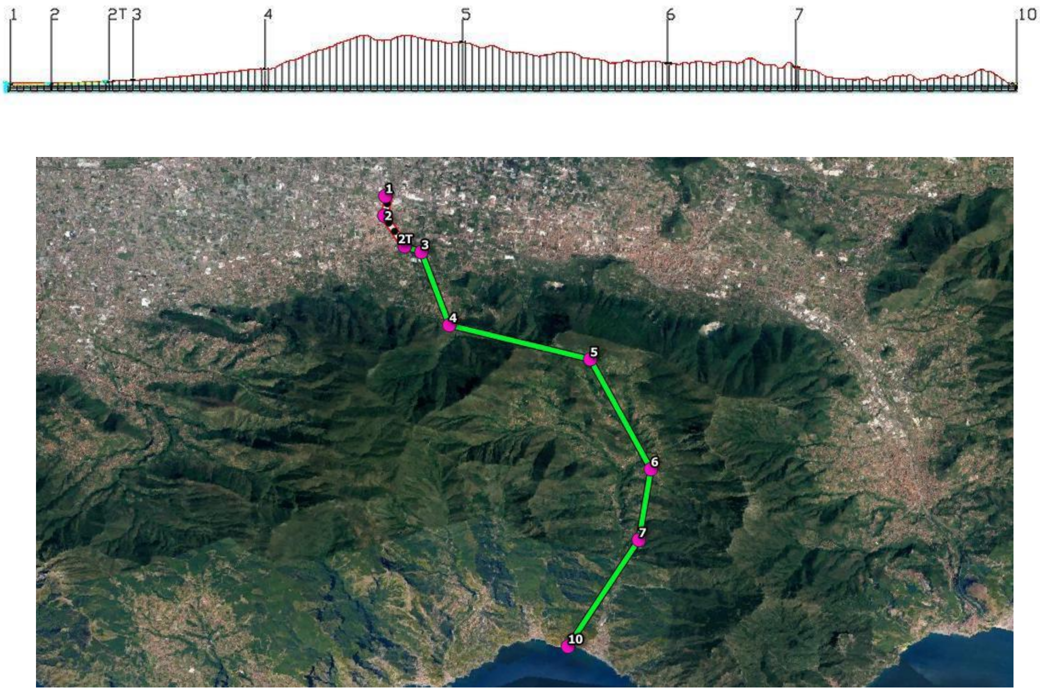


Figure 108-Altimetry and planimetry of the second scenario line

As regards the urban section of the Angri area (*Figure 109*), sections 1-2 and 2-2T are allowed by rail technology and would not be possible with a traditional monocable gondola; this path is developed in tunnels, in order to minimize the interference with the town of Angri. At point 2T is not foreseen a station, so there is not the possibility for passengers to embark or disembark, but only the artifact for the emersion of the line, that is designed through ramp, as per *Figure 100*.

Figure 109-Planimetry of the urban part in Angri of the line in the second scenario. With the red/black line the rail stretch is represented, while in green line the cable segment is indicated

10.3 Genoa- Forte Begato

This project was conceived as a feasibility study of the connection between the Port area and Forte Begato, in Genoa, crossing the highly anthropized urban area of the "Lagaccio" district of the Ligurian capital, where there are strong urban and anthropic constraints such as: the Port, the “Villa del Principe” monumental house of great historical and cultural interest, the Genoa Elevated road SS1, the railway line, the Lagaccio torrent in tunnel underground the district, the Hennebique building, and the Don Acciai bridge. The compliance of the plant with respect to the aforementioned constraints is one of the major design challenges of this project.

An intermediate station is planned in the "Lagaccio" area which divides the mobility system into two parts with very different needs and requirements.

i) The first segment “Port Area- Lagaccio” (S1-S2 in the *Figure 110*) is located in a heavily urbanized and anthropic context and will perform an urban transport function, connecting the northern area of the Lagaccio district with the port of Genoa, also allowing interconnection with other transport systems (buses, trains, subway) currently in operation.

ii) The second segment “Lagaccio-Begato" (S2-S3 in the *Figure 110*) is instead proposed in an area with limited anthropization, and will allow the connection with Forte Begato, a touristic area and venue for events, which will be easily and quickly reachable by tourists departing directly from the port area .

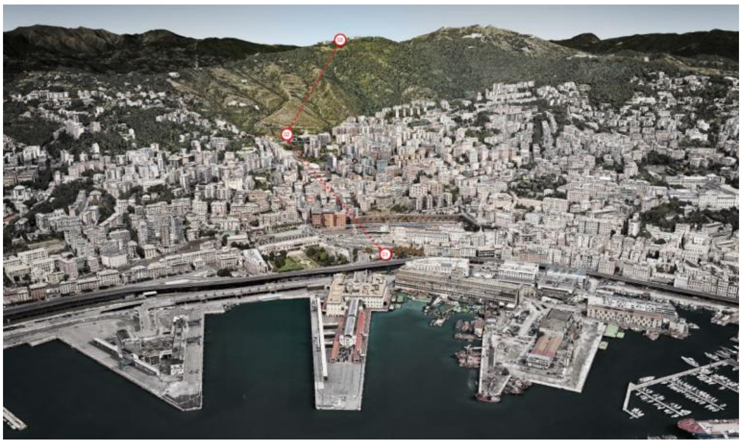


Figure 110-Genoa-Forte Begato line

As far as this project is concerned, the technological choice fell on a bicable gondola, in order to minimize the effects of the wind, both in terms of comfort inside the cabins and in terms of stability when passing the roller assemblies and at the entrance to the stations. Furthermore, the bi-cable gondola configuration allows to have clearance overflights with respect to the ground up to 60 m. in accordance with the legislation in force at the time [R40] (the project was performed in 2020, before entry into force of

[R37], Dalla Chiara B., Alberto D., Zannotti G., “Impianti a fune per trasporto persone e materiali - Evoluzione, elementi costitutivi, progettazione ed esercizio, I edizione”, EGAF, 2022

[R38] Vitali, C.D.P. Software per verifica linea monofuni (tipologie : morsa fissa, automatica, pulsè e telemix), realize 0110, giugno 2017

[R39]). The high ground clearance reached by the proposed cable car allows to fly over the urban obstacles present in particular in the first segment, minimizing the impact of the system on the urban fabric of the Lagaccio valley.

The hybrid technology would allow for a lower energy impact of the system, as the motion of the vehicles in the stations would be guaranteed through the motorized wheels mounted on the vehicles and not by the energy-intensive and inefficient mechanisms of the station; and would allow for a simplification of the station geometries and their easier integration into the urban context. Furthermore, the hybrid system would allow, through future expansions, the creation of a transport network in which passengers, without getting off the vehicle, can reach different network nodes along different lines.

Transport systems for the overcoming of differences in high	**Reason for incompatibility in the Genoa-Forte Begato project**
Inclined lift	The distance separating the two terminal stations, around 8 km as the crow flies, is absolutely incompatible with the application domain of inclined lift that is limited to some hundreds of meters. Moreover, the impact to the soil is not compatible with the building of the plant inside the urban fabric of the Genoa Lagaccio neighbourhood.
Cog railway	The impact to the soil of the railway-type line is not compatible with the building of the plant inside the urban fabric of the Genoa Lagaccio neighbourhood.
APM Perugia style	The impact to the soil of the railway-type line is not compatible with the building of the plant inside the urban fabric of the Genoa Lagaccio neighbourhood.
To-and-fro ropeway	It would be hardly to integrate the voluminous stations, which should be built in the urban area of Genoa, with particular reference to the downstream station located close to the maritime port. Furthermore, the length of the line would hardly be compatible with the desired hourly capacity (in a to-and-fro system, the hourly capacity are inversely proportional to the length of the line)
Monocable traditional gondola	Monocable traditional gondola would allow the overfly of building and other obstacles in urban Genoa fabric, but, due to the high-wind condition in the area, it would suffer the weather conditions in terms of vehicle oscillation and less comfort in the vehicles
Funicular railway	The impact to the soil of the railway-type line is not compatible with

	the building of the plant inside the urban fabric of the Genoa Lagaccio neighbourhood.

Table 64-Reason for incompatibility of traditional transport system for the overcoming of differences in hight in the Genoa-Forte Begato project

The *Table 64* shows how the traditional transport systems for overcoming difference in high fail to match the peculiar needs of the case study subject of this chapter. So, also in this case of study, the hybrid system is referred to as the optimal system with the actual constrains of the project.

First stretch

The complexity of the urban context and the difficulty in finding solutions compatible with the functional needs of the transport system have led to the analysis of three possible alternatives as regards the stretch "Port area- Lagaccio" respectively starting from:

− Hypothesis 1: "Principe" (*Figure 111*). Departure with the position of the downstream station located between Alpini d'Italia street and Principe place in the area where the Principe Sotterranea railway station is located.

− Hypothesis 2: “Hennebique”. Departure from the downstream station at the top of the former Hennebique granary silos, the first building in Italy to have used the 1892 patent for reinforced concrete by Francois Hennebique.

− Hypothesis 3: "Sea" Departure with position of the downstream station located between the Hennebique building and the Genoa maritime station.

Figure 111-First segment of the line with the "Principe" downstream terminal station hypothesis, with particular reference to the integration in the urban area

The first stretch of the plant crosses the Lagaccio district, which has the typical characteristics of a totally urbanized area. The aerial system allows to overfly this neighborhood, minimizing the impact on the ground and reducing it to being punctual at the towers and stations.

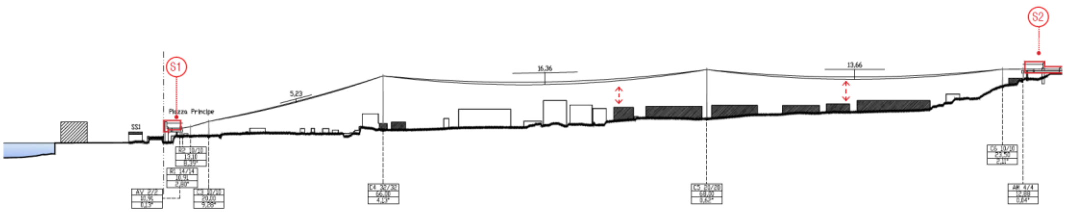


Figure 112-Altimetric profile of the line in its urban stretch Port-Lagaccio

Unlike cableway systems installed in mountain contexts, the conditions imposed by the territory in urban areas lead to having very high line supports, as to fly over the urban fabric and all the urban constraints and points of interest, including the elevated road SS1, streets, the Genova Principe underground station, the railway, residential and other-uses buildings.

Consequently, some supports have considerable heights (up to 83m, a drawing of which is represented in *Figure 114*); which, however, are not so innovative in the field of urban cableway transport systems: for instance, the existing Emirates Air Line gondola located in London-UK built in 2012 (*Figure 113*) is equipped with towers with dimensions comparable to those of the proposed ones, however well integrated into the urban fabric.

In addition to the line roller-assemblies, the supports of the first section also house roller-assemblies for the recovery rope: the high vertical clearances of the line and flying over buildings are in fact incompatible with the evacuation of passengers by lowering them to the ground in the event of system failure, and the evacuation should then take place through a rescue vehicle passing on a parallel rescue line.

The high height of the towers, in addition to allowing overflying of existing buildings and compliance with the legislation in terms of vertical clearance, allows the definition of particularly long spans (up to 446.25m in the plant in projects).

Figure 113-Picture of the towers of the traditional monocable gondola "Emirates airline" in London- UK

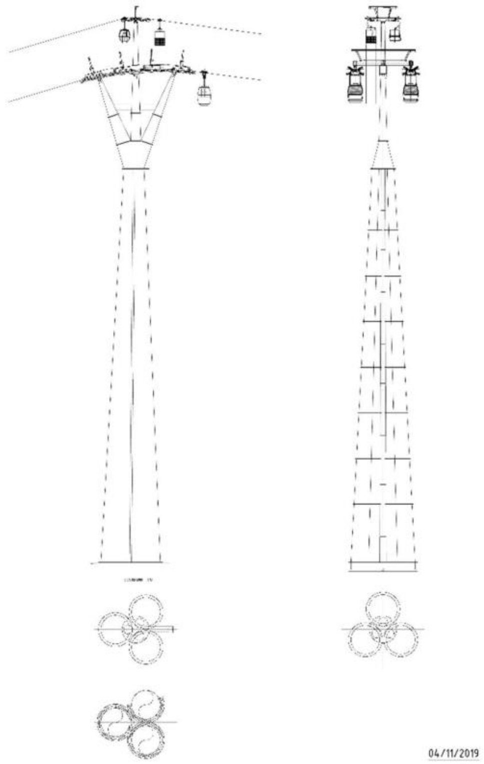


Figure 114-Draw of a high tower in the first stretch of the Genoa-Forte Bagato plant

Second stretch

The intermediate station, located north of the Lagaccio district (*Figure 115*), makes it possible to divide the line into two segments with very different transport needs: while the first stretch mainly performs the function of urban public transport, the upstream section (which connects Forte Begato, point of touristic and cultural interest, at the center of the city of Genoa) will be used mainly as a touristic line.

Figure 115-Area of installation of the intermediate station in Lagaccio district

The second section "Lagaccio-Begato" has the typical characteristics of a mountain line, as the crossed area does not have any constraints dictated by the pre-existing urbanization. The position of the upstream station (*Figure 116*) was chosen in order to make the connection with the Begato fort, both for tourist and sporting purposes, as easy as possible.

Figure 116-Area of installation of the upstream station in Forte Begato

Chapter 11

11. Conclusions

The analyzes summarized in this document, and in general the entire work carried out during the PhD program, have highlighted some undoubted advantages of an innovative hybrid rope-motorized wheels system compared to existing traditional transport alternatives, with particular reference to systems for overcoming differences in high.

In particular, hybrid system makes it possible to overcome the weaknesses of a traditional cable car, which have not yet allowed this technology to enter in the urban mobility market widely. In fact, a traditional monocable system, appears to be intrinsically limited by some technological constraints such as the impossibility of defining curved stretches, the relative complexity of the stations and the non-electrification of the vehicles, which does not allow the installation of video surveillance and comfort systems on board. These factors distance traditional monocables systems from the demand needs and from the requirements dictated by the urban contexts, and constitute an explanation of why traditional monocable systems, despite their undoubted strengths in terms of overcoming differences in high, anthropic and natural obstacles with low impact on the ground and low environmental and energy impact, are not frequently adopted yet. Indeed, they are still rare monocable-based systems performing the function of public transportation, and are mainly relegated to South American metropolises (where the need to cross highly anthropized neighborhoods, e.g., favelas, is central), or to particular needs such as overcoming rivers (e.g., Air Emirates cable car in London) or overcoming height differences in heigh in peripheral areas (e.g., Montjuic in Barcelona).

On the other hand, the hybrid system is able to maintain the strengths of traditional cable car technology, and to overcome its limitations. In this system, in fact, motion can be supplied to the vehicles (derived from the cableway technology ones) in two ways:

- Through a rope, in a similar way to a traditional cable car. In those segments, the vehicle is clamped to the hauling rope, and the movement takes place thanks to the rope. The ancillary systems and thermal comfort inside the vehicle are however guaranteed by the batteries mounted on board of the vehicle.
- Through motorized wheels mounted on the top of the vehicle, which are powered by batteries mounted on board. In these segments, the system operates in similar way than an elevated monorail.

In the cable stretch, the hybrid system maintains the advantages and disadvantages of a traditional gondola, while in the rail segments it inherits the characteristics of a wheel-based system, and is therefore able to define curvilinear routes and to efficiently adapt to the urban fabrics. The hybrid system therefore offers undoubted advantages of urban integration, which have been explored in the three case studies elaborated:

i) As regards the Sorrento-Sant'Agata project, the route on the rail segment allows the definition of stretches in underground tunnels, which is difficult to implement in the case of cable-based systems due to the high oscillation angles of the vehicle around the clamp-rope constraint, which increases the limit section and, ultimately, increases sections and costs for the excavation. In this context, the integration of the plant into the urban fabric was necessary to preserve the historic centre of the Campania town and to prevent the transport system to have high visual impact in one of the places of the highest cultural and touristic value in the world. At the same time, the same system is able to overcome the high difference in height in the segment covering the hilly line climbing towards the Sant'Agata bourg.

ii) Similar requirements for integration into the urban fabric were found with regard to the connection between Angri and Maiori, in which, similarly to the previously mentioned project in Sorrento, the dual cable-based and wheel-based nature allowed on the one hand easy integration of the urban sections, thanks to segments in tunnel and rail, and on the other hand the overcoming of huge differences in height with a limited energy impact. Furthermore, the considerable length of the planned line (more than 14 km) made the presence of ventilation, air conditioning, info-tainment and video surveillance systems essential for passenger comfort, and hybrid system made it possible thanks to the fact that vehicles are equipped with electric power, as they house energy storage and electric movement systems on board.

iii) In the Genoa-Forte Begato project, the very stringent urban constraints of the project area (i.e. a district of a large city with a very high density of buildings) have required to particular attention to integration issues, reconciled with the need to have a very low impact on the ground so as not to impact the saturated area in terms of anthropization. Furthermore, the high wind conditions of the project area made it appropriate to use bi-cable technology in order to minimize vehicle oscillations and maximize passengers' comfort.

In the contexts related to the three case studies above- mentioned, it has been demonstrated that the hybrid system is optimal compared to the other systems for overcoming difference in height. In general, the hybrid system appears to better match the transport needs and the context constraints in projects where the requirements of integration into the urban fabric and of overcoming differences in high, natural and anthropic obstacles with low impact on soil are at the same time central.

On the other hand, the described hybrid system has hourly capacity limited to around 5,000 people per hour per direction, dictated by the relatively low speed reached (maximum 6m/s in the rope segment, maximum 4m/s in the rail one), by the relatively small vehicles, typical of PRT-based systems and by the clearance spacing between two successive vehicles, dictated by models based on block section technology.

For this reason, the hybrid system described in this document cannot replaced metro systems or systems based on metro technology, which can reach and exceed 20,000 passengers per hour per direction, but it can find its typical niche of use in APM systems domain.

About the energy and environmental impact of the system, it is considerably lower than traditional public transport systems: indeed, a specific consumptions (in the case of horizontal lines) of 0.0269 kWh/passenger/km in rail segments and passengers' of 0.07576 kWh/passenger/km in cable segments have been demonstrated, of which 0.01614 kWh/passenger/km and 0.065 kWh/passenger/km respectively for motion (the remaining consumption is related to ancillary systems e.g. air conditioning and video surveillance system). The above-calculated values for the ropeway section are related to a line with a capacity of 1,480 passengers per hour per direction, and is reduced to 0.040 kWh/passenger/km for the motion in the case of a line with 5,000 passengers per direction. So, it has been demonstrated that, as the hourly capacity increases, the consumption associated with the plant increases less than linearly, thus causing a specific consumption curve that decreases as a function of the hourly capacity.

Another factor that influences the definition of specific consumption is obviously the average load of the vehicles, since the total consumption is allocated to a different number of passengers. Despite this, as the vehicles have a relatively low weight when compared to other urban transport systems (the ratio between the weight of the passengers and the vehicles one is around 32%, compared with 28% of tram, 30% of sub-urban bus and 32% of urban bus [R51]), less use of the line is associated with lower consumption.

Therefore, also in this case, a sub-linear correlation is demonstrated between the load index and specific consumption. Furthermore, it is demonstrated that, for horizontal stretches, the distribution of the load (how many passengers are on one stretch and how many passengers are on the other one) does not affect the energy performance, which is therefore a function only of the number of passengers and not of their location along the line.

This result is not valid in tilted lines where, especially in rope segments, the descending payload has a positive effect in terms of reducing the energy performance of the system, as it supplies work and decreases the energy demand. The breakdown point, in which the weight of the loaded vehicles going downhill covers the friction and supplies power to increase the potential energy of the unloaded vehicles in the upstream segment is about 60%: around that value, indeed, the absorption of a system with a fully loaded upstream branch and a completely unloaded downstream branch is negative, reaching a specific consumption of -0.001 kWh/pass/km.

It is possible to recognize an energy recovery of the descending stretch vehicles in the rail branch also, thanks to the electrical storage systems installed on board. However, it should be remembered that the maximum gradient limit in the rail section is around 7%, due to constraints related to adherence.

For these reasons, in its domains of application in terms of demand and needs, the hybrid system can reduce the pressure of the urban transportation sector in terms of energy consumption and emissions, helping to overcome the now unsustainable mobility paradigm based on the private car.

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