Modelling intermodal re-balance and integration: planning a sub-lagoon tube for Venezia

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Abstract

The increasing need, in the transportation sector, for new policy initiatives that generate positive and sustainable environmental, social and economic impacts is increasingly directed towards the promotion of intermodal integration in transportation that may prompt a re-balance in the mobility pattern in relevant areas, especially in an urban environment.
An interesting example of a city with a great variety of such complex transportation challenges is the Venice area in Italy.
In this paper a feasibility study for a sub-lagoon tube connection between Venice island and its mainland is presented. This project aims to improve accessibility and sustainability in the Venice region, by favouring an intermodal re-balance in the local transportation system. In particular, the methodology of transportation evaluation and of scenario simulations will be highlighted, while the main results of the study will be presented and discussed. Multi-criteria analysis is used here inter alia as an important assessment and evaluation method. The case study of Venice can be considered as an illustrative study, in which a novel and challenging urban plan is followed by specific studies assessing the overall sustainability of the proposed policy intervention, even though it is not ensued by an immediate implementation.

Keywords: modal integration, cost-benefit analysis, environmental sustainability, re-balance

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Integrated and intermodal transport: a matter of sustainability

The debate on sustainable development is already more than two decades old. It has focussed in more recent years in particular on sustainability governance, especially from a regional (local) and/or domain (sector) perspective. Transportation is one of the prominent sectors often addressed in this context. And policy-makers are desperately seeking for solutions to cope with the sustainability challenges related to modern transport and mobility.

Transport is a necessary activity in a modern society, as it acts as the lubricant for consumption and production in our world. It is an input for our production processes, but may also be an output (e.g. leisure activities). The rise in globalization has of course reinforced the international importance of the transportation sector, a situation which calls for a creative policy in this industry, including intermodal transport solutions.

Transport is one of the world's largest industries and in many countries it accounts for up to 20 per cent of the nation's gross domestic product. Clearly, transport has environmental externalities. It is also noteworthy that transport has stirred up environmental debates throughout recorded history. Reliable road and maritime transport was vital to the conquests of the Roman Empire, for example, but the noise caused by wagons in the streets of Rome resulted in curfews. The problems of reconciling the transport needs of modern society with the noise, fumes, and, often, ugliness of transport remain a major issue today which in some areas is seemingly becoming more intractable (see also Nakamura et al., 2004).

This should not necessarily be taken to imply that the environmental costs of transport are all over-rising. In many areas pro-active public policy has been extremely successful in reducing the environmental burden. Smart intermodal solutions, for instance, have contributed to the efficiency and sustainability of the sector. The introduction of catalytic converters has considerably reduced acid rain gas emissions in many countries, and lead in gasoline has largely been removed in many nations. Technology has encouraged the development of policies that now make commercial aircraft quieter and ships less likely to leak oil after a collision. However, fresh issues are emerging, as new information becomes available and as the population's tastes change. Also, not all of the more traditional problems have entirely vanished and others have taken new forms; planes, for instance, may be quieter but there are now more of them (see also Robert and Jonsson, 2006).

There is, however, a cost associated with this evolution of transport. The history of motorized transport is one of large-scale environmental intrusion and in many respects it is becoming even more harmful with its extensive use of fossil fuel. Transport poses many operational and logistic policy problems, but the environmental implications of the motor car, trucks, aircraft and the like are indeed very challenging (Banister and Button, 1993; Button and Nijkamp, 1997; Button and Stough, 1998; Button et al., 1996). The projected trend in growth in motorized land-based traffic, aviation and shipping into the new century means that current policies will at least need refining to cope with the situation.

One major problem is the diversity of impacts associated with modern transport (Button, 1993). It has local and immediate effects – noise nuisance and local atmospheric pollution – that have major public health implications as well as being unpleasant; regional effects – for example 'acid rain' gas emissions (such as sulphur and nitrogen oxides) and oil spills – that transcend the immediate areas where the transport is undertaken; and global effects – for example, greenhouse gas emissions such as CO_2 – that may affect global warming. Unlike a power generating station, for example, there are clearly inevitably large numbers of environmental trade-offs that have to be made when designing a balanced ecological and transportation policy. Linked to this, almost by definition, transport is a mobile source of noise and pollution. This raises problems of attribution and of responsibility that are much less of an issue in many other areas of environmental concern.

Transport is also often demanded in close proximity to where people live, work and spend their leisure time. Indeed, it is the very access afforded by transport that permits the modern lifestyle we find in the developed world (Button and Nijkamp, 1997). This again poses many more problems when contrasted with other major sources of environmental damage. In developed countries, populations find limited incentive to use less environmentally intrusive modes of transport and policy makers are finding it difficult to obtain anything but minimum intermodal shifts from the use of the motor car and from trucking. The car affords a number of private benefits over public transport. In practice, the lure of the motor car is much stronger than most transport forecasting models predict and many efforts to foster more environmentally-benign public transport use ignore the massive quality differences involved in getting straight into a car at one's home after being able to choose exactly when to leave the house, adjusting the temperature to that desired, listening to music that one likes in one's own company or company of one's choosing, being able to carry large packages conveniently in security, to select alternative routes periodically to avoid boredom, sitting in seats that have been selected from the wide range that are available in different vehicles and so on. Public transport does offer an attractive variation on dry days when the timing is convenient and one has little to carry but in most cases there are major differences in service quality. Getting people to switch to public transport requires sticks as well as carrots (see Banister et al., 2000). Integrated transport policy is indeed a major challenge.

Public policy with regard to tackling the conflict between narrow economic considerations and the environmental costs of transport differs between countries (Barde and Button, 1990) and has inevitably changed with time. While in the past, several measures have often been almost exclusively concerned with urban problems of noise and fumes, the scale of transport activities and their continued growth has now brought forth a broader approach. In particular, many countries now realize that is not tenable in the longer term to construct the infrastructure needed to cater for projected car traffic into the next century and instead are seeking ways of restraining the growth (for example, UK Department of Environment and Transport, 1998).

These policy changes have not been entirely the result of a practical inability to cater for unrestrained demand, but are also due to a combination of influences. First, we now know more about the environment and with this knowledge has come the social demand for new policy initiatives aimed at meeting these freshly discovered challenges. The discovery of the implications of

emission of nitrogen oxides (NO_x) on trees and water courses is an illustration of this. Equally, there have been important reassessments of social priorities, partly due to new scientific insights but also due to such factors as rising income, which bring forth demands for a better quality of the environment for current and future generations. The ongoing concern with sustainable development is a manifestation of these interacting forces (World Commission on Environment and Development, 1987).

At the micro level, where environmental concerns with noise, fumes and the like have more traditionally been focused, there is also the issue that while some policies have proved to be very successful, many problems still remain or have been created. Lead, for example, has been removed from gasoline in many countries but, for combustion reasons, many types of fuel now contain cocktails of aromatics that have other potentially harmful effects. Equally, the adoption of the 'zero emissions cars' policy in California may introduce a small number of electric cars into the system, but of itself it simply moves the location of much of the pollution from the streets to other power generation sites.

There are a number of detailed policy approaches that can be, and have, been used to tackle the problems associated with transport. In broad terms, these can be divided into technological, institutional and enlightening policies.

Technological policies are direct and consist of measures that make the vehicle or infrastructure more environmentally benign. They embrace, for example, improved vehicle/vessel technology (including improvements to the gasoline engine, electric and hybrid low emission vehicles and the development of alternative fuels), infrastructure quality, design and construction technology (including new techniques for building tunnels, bridges and earth embankment and cuttings) and infrastructure management (including air traffic control systems, urban traffic demand management, junction controls and intelligent transport systems). Technical solutions have been widely used and with considerable success. Some have got to the root cause of the problem (for example, the removal of lead from gasoline), while others represent end-of-pipeline treatments (such as catalytic converters and noise suppressers on aircraft engines). There is, however, potentially a limit to what technology can do. The current concern with greenhouse gas emissions, for instance, is reduced with the adoption of more fuel efficient engines, but the benefits from technical advances are likely to be speedily overtaken by the sheer increase in vehicle numbers. Also technology often involves tradeoffs (for example, catalytic converters reduce acid rain emission but increase fuel consumption with implications for greenhouse gas emission) and solving one problem can, therefore, lead to others. Finally, technology has to be implemented and there are a number of policy instruments that may do this.

The supply and management of transportation is too important to be left to the market, especially given that transportation is a sector where the free market does not necessarily bring the optimal social outcome. Transportation planning, therefore, deals with the ways in which governments, at various levels, try to ensure that transportation effectively and efficiently moves people and goods, shapes urban form, affects economic vitality and impacts quality of life to meet wider social objectives. It includes issues such as roadway congestion, transit services, and non-

motorized travel. The challenges posed on transportation planning have continuously grown over the years due to mounting problems of congestion, new concerns with environmental degradation and global warming, enhanced awareness of safety, and increasing complexity of travel behaviour patterns associated with modern life. Although, it should be added, that the tools available for implementing transportation plans have at the same time advanced as computerization and, hence, sophisticated real-time information systems (especially geographical information systems) have emerged (see also Shiftan et al., 2007).

Travel patterns, in particular though, have become more complex due to decentralization of residential, commercial and work places, more leisure time and more travel for non-work purposes, more flexibility in work hours, increasing participation of women in the work force, and the introduction of information and communication technologies that enables substitute travel for all purposes. On the production side, there has been a shift to the service sector, the emergence of just-in-time supply logistics, and globalization of sourcing. At the same time, these changes have significantly increased congestion and air pollution from motor vehicles, raising as a result the need to develop new, or at least modified, objectives of policy and planning towards sustainable transportation.

For all these reasons, European countries are mainly focusing on the integration of transport modes, whose key factors lies in public transport quality, coordination and affordability and in the collaboration among different institutional levels, as well as on a good presentation to the public (UK Commission for Integrated Transport, 2007). We will now illustrate these observations on the basis of an interesting case study in the Venice area, where integrated and intermodal options are a prerequisite for accessibility and sustainability in the local transport system.

Modal re-balance and intermodal integration for sustainable transportation systems

The aim of the present paper is to present the results of a study carried out in the city of Venice in which a modal re-balance and intermodal integration have been experimented to increase the sustainability of the existing transportation system. As previously stated, if it is clear that the pathway to a more sustainable transportation system has to take into account a strong reduction of the private cars' circulation, it is not as clear how to make this feasible. A universal recipe still does not exist, even though several policies have been variously tested in the world. In a recent study (Garling and Schuitema, 2007) the authors have analyzed the impact of several travel demand management measures and have concluded that the only way to make such measures effective is to combine together coercive and non-coercive ones, i.e. introducing obstacles to car usage but contemporary increasing the attractiveness of the other transportation modes. In this light an important role to achieve a sustainable mobility is played by a mix of policies of intermodal integration and modal re-balance.

This idea of modal reconfiguration is also confirmed elsewhere. In particular in Potter and Skinner (2000), an interesting perspective is proposed in which transport planning should follow a *holistic objective-led approach*. The basic idea is that an effective planning has to take into account all the dimensions of the travel choices: the choice of travelling, the choice of the destination, the

choice of the mode and finally the choice of the path. Only by regulating all these dimensions it is possible to create a well organized system. Despite being very interesting this idea is not very easily implementable, above all because the personal choices are very difficult to be identified and influenced. However, the idea of integrated planning is becoming fashionable and can be used on a case study by case study approach to be adapted in the best possible way.

Another interesting analysis carried out concerns the Greater Toronto Areas (Kennedy, 2002) and calls for a new transportation system organization in which a mixture of modes have to be managed at once. Also, in other studies (see e.g. Musso et al., 2008), the steps followed in the Italian cities of Rome and Napoli to improve the cities' environmental conditions and liveability and the role played by the integration of all transportation modes of the city are described.

In conclusion, there is a common perspective to highlight: in order to obtain a transportation system that at the same time is as efficient as possible and wastes as few human resources as possible (in one word a *sustainable* transportation system), a high level planning approach is necessary in which all relevant factors influencing the mobility in a certain area are considered and organized together. In this light, this paper briefly presents an integrated approach that has been adopted to design a feasible solution to the congestion problems of the city of Venice.

As will be detailed in the remainder, the proposal of the integrated policy intervention in Venice is based on the construction of a sublagoon tube connection between Venice island and the mainland. The analyses in our paper are focused on the impacts on the modal split of the new access mode to the Venice island (i.e., the Historic City) and of the new inter-modal terminal on the only mainland access point, where the terminal, connected to the airport station, will also integrate the Regional Metropolitan Rail System and the highway system. The study represents an illustrative case of the chance of incisively impacting on the integrated land-use/transport system by means of sustainable mobility measures, aimed at modal re-balance and inter-modal integration. Such evidence has been magnified by the peculiarity of Venice, which represents a unique laboratory for experimenting sustainable mobility policies, due to its morphological, urban, social and land use characteristics.

Simulations carried out in the study allowed identifying the most suitable layout of the sub-lagoon tube and the best localisation of the metro stations. The main evaluation criteria used are *(i)* the reduction of the total "running" time, *(ii)* the increase of the revenues for the areas impacted by the project and *(iii)* the reduction of pollution due to minor private car traffic flows. The outcomes are then used to evaluate the integration of the sub-lagoon tube within the wider transportation system of the area, first looking at quantitative indicators directly derived from the simulations of the transportation system, and then performing a multicriteria analysis of the scenarios by means of the Regime method. The attractiveness of the new metro system has been the key factor in our analysis, indeed leading to traffic reduction on the existing networks, and, subsequently, to a decreasing negative impact on existing social and environmental issues.

The island of Venice: setting the scene

The uniqueness of the city of Venice for experimenting sustainable mobility policies is highlighted by different factors. First of all, the city of Venice is composed by 118 small islands connected by means of 354 bridges and divided by 177 channels. For these unique geographic features the transport supply of the city is, by nature, an intermodal supply. The access from mainland to the Historic Centre (HC) is allowed by lagoon boat services, or alternatively by the only available land connection, the "Ponte della Libertà" (Fredoom Bridge), which gathers a rail public service and the road transport, both for private use and for transit lines. Once reached the HC, the transport alternatives reduce to canal boat services and to pedestrian mobility. Hence, movements towards internal destinations of the HC may be fulfilled only as trip chains involving at least two transport modes.

Secondly, the transportation demand pattern in the island is peculiar as well. Very few inhabitants still live on the islands. Actually, the city is dominated by a lot of economic activities and touristic attractions. For this reason there exist two main demand categories for trip purposes, work and tourism. They have roughly the same weight but, of course, are really different both for the daily and seasonal trends and for the underlying behaviours in travel choices.

Moreover, the very high number of daily commuters who reach the island from Venezia-Mestre (mainland) and the unique land connection to the HC lead to heavy congestion phenomena that involve to large extent also the Mestre road network on the mainland. Even the pedestrian network of the city centre is affected by non-negligible congestion problems.

Finally, the environmental constraints in the area strongly influence the possibility to suitably manage and modify the transportation system. In particular, the hypothetical opportunity to encourage the navigation of the bay and of the various channels of the city cannot be fulfilled. Boat movements, indeed, must be limited in order to preserve the delicate microcosm of the lagoon and to limit damages to the ancient buildings caused by the wave motion.

For all these reasons, to study the impact of an important infrastructural intervention, like the construction of a sub-lagoon metro line, a detailed and careful scenario analysis is necessary.

Integrated plan description

The methodology used in this study has followed the typical path of a transportation study. In particular, after the analysis of the current transportation system and the definition of the scenarios of intervention, a simulation of the transportation system has been performed in the different scenarios. The peculiarity of the used approach is related to the fact that variables like the best localisation of the metro stations, that at this planning level are usually considered of minor relevance, have been at the outset taken into account in order to identify the most suitable (sustainable) layout (if any) of the improved transportation system of the city of Venice.

The current transportation system

As anticipated above, the transportation system which connects Venice Island to the mainland is composed by a road infrastructure as well as by a rail infrastructure: the "Ponte della Libertà" bridge, a group of parking areas for cars and buses concentrated at the end of this bridge, and a set of docks for lagoon boats. Apart from the lagoon boat services, all the connections to the islands are

focused towards the “Ponte della Libertà” bridge (Figure 1), with too much concentration of vehicular and pedestrian traffic on the extreme points of the system (bridges, station, harbour); lagoon transportation services are rather slow (the maximum allowed speed in the lagoon is 6 knots), and not frequent; in particular, the system is influenced by the lack of a direct connection between the island and the airport.

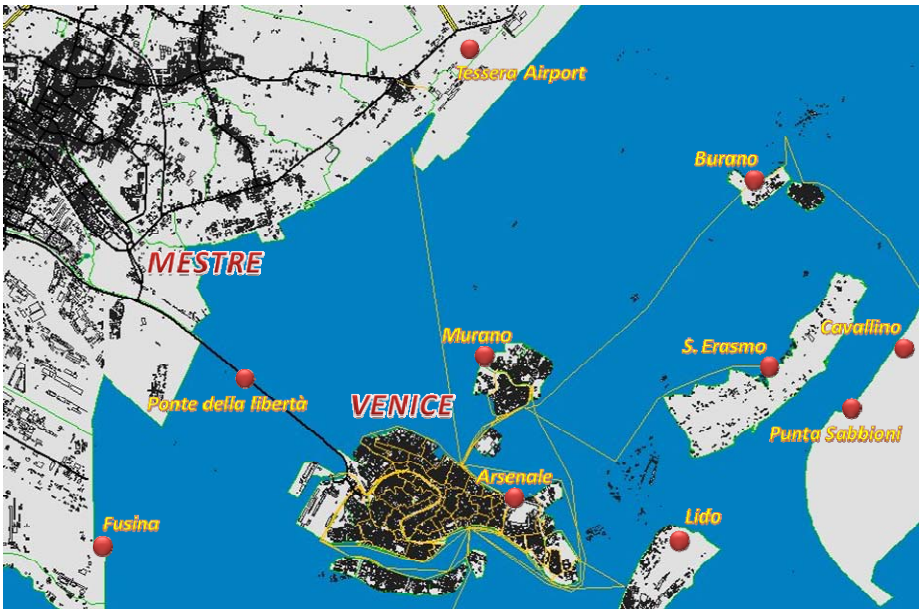

Figure 1 Current connections between Venice Island and the mainland

Moreover, the current configuration of the transportation system has led to an excessive localisation of activities next to the bridge on the Island, while further zones, in particular the area of Arsenale, have been progressively abandoned, thus suffering nowadays of urban decay (Figure 1).

A lively debate about the urban recovery model of the Historic Centre of Venice has led to the formulation of the so-called P.r.u.s.t (Plan for the urban requalification and the sustainable development of the land-use) for the lagoon area, which, among other things, claims the necessity of the realisation of a new high frequency, not polluting, not too invasive transport connection, between Tessera airport of Venice and the Arsenale area with a twofold aim: first, to reduce congestion on the “Ponte della Libertà” bridge and the surrounding areas; secondly, to contribute to the revitalization of the Arsenale area.

In order to evaluate the technical and financial feasibility of the initiative, the Municipality and the Chamber of Commerce, Industry, Crafts and Agriculture (CCIAA) of Venice, have promoted a set of planning studies, of a technical, environmental, financial and economic nature; in particular, a specific study (Torrieri et al., 2002) has been conducted on the system of the connections between the Island and the mainland, in order to forecast traffic volumes on the new links, and to evaluate the benefits useful for land-use, and the recoverable aliquot of the investment by means of the management of the new transportation services.

The planned scenarios

Currently the connections of Venice Island (Figure 1) with the mainland (Mestre, and the coast of Cavallino) and with the other islands of the lagoon (Murano, Lido) are assured by the following transportation services (Figure 2):

- National and regional rail services, based at the station of S. Lucia;
- Touristic bus services, based in Tronchetto, a small island connected to the "Ponte della Libertà" bridge;
- Public road transport services, based in Piazzale Roma;
- Private self-produced transport (cars and motorcycles) with parking areas localised next to Piazzale Roma and the island of Tronchetto;
- Lagoon boat services, localised at the southern side of Mestre (Fusina); at the northern side of Mestre (Tessera); and at the eastern side of the lagoon (Punta Sabbioni-Lido).

The planned intervention of the Sub-lagoon tube described above is included in a more comprehensive strengthening program of the transportation system of the area, whose main projects were:

- Implementation of the Regional Metropolitan System, in order to improve the public rail transport services in the provincial area;
- Doubling of the highway link in Mestre, in order to reduce the congestion on the peripheral road network of Mestre;
- Construction of an urban tram line in Mestre.

Figure 2 Location of the main transportation services

In this framework, the realization of the Sub-lagoon tube, with its new terminal point in Tessera, aims at strengthening public transport in the Venice area, by offering an alternative to both current individual users of private transport, and to tourists who reach the Island by bus, thus providing a real alternative to the terminal of Piazzale Roma.

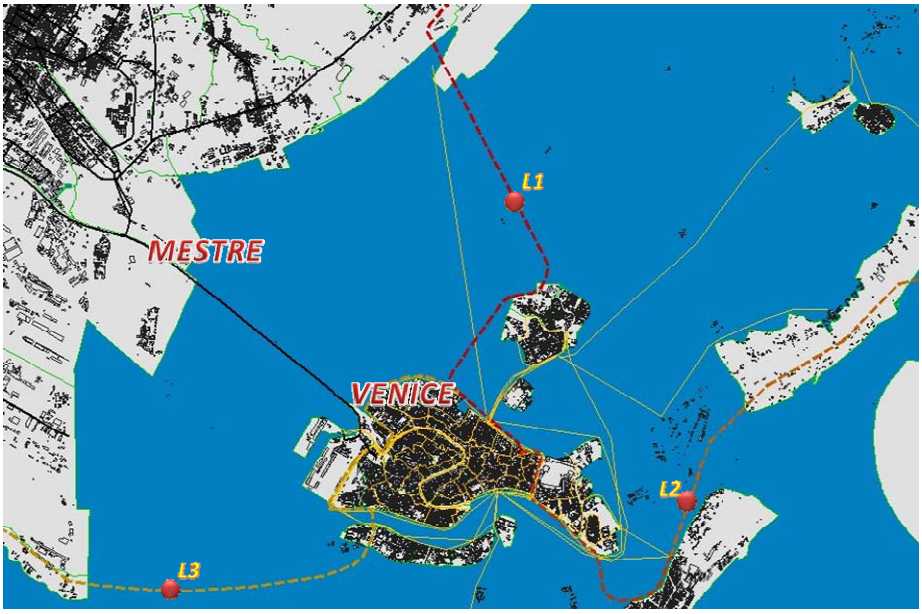

Figure 3 Scheme of the designed lines of the Sub-lagoon project

In particular, the project includes the construction of an underground metro line in the lagoon, allowing the circulation of vehicles of average dimensions and capacity (150-200 seats), articulated in the construction of three lines, as described in Figure 3:

— Line 1 (L1), with two stations on the mainland (Tessera Airport and Terminal Tessera), a stop on Murano island, three stops on Venice island (Cannaregio, Fondamenta Nuove, Arsenale);
— Line 2 (L2), continuing from Line 1 towards the Island of Lido with stops in Arsenale, Giardini di S Elena, S.M. Elisabetta, and Aeroporto "Nicelli" (Lido);
— Line 3 (L3), adding the following stops to Line 2: S.Lucia, Dorsoduro, Fusina

It goes without saying that the plans for such an ambitious underground system call for a systematic assessment and evaluation. We will present here now the various choice possibilities in the form of a policy scenario analysis. For what concerns the evaluation scenarios, the following configurations have been considered:

— *scenario 0*: the system in the current situation is simulated and integrated with the works in progress on the existing transport infrastructures (Regional Metropolitan Service, Highway link of Mestre, Tram line).

— *scenario 1 (L1)*: the designed system is simulated, with the insertion of line L1: Tessera-Murano- Arsenale, and the parking facility of Tessera; the beginning year for the running of this service is set at T1=6 years.
— *scenario 2 (L1+L2)*: includes the addition of a new stretch (line L2): Arsenale-Aeroporto "Nicelli" (Lido); beginning year of the service is set at T2=T1+4
— *scenario 3 (L1+L2+L3)*: the construction of line L3: Arsenale-S.Lucia-Dorsoduro-Fusina is modelled and planned; beginning year of the service at T3=T1+14.

It is worth noting that the scenarios analysed are to be considered integrative and sequential, rather than real alternative ones. In the next section, we will concisely present the underlying transportation system model for Venice.

The integrated transportation system model

The study area and its traffic zones

The study area includes the entire territory of the province of Venice. The activities are supposed to be localised in 398 zones, whose subdivision is described by previous official studies, according to the scheme in Table 1.

Table 1 Zoning of the study area

Venice Historic Centre	41 (zoning adopted by Venice municipality)
Other lagoon islands	8 (zoning adopted by Venice municipality)
Venezia Municipality (excluding islands)	36 (zoning adopted by Venice Province)
Venice Province	314 (zoning adopted by Venice Province)

The supply model

The transportation network of the Province of Venice is clearly multimodal. Despite the difficulty of modelling all transportation modes together, it was indispensible to achieve a realistic estimation of the effects of the new transportation system. For this reason the supply model is composed of the following infrastructures and services:

- The private (self-produced) transport network: road network, parking areas,
- The transit road network (buses)
- The transit rail network (trains)
- The pedestrian network on Venice island
- The lagoon boat services network.

Clearly, the current railway network has not been considered in the simulations, because the part of the traffic demand that may be attracted from the new transportation system may be

considered rather marginal. Indeed, the railway system is mainly used by passengers (commuters, visitors) that reach the city of Venice directly from outer parts of the province or even from other provinces, without stopping in Mestre. On the other hand, the pedestrian network has been included, because the traffic in the future scenarios can be significantly influenced by the connections between the sub-lagoon stations and the pedestrian roads on the island. In our future scenarios, the network model is integrated with the Sub-lagoon tube services. All network models have been represented by means of a geo-referenced oriented graph. We will now briefly describe the various submodels.

The road network

The road network comprises the main road infrastructures of the Province of Venice. It obviously does not include any road in the city centre of Venice, since there isn't any. For each link, the following characteristics have been considered:

- Length, width and number of lanes;
- Capacity for each direction, defined as the maximum number of vehicles that in a hour can pass through the road link, excluding preferential lanes, and the lanes exclusively dedicated to the residents in the historic centre;
- The average free flow speed;
- The travel time on the link. This obviously depends on the traffic flow that exists on the link. For this reason, for each link two values of travel time have been considered, one corresponding to the expected average flow during the peak period and the other during the off-peak period. Its value has been obtained using the standard BPR model (U.S. Bureau of Public Roads, 1964);
- The average delay at the signalized intersections and at the level crossings (queuing links), in both peak and off-peak hours.

The road transit network (buses)

A specific local transit network was not created. The demand estimated for the transit system was considered to be allocated over the entire road network. For the Venice area, this hypothesis was necessary, since it is not meaningful to evaluate a future scenario (that certainly will influence the future transit lines' layout) on the basis of the present lines which, for example, do not allow passengers to reach new destinations foreseen in the new project plan. In this light, simulation results are useful to design the transit lines' layout most desired by the users (thus most attractive) in the future.

The pedestrian network

The pedestrian network was only implemented for the city centre of Venice. Each link of the pedestrian network has been given a constant speed of 4 Km/h. Clearly, in common practice pedestrian networks are considered usually uncongested, but in this case this is not always realistic due to the large number of people that daily walk on the narrow streets of the city. However, this

simplistic hypothesis has been maintained in the study (although by means of a sensitivity analysis this could be further investigated).

The lagoon boat services network

The lagoon boat services network has been implemented by means of an oriented geo-referenced graph, whose nodes represent the docks and whose links represent the lagoon connections. Each lagoon transport line is characterised by a specific commercial speed, that takes into account the cumulative times (stop delays, part of journeys in accelerated, decelerated and regular motion) experienced along each path with the service frequencies. Speeds and frequencies are deducted from the official time schedules of the agency (named ACTV) supplying the transportation services.

As an example, in Figure 4 the pedestrian and lagoon boat services networks are schematically illustrated (in yellow and orange respectively).

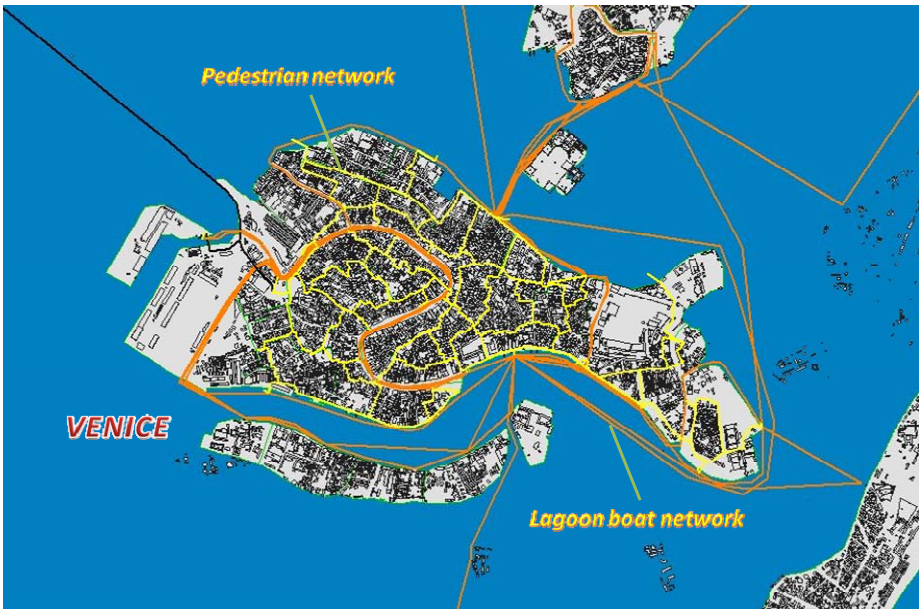

Figure 4 Pedestrian and lagoon boat services networks of the island of Venice

The sub-lagoon tube network

The specification of the new transportation services offered by the tube system depends on the particular technological choice. However, hypothesizing a system like a light rail transit, the performance indicators considered for the vehicles have been the ones reported in Table 2, where v_m is the average speed on the link, and a_m is the average acceleration.

Table 2 Performance indicators of the chosen vehicles

Normal speed links			High speed links		
v_m	22	m/sec	v_m	25	m/sec
a_m	1.3	m/sec^2	a_m	1.3	m/sec^2

The demand model

On the basis of information from previous studies and surveys, the mobility demand among lagoon islands and the mainland, as well its temporal, spatial and motivational characteristics are known. Also the modal split among the existing transportation services is known from previous statistical information. In particular, the available data sources were the following:

- Origin-Destination (O-D) matrix of light and heavy vehicles for the year 1998 (Province of Venice);
- Traffic counts on the road network of the Province of Venice for the year 2000 (ANAS, that is the National Road Board);
- Motivational survey for people entering the city centre in the year 1997 (Municipality/ACTV);
- Lagoon boat passengers counts for the year 1997 (ACTV).

As a result of the availability and statistical analysis of this huge amount of data, it was possible to obtain the complete O/D matrix for the Province of Venice, as well as to retrieve the temporal, spatial and motivational characteristics of the traffic demand. In the following figures and tables, the main results of this experiment are summarized.

In Table 3, the matrix dimensions and the aggregated daily volumes are reported. These data are here shown to give the reader an idea of entire traffic pattern within the region.

In Figure 5 the spatial characterisation of the traffic demand in the city centre is shown. In particular, the traffic zones attracting the highest demand in the Historic Centre (HS) are S. Marco, S. Croce, Dorsoduro, Castello and S. Paolo. Among these, S. Marco and Castello particularly suffer from the distance to the only access point of the city and these zones are supposed to be, together with S. Paolo, the traffic zones that will benefit most from the introduction of the new transit system.

Table 3 Pedestrian and vehicular daily average volumes directed to the lagoon islands and passed through the "Ponte della Libertà" bridge (2002)

Current daily demand volumes towards Historic Centre of Venice (HS)		
Access mode to the HS	*O/D Matrix dimension*	*Daily volume*
Private road transport	350 × 49	19 855 pax
Road transit	350 × 49	37 559 pax
Rail transit	1 × 41	23 681 pax
Tourist buses	4 × 2	12 443 pax
Lagoon navigation Lido-P.ta Sabbioni	1 × 41	12 728 pax
Lagoon navigation from Tessera	1 × 41	600 pax
Total daily volume of pax entering HS	350 × 49	106 866 pax
Current daily demand volumes in the study area		
Access mode to the HS	*O/D Matrix dimension*	*Daily volume*
Private road transport	350 × 350	980 657 light vehicles 106 581 heavy vehicles

Considering the variability of the seasonal cycle (Figure 6), we may argue that the traffic volumes reported in Table 4, referred to an average annual day, can be considered valid for 310 days on average, so that for these circumstances the annual volume can be obtained by multiplying the

daily volume with a factor of 310. To calculate the overall volumes two characteristic periods are included in Table 4:

- The peak period lasting 6 hours, in which about 70% of the daily average traffic is registered.
- The off-peak period, lasting 8 hours, in which about 30% of the daily average traffic is registered.

The remaining 11 hours, occurring during the night, are of course not considered in the analysis, because they are not interesting for the purpose of the study.

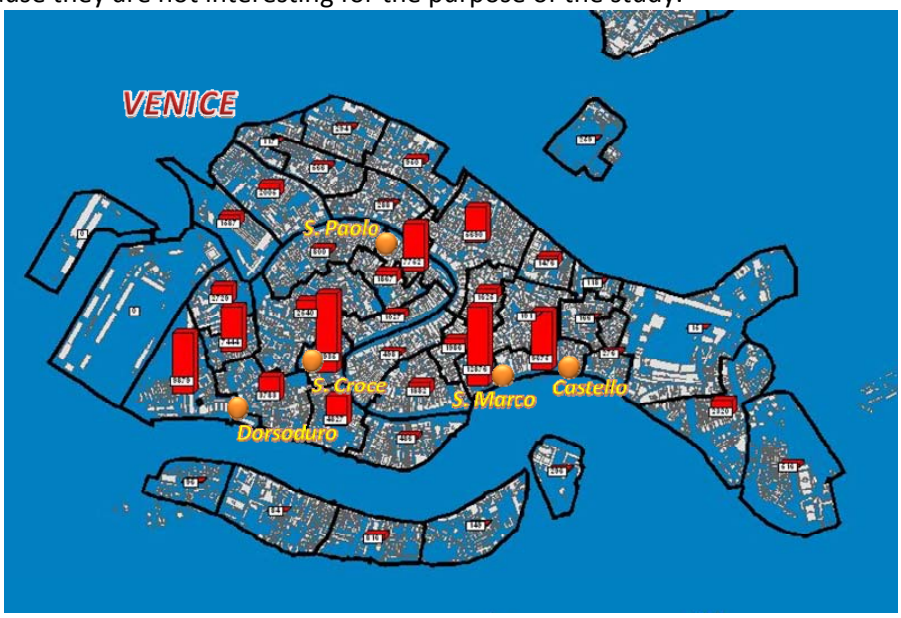

Figure 5 Mobility distribution subdivided by destination in the lagoon

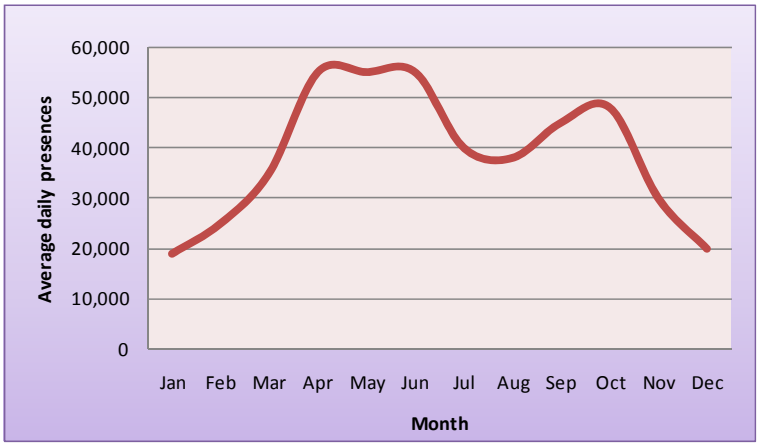

Figure 6 Yearly mobility trend (Venezia – Historic Centre 2000-2001)

Table 4 Peak and off-peak period traffic volumes

	Average annual daily traffic (veh)	Hourly traffic (veh)	%
Peak hours	11,272	1,879	11.61
Off-peak hours	4,909	614	3.79
Total	16,181	2,493	

The motivational characteristics regard almost completely the drivers of systematic trips and the trips of tourists visiting the region. For both motivations the demand elasticity with respect to the supplied performances can be assumed about null.

The integrated traffic forecasting model

Expected growth

On the basis of surveyed historical trends and existing previous studies about mobility patterns in the study area, the trend curve has been estimated and presented in Figure 7 by means of a logistic model. It indicates that the growth in 20 years is equal to 15% of the registered volume of 2003.

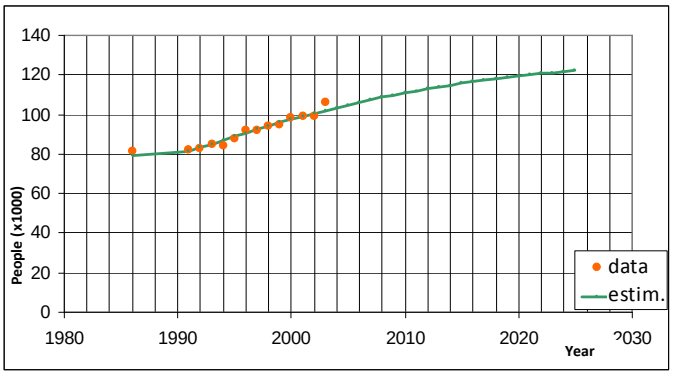

Figure 7 Trend curve of mobility of travellers entering the Island of Venice

Simulation experiments

After the design of the supply model for the whole transportation system and after the estimation of the traffic demand, the different scenarios described above have been simulated by means of the (commercial) software TransCAD (Caliper Corporation, 2005). For each scenario, two simulations have been performed, one for the peak period and the other one for the off-peak period.

Moreover, the traffic assignment to the network has been performed in two steps. First, a Stochastic User Equilibrium assignment has been performed on the entire network (with the vehicular demand matrix whose dimensions were 350×350, because the city of Venice was represented by only one point) to identify the equilibrium configuration of the flows on the road network; then a stochastic network loading (with constant costs equal to the ones obtained as the output from the first assignment) has been performed on the multimodal network to identify the path (and modes) chosen to reach the city centre (in this case the demand matrix was the complete matrix of passengers directed to the city centre and therefore its dimensions were 350×49). In this way it was possible to identify the vehicle and passenger flows on the whole network.

The traffic implications of the new transportation system were assessed comparing the results of the different scenarios. In the remainder, several interesting outcomes are reported. In Table 5 the

percentage of passengers detracted from the existing transport modes by the Sublagoon Tube in scenario 1 is highlighted.

Table 5 Percentage of passengers detracted from the existing transport modes by the Sublagoon Tube in L1 scenario

SUBLAGOON TUBE traffic volume	Scenario 1
From tourist buses	4.68%
From cars and motorcycles	6.98%
From transit system	4.66%
From lagoon boat services from P.ta Sabbioni to Lido	--
From lagoon boat services Tessera	0.61%
TOTAL SUB-LAGOON TUBE (L1)	16.93%

In Figure 8, the distribution of the traffic volume attracted for each traffic zone per different access mode is reported. As expected, the higher the distance of the zone from the Ponte della Libertà bridge, the higher is the percentage of passengers using the sub-lagoon tube connection.

Next, in Table 6 the estimated traffic volumes in all three future scenarios are reported for the sub-lagoon line as well as for the other access modes to the historic centre. It is evident from these results to recognize that in Scenario 2 the Sub-Lagoon system is already the most used access mode to the city of Venice.

The estimated data offer also the possibility to design the supplied service capacity in the peak hour period, proportional to the maximum expected value in the 20-years projection (in particular, the maximum estimated value is about 2326 pax/hour per flow direction). It is worth noting that the traffic estimates on the L1 line after thirty years are more or less constant, regardless of the presence of the lines L2 and L3; the same holds for line L2, in the presence of line L3. It is thus clear considering that the three evaluation scenarios are, as anticipated above, integrative alternatives.

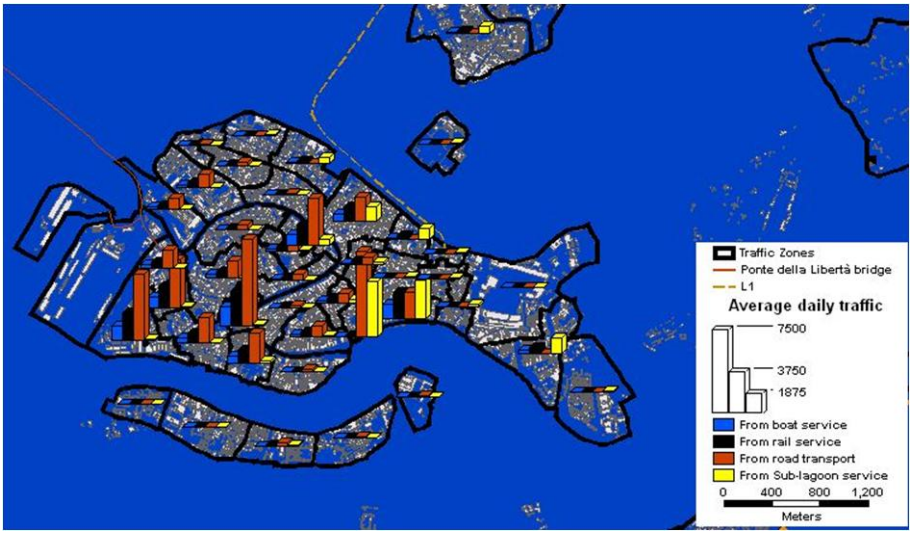

Figure 8 Traffic volume by destination to the historic centre per access mode: L1

Figure 9 further clarifies what was already stated before: in scenario L3 the integration of all transportation modes and the implementation of the three lines of the sub-lagoon transit system allow the fulfilment of a balanced distribution of the traffic among the available transportation modes. In particular, as it is clearly shown, only few people are forced to walk a long distance to reach their destination. Moreover, the zones of the islands closer to the Arsenale appear now to be very close to the airport and this will surely influence their future development.

Table 6 Average daily traffic per access mode to the historic centre (passengers)

		Ex-Ante	**Ex-Post**		
Projection years for each scenario		**0**	**T1**	**T2**	**T3**
Line	**Access mode to the historic centre**	**0**	**6**	**10**	**20**
Line L1: n° of access points at the terminal of Tessera	from cars and motorcycles	-	7 885	8 371	9 852
	from tourist buses	-	5 284	5 499	6 074
	from public extra-urban road transport	-	-	-	-
	from public urban road transport	-	5 267	5 757	6 428
	From lagoon transport services P,ta Sabbioni - Lido	-	-		-
	From lagoon transport services Tessera	-	684	711	786
	Total SUBLAGOON TUBE (terminal of Tessera)	-	19 120	20 338	23 140
Line L2 n° of access points at the Lido stop	from cars and motorcycles	-	-	-	-
	from tourist buses	-	-	-	-
	from public extra-urban road transport	-	-	-	-
	from public urban road transport	-	-	-	-
	From lagoon transport services P,ta Sabbioni - Lido	-	-	13 753	15 191
	From lagoon transport services - Tessera	-	-	-	-
	Total SUBLAGOON TUBE (stop of Lido)	-	-	13 753	15 191
Line L3 n° of access points from the terminal of Malcontenta	from cars and motorcycles	-	-	-	4 005
	from tourist buses	-	-	-	9 103
	from public extra-urban road transport	-	-	-	-
	from public urban road transport	-	-	-	3 902
	From lagoon transport services P,ta Sabbioni - Lido	-	-	-	-
	From lagoon transport services - Tessera	-	-	-	-
	Total SUBLAGOON TUBE (stop of Malcontenta)	-	-	-	17 009
Total SUB-LAGOON TUBE		--	*16.93%*	*29.00%*	*42.62%*
cars and motorcycles (P.le Roma and Tronchetto)		*18.63%*	*11.65%*	*11.51%*	*7.96%*
touristic buses (P.le Roma and Tronchetto)		*11.69%*	*7.01%*	*7.01%*	*0.00%*
extra-urban road transit (P.le Roma and Tronchetto)		*20.98%*	*20.98%*	*20.98%*	*20.98%*
urban road transit (P.le Roma and Tronchetto)		*13.88%*	*9.22%*	*8.98%*	*0.00%*
tram (P.le Roma and Tronchetto)		--	--	--	*5.92%*
lagoon transport services from P.ta Sabbioni to Lido		*11.96%*	*11.96%*	*0.26%*	*0.26%*
lagoon transport services - Tessera		*0.61%*	*0.00%*	*0.00%*	*0.00%*
rail transport		*22.25%*	*22.25%*	*22.25%*	*22.25%*
TOTAL		***100%***	***100%***	***100%***	***100%***

For what concerns the expected impacts of the project, Figure 10 shows how the travel time distribution between the HS zones (by foot) changes, and this translates into significantly lower values.

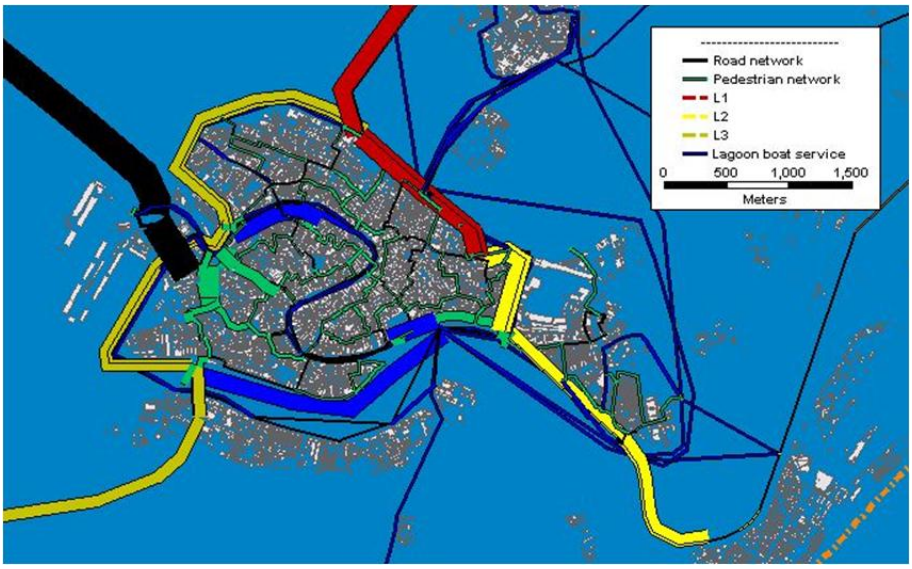

Figure 9 Traffic flows entering the historic centre of Venice with the Sub-lagoon line L1, L2 and L3.

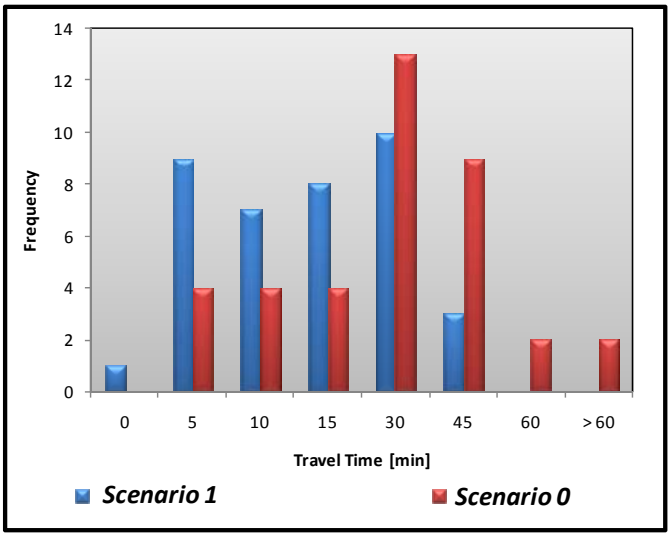

Figure 10 Pedestrian travel time distribution within the city centre with and without the Sub-lagoon line L1

Expected impacts of the project

In this section, the expected impacts from the Venice project will be further investigated. According to the general aims of the study, these impacts can be summarised as:

- a reduction of the total running times in the connections with the Island of Venice;
- a increase in income for the areas affected by the project;
- a reduction in pollution due to lower private car traffic flows.

In Table 8 the reduction of the travel times is presented, for the two different demand categories distinguished. Considering a value of time equal to 0,065 €/min (i.e. the value of around 4€/h commonly used in transportation studies in which only one user's category is considered), and assuming a zero economic value to the saved time by occasional users, then the economic value of the total time savings is at least equal to 10,2 million €.

Table 8 Average travel times saved for different demand categories in Scenario 3.

	Demand category	Minutes
Saved travel times per trip (min)	Systematic trips/ from cars	21,4
	Systematic trips/ from transit	14,0
	Non-systematic trips	25,4

The environmental benefit is tied to the reduction of pollution, noise, accident rates, and greenhouse gases. In a complementary study (see Torrieri et al., 2002) this was given an economic value ranging between 50 and 100 millions €/year.

The increase in income is assessed in relation to the induced activities in the areas served by the Sub-lagoon Tube. Assuming a start-up of about 100 new firms in the Historic Centre, and 30 new firms in Murano, this leads to an added value of about 34,3 mllions € in 20 years.

The estimated net present value[3] of the benefits generated by the Sub-lagoon tube intervention in 20 years, is reported in Table 9, for each category of benefit. Here, the revenues from the traffic system have been evaluated on the basis of the following assumptions on the fare system:

- Systematic users: 2 (€/trip)
- Occasional users 6 (€/trip)

Assuming a unitary net management cost equal to 3,3 €cent/(place km), the overall balance sheet can be found in Table 10.

Table 9 Estimated net present value of the direct and indirect benefits generated by the Sub-lagoon Tube in 20 years

Category	**Actual benefits**	**%**
Time	€ 138,422,661	20.67%
Income impacts	€ 463,430,128	69.19%
Pollution reduction	€ 67,951,632	10.14%
Total	€ 669,804,421	100.00%

Table 10 Estimation of the balance sheet

Cash flows	**€/year**
Management costs	5,155,920
Revenues from traffic	29,433,880
Management profits	24,277,960

[3] The rate of discount is assumed to be equal to 5% on a one year-basis.

For what concerns the total cost of the investment, this has been estimated to be about 330 Millions €.

Integrated multicriteria evaluation for the Venice sub-lagoon system

Introduction

Multicriteria analysis is an established decision support tool in decision and choice problems that are characterized by (i) a set of distinct choice alternatives; (ii) a set of mutually incompatible (conflicting) decision criteria; (iii) the presence of different priorities (weights) attached to the various decision criteria; (iv) the need to identify 'the best possible' choice alternative. The information necessary to perform a multicriteria analysis is normally included in a so-called effect (impact) matrix which contains the expected outcomes of each alternative to be considered for all relevant choice criteria. In addition, it is necessary to have insight into the decision makers' preferences for each of the decision criteria (see Munda, 2008).

The above presentation of a multicriteria analysis implies a systematic assessment of the impact of the various alternatives. This impact assessment may include direct and indirect impacts, short-term and long-term impacts as well as social or geographical distributions of such impacts. It goes without saying that a solid impact assessment lies at the heart of any multicriteria analysis and calls for a balanced operational methodology including sensitivity analysis and feedback presentations of relevant stakeholders.

In addition, the estimation of a decision-maker's preference structure (weights set) is a central element in each multicriteria analysis. This can be based on stated preference techniques, posteriority analysis, simulation analysis etc. Especially in a multi-decision-maker context, the assessment of weights is not easy, reason why in practice often 'fictitious' weights are deployed in order to analyze 'what-if' conditions.

Another critical element in multicriteris analysis is the level of measurement of both the impact (effect) table and the weights set. The precision of measurement may range from cardinal to ordinal information, from crisp to fuzzy information, and may also contain alpha numerical information. The level of measurement is essential for the type of methodology to be used in a multicriteria analysis. In the past decades, dozens of multicriteria decision support tools have been developed, each with commonalities but also differences regarding the treatment of the information (see for a review inter alia Munda, 2008 and Nijkamp et al., 1990). A wide variety of software packages has in the meantime been developed to offer an operational decision support system to planners and decision-makers.

Multicriteria analysis has over the past decades been applied tio a wide array of evaluation problems, for example, in the field of environmental management, energy policy, industrial planning, land use planning, public facilities management and so forth. It has also found a wide application in the field of transportation planning.

Transportation provides many illustrations of the applicability of multicriteria analysis in complex decision-making. Transportation projects are usually discrete choice projects, which have a

variety of relevant dimensions for balanced and multi-faceted decision-making, such as cost items, security and safety aspects, land use dimensions, environmental factors, social (distributive) elements, etc. In the literature on transportation planning many examples of the application of multicriteria analysis can be found. In the following section, the hierarchical Regime method (Hinloopen and Nijkamp, 1990) will be applied to evaluate the scenarios discussed so far.

Regime analysis

The hierarchical Regime analysis is able to deal with both qualitative and quantitative plan or project effects. In our scenarios, the cost/benefit indicators are numerical in nature, but as there are some missing data, we have preferred to transform such cardinal information into rank order information, in order to consistently compare the outcomes. The total effect matrix related to our project assessment model is presented in Table 11, where all entries have a positive meaning (i.e., the higher, the better).

Table 11 Effect Table for Regime Analysis

Nr.	***Effects***	***Scenario***			
		0	*L1*	*L2*	*L3*
1	Average network speed	1	3	3	4
2	Total kilometres made by cars directed towards HS	1	3	3	4
3	Total kilometres made by tourist buses directed towards HS	1	3	3	4
4	Total kilometres made by heavy vehicles directed towards HS	1	3	3	4
5	Total travel time – cars	1	3	3	4
6	Total travel time – tourist buses	1	3	3	4
7	Total travel time – lagoon boats Tessera	1	2	3	4
8	Total travel time – lagoon boats Lido	1	1	3	4
9	Average value of congestion (VOC) (peak hour)	1	1	1	1
10	Percentage of saturated links	1	3	3	4
11	Total Vehicles km (VKT) – peak hour	1	3	3	4
12	Percentage of passengers reaching HC with the Sub-lagoon Tube	1	2	3	4
13	Percentage of traffic volume using Sub-lagoon Tube	1	2	3	4
14	Investment cost	4	3	2	1
15	Time savings	1	3	3	4
16	Income impacts	1	2	3	4
17	Pollution reduction	1	3	3	4

Our hierarchical multicriteria analysis using the Regime method was implemented in a stepwise (hierarchical) way by grouping together first the effects regarding total kilometers (2-3-4); then, the effects regarding the total travel time (5-6-7-8), the effects related to congestion (9-10-11), and the effects regarding traffic volume (12-13). Thus, a Regime analysis was applied to each of these

subsets. The analysis was carried out without assigning weights to the effects. Next, the overall Regime method was applied to the remaining aggregate effect matrix.

The outcomes, illustrated in Figure 11, show that the most preferable scenario is L3. These results confirm the plausibility of the cost-benefit analysis, using as indicators the Net Present Value (NPV) and the Internal Rate of Return (IRR). From a financial perspective, the NPV is negative without any public investment. With a public financing of about 30%, the NPV becomes positive and the IRR assumes a value of about 7%. From an economic perspective, the NPV is positive and the IRR is estimated around 14%.

These results support obviously the Public Authority decision of considering the public utility of the project concerned and to promote its realization on the basis of project financing supported with a 30% public investment involvement.

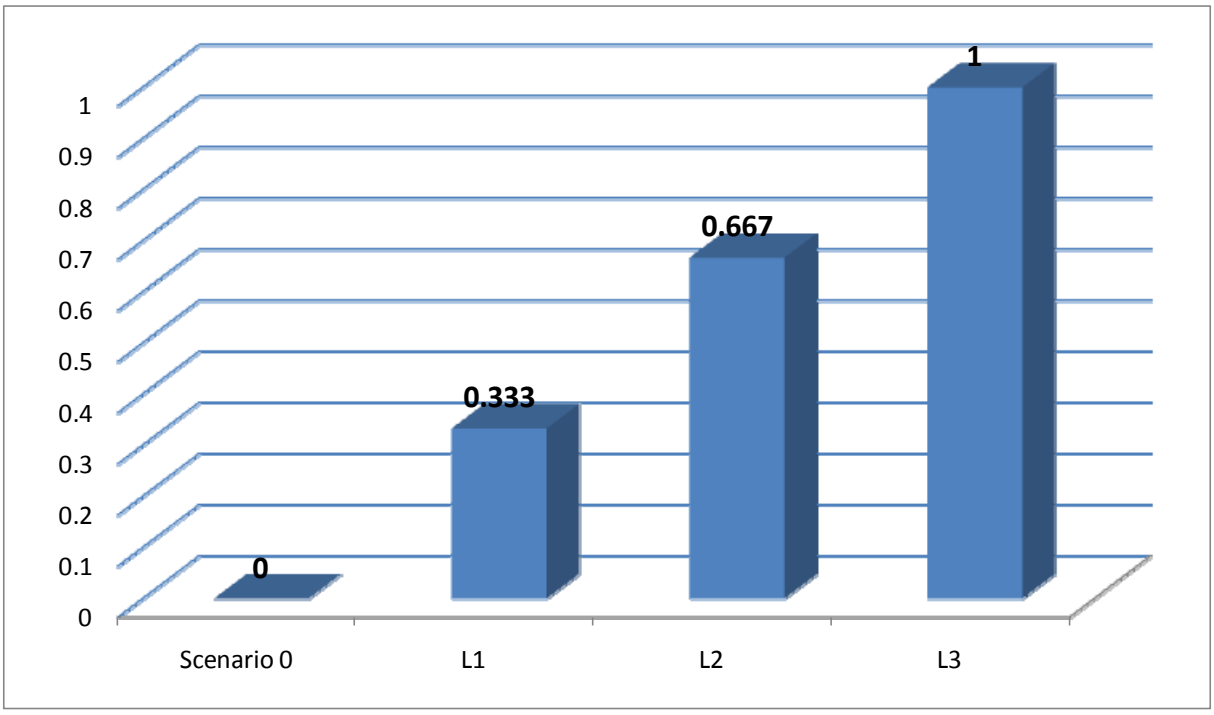

Figure 11 Predicted performance index for each scenario by means of Regime analysis.

Conclusions

In this paper, the main outcomes of a feasibility study regarding an integrated new transportation infrastructure for the city of Venice have been presented, with particular attention for the part of the study related to the current and future organization of the intermodal transportation system of the area. After a brief overview in which the integration of different transport modes has been considered as a possible significant contribution to the challenge of sustainability, the case of Venice has been presented as an illustrative case, even though it is full of peculiarities due to the physical morphology, the demand pattern and the multimodal structure of the study area.

The case study presented here, although still lacking a comprehensive methodology for the impact evaluation, is interesting for different reasons. First, it has brought to light some of the usual contradictions in the decision-making process: supported by earlier decisions stated in official urban plans, the project has been the object of a complex and broad feasibility study, requiring research efforts from several panels of experts in the field of transportation and economic evaluation, as well as the use of time and financial resources. Such studies, as explained in our study, have predicted the success of the application of a multimodal approach from different points of view. Nevertheless, since 2002 the project is still not ready for implementation, due to the difficulties encountered in the public debate with several private and public stakeholders involved, as well as due to lack of both private and public funds.

Secondly, the above mentioned general urban plan, promoting multimodal and integrated approaches to the transportation system management, has allowed and encouraged the fulfillment of an in-depth analysis whose main outcomes, presented in this paper, have highlighted the necessity of the planned approach in order to solve effectively the problems of congestion, pollution and progressive urban decay of some areas of the city of Venice.

Thirdly, the study confirms the need for a clear future perspective for the area concerned, in order to assess the feasibility as well as the sustainability of the foreseen investments. Indeed, looking only at the financial indicators, there is no evidence of significant and sufficient financial benefits: the project is worth realizing only if we consider the economic translation of social and environmental benefits. This emphasizes moreover the importance, already stated by several studies (see for example Brons, 2006), of developing more reliable and precise methods for the evaluation for the economic impact of new transportation infrastructures.

It is evident that further steps are still needed to complete the study, including the use of fine-tuned indicators to perform a solid and comparative methodology for the evaluation of the impacts of the new public transport investment plan.

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