sustainability

MDPI

Article

A Methodology for the Definition of the Acoustic Capacity of a Road Infrastructure

Marino Lupi *, **Chiara Pratelli** and **Alessandro Farina**

Department of Civil and Industrial Engineering, University of Pisa, 56126 Pisa, Italy; chiara.pratelli@for.unipi.it (C.P.); alessandro.farina@unipi.it (A.F.)
* Correspondence: marino.lupi@unipi.it

Abstract: In this paper, a new methodology for the assessment of the so-called "acoustic capacity" of a road infrastructure is proposed. This aspect is very important in the field of transportation planning as, currently, road infrastructures are verified only in terms of physical capacity; at most, the environmental capacity due to atmospheric pollutants is taken into account, while the acoustic capacity is completely neglected. The acoustic capacity is assessed based on the Harmonoise model, which is widely recognized at the European level. The Harmonoise model, starting from traffic data, such as traffic flows, average speed, and typologies of vehicles, provides the levels of noise emissions and immissions, which can be compared to the noise limit levels established by law. The validity of the proposed methodology was assessed on a test network. The results of this analysis show that, generally, the acoustic capacity is actually a capacity constraint, which involves several traffic flows: this occurs in particular in the case of an intersection, but also in the case of a bi-directional road. Furthermore, the acoustic capacity of a road infrastructure is generally lower than its physical capacity.

Keywords: road acoustic capacity; road traffic noise; Harmonoise model; road infrastructure

Citation: Lupi, M.; Pratelli, C.; Farina, A. A Methodology for the Definition of the Acoustic Capacity of a Road Infrastructure. *Sustainability* **2021**, *13*, 11920. https://doi.org/10.3390/su132111920

Academic Editor: Antonio D'Andrea

Received: 9 September 2021
Accepted: 24 October 2021
Published: 28 October 2021

1. Introduction

The "physical capacity" of a road infrastructure can be defined as "the maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental or control conditions; it is usually expressed as vehicles per hour, passenger cars per hour, or persons per hour" (Highway Capacity Manual (HCM) 2000 [1], Chapter 5 "Glossary", pages 2–5).

Generally, in transport network planning and design, only the physical capacity is considered. Sometimes, the environmental capacity due to atmospheric pollutants is also taken into account (Ferrari [2]).

The concept of the physical capacity of a road was first defined in the earliest Highway Capacity Manual, released in 1950. The concept of the environmental capacity of a road section was introduced in 1963 in the work of Buchanan [3], but it was based only on the delay suffered by pedestrians wishing to cross the road and on pedestrian safety.

After, Sharpe and Maxman [4] in 1972 and Holdsworth and Singleton [5] in 1979 first studied the environmental capacity not only in terms of pedestrian safety, but also in terms of atmospheric pollutants and noise emissions.

The environmental capacity due to atmospheric pollutants was widely studied in the following years, and a methodology to assess this capacity, based on emission and concentration models, was developed by Ferrari ([2,6]). However, to the authors' knowledge, a methodology to assess the acoustic capacity of a road section due to noise emissions has never been developed.

The assessment of the environmental capacity due to the atmospheric pollutants generally considers carbon monoxide, VOC (volatile organic compounds), NO_x, benzene, total suspended dust, and PM_{10} (Ferrari [6], Zachariadis [7], Emisia [8]). In addition, some studies have been performed on materials for the reduction of the emissions and concentration of air pollutants, for example Wang et al. [9] and Ouyang et al. [10].

The environmental capacity of a road section, due to atmospheric pollution, is defined as the traffic flow at which the concentration of at least one of the considered atmospheric pollutants is equal to the limit value (established by law), while the concentration of the other pollutants is below, or at most equal, to their respective limit values (established by law).

Very often, but not always, the environmental capacity due to atmospheric pollutants is less than the physical one. In several cases, the physical capacity constraints are satisfied but not environmental ones; see Wang et al. [11], Koorey and Chesterman [12], and Distefano and Leonardi [13].

As shown in Section 2, the current standards on acoustic pollution establish two types of limit values: one is related to noise emissions and the other to noise immissions. Following the scheme of environmental capacity due to the atmospheric pollutants, the acoustic capacity of a road section can be defined as the traffic flow at which one of the two values, either the emission or the immission one, is equal to the limit value (established by law) while the other one is lower, or at most equal, to the limit value.

Consequently, the environmental capacity tout court of a road section can be defined as the lower value between the environmental capacity due to atmospheric pollution and that due to acoustic pollution.

Ultimately, the capacity of a road section is the smaller value of the physical and environmental one.

In this study, the Italian and European standards were taken into account for the definition of the limit values, but the proposed methodology is valid everywhere.

The Italian standards (in particular the DPCM 14 November 1997 [14] propose two limit values for noise: one for noise emissions and the other one for noise immissions:

- Limit value of noise emissions: it is the maximum value of the sound pressure level (expressed in dBA), emitted only by the given source, measured at a receiver point. The Italian standards are not precise as they report that the receiver point is located on the side of the road. However, the European laws (Recommendation of the European Commission of 6 August 2003 [15]) specify that the emission values must be measured, as suggested by the French Guide du Bruit of 1980 [16], at 7.5 m of distance from the source; see Recommendation [15], Section 3.1.1, page L212/58. This last approach was taken into account in this paper.
- Limit value of noise immission: it is the maximum value of the sound pressure level (expressed in dBA) measured at a given receiver point, immitted by all noise sources. The standards about traffic noise define a limit value of sound pressure level, to be measured close to the most sensible receiver, in the "range of acoustic pertinence" whose width is defined for each type of road. However, the standards also define some limit values in each zone into which the urban area is divided according to the intended use. Moreover, these limit values can be a constraint for the acoustic capacity of a road section. For example, hypothesizing that the range of acoustic pertinence of a road section is 30 m, there could be a hospital at 50 m from the side of the road which is the strongest constraint to the value of acoustic capacity of the road. Indeed, a hospital is considered a "particularly protected zone" by the laws on acoustic pollution, as shown in Section 2 of this paper.

The limit values are expressed as equivalent sound levels; that is, given a fluctuating noise, in a given period of measure T, the equivalent sound pressure level is calculated, and it is compared with the limit values. The equivalent sound pressure level, of a noise variable over time in a given period T, is the constant sound pressure level having the same energy as the variable noise (Guide du Bruit [16]).

The modeling of the noise phenomenon due to traffic flows is composed of the following two phases:

- modeling of noise emissions: assessment of the noise emitted in the environment by the road traffic;
- modeling of road traffic noise propagation in the environment: assessment of the noise immission measured at a given receiver point.

In this paper, for the modeling of noise emissions and propagation, the Harmonoise model was taken into account. The Harmonoise model is recognized at the European level and it has replaced the large number of small models valid only in specific countries or specific application fields (Salomons et al. [17]).

This research was performed within the European project LIST Port ("*Limitazione Inquinamento Sonoro da Traffico nei Porti commerciali*", that is "Limitation of Traffic Noise Pollution at Commercial Ports"), which regards the investigation of the noise pollution due to commercial port traffic. In particular, the project LIST Port is focused on the traffic along the entrance and crossing roads of the city that lead to the port entrances [18].

The choice of the Harmonoise model was also made because it is embedded in the simulation software SUMO (Simulation of Urban MObility) which was adopted to perform traffic analyses in the LIST Port project. This software is open source; in the LIST Port project, it was required to use an open-source software to perform traffic and noise analyses [18].

The methodology described in this paper was initially developed with the aim of reducing noise pollution in the urban roads leading to port terminals, as this was the target of the LIST Port project, but it is valid for any urban environment.

In this article, first, in the literature review, the main European and Italian laws are examined: they provide the limit values for noise emissions and immissions and the ways of measuring noise. After, the Harmonoise model is briefly presented, as well as its use for the assessment of the traffic flows respecting the acoustic capacity constraints. Finally, in the Discussion and in the Conclusion sections, the main advantages and limitations of the proposed model are presented.

2. Literature Review

The proposed methodology was developed, for the sake of example, for the Italian scenario. Therefore, in the following, the main European and Italian laws about noise pollution are presented. However, as already reported in the introduction, the proposed methodology has global validity. In Table 1, a summary is provided on the rules, established by the European and Italian laws, that are significant for this research. Details on the main European and Italian laws on acoustic pollution are provided in the following.

Table 1. Summary of the main rules imposed, or recommended, by the European and Italian laws or standards.

Standard/Law	Topic	Description
French/European standard: Guide du Bruit of 1980 [16].	Receiver position. Calculation methods of acoustic descriptors.	Detailed methodology for the measurement of noise emissions and immissions (*). Position of the receiver to measure noise emissions, also in the case of road intersections (*). Early simple methods for calculating noise emissions and immissions (a).
Italian law: DPCM of 1 March 1991 [19].	Earliest thresholds for noise emissions and immissions.	Earliest limit values for sound pressure immissions; it introduced the acoustic zoning of the territory and the so-called "recovery plans" (b).
Italian law: law no. 447 of 1995 [20].	Main general concepts.	Concepts of noise emission and immission limit values, attention values, and quality values (*). Definition of the types of noise sources (*).

Table 1. *Cont.*

Standard/Law	Topic	Description
French standard: NMPB-Routes of 1996 [21]	Calculation methods of acoustic descriptors.	Methodology to calculate noise emissions and immissions (a).
Italian law: DPCM no. 413 of 14/11/1997 [14].	Thresholds for noise emissions and immissions.	Classification of the municipal land into six classes according to the vulnerability of receivers (*). Definition of the noise emission and immission limit values for each of the six classes (*).
Italian law: Ministerial Decree of 16/3/1998 [22].	Receiver position.	Definition of the periods of measure of the acoustic pollution (*). Positions of the receiver for the measurement of noise immissions: at a horizontal distance of 1 m from the most exposed building façade and at a height of 4 m from the road surface (*).
European law: EU Directive no. 2002/49/CE of 2002 [23].	General concepts. Calculation methods of acoustic descriptors.	Introduction to the acoustic descriptors L_{den}, L_{day}, $L_{evening}$, and L_{night}. Methodology to calculate descriptors: NMPB-Routes of 1996 ("old" French method) (a).
European law: European Commission Recommendation of 6/8/2003 [15].	Receiver position.	Position of the receiver to measure noise emissions and immissions. The receiver for noise emissions must be placed at 7.5 m horizontal distance from the vehicle trajectory and at 1.2 m height. To assess noise immissions, the receiver must be placed at a height of 4 ± 0.2 m from the ground (*)
Italian law: DPR no. 142 of 30/3/2004 [24].	Thresholds for noise immissions.	Concept of acoustic pertinence range of a road infrastructure. Definition of the width of the pertinence range and of noise immission limit values in the pertinence range (*).
Italian law: Legislative Decree no. 194 of 19/8/2005 [25].	General concepts.	Adoption of EU Directive no. 2002/49/CE in Italy: introduction of the acoustic descriptors L_{den}, L_{day}, $L_{evening}$, and L_{night} (*). Methodology to calculate descriptors: NMPB-Routes of 1996 ("old" French method) (a).
European standard: UNI no. 11,143 of 2005 [26].	Receiver position.	Position of the receiver for measuring noise emissions (recognized only in Italy) (*).
European law: European Union Directive no. 2015/996/EU of 2015 [27].	Calculation methods of acoustic descriptors.	New methodology for the calculation of noise emission and propagation in the case of road, railway, industrial, and aircraft noise. This methodology is called CNOSSOS-EU and is essentially a simplified Harmonoise model (*).
Italian law: Legislative Decree no. 42 of 17/2/2017 [28].	Calculation methods of acoustic descriptors.	Adoption in Italy of the European Union Directive no. 2015/996/EU and of the CNOSSOS-EU methodology for calculating noise emissions and propagation (*).

(*) law or standard still in force. (a) replaced by the European Union Directive no. 2015/996/EU of 2015 [27] and, in Italy, by the Legislative Decree no. 42 of 17 February 2017 [28]. (b) replaced by the Italian law no. 447 of 1995 [20] and by the DPCM no. 413 of 14 November 1997 [14].

The earliest general concepts and methods in the acoustic field were introduced by the Guide du Bruit of 1980 [16]: this French standard, recognized in all of Europe, provides detailed information on the ways to measure noise emissions and immissions and on position receivers that were later confirmed by the more recent laws.

The main general concepts on acoustics in Italy were introduced by the so-called "framework law" about acoustic pollution, no. 447 of 1995 [20], and in Europe by the EU Directive 2002/49/CE [23] (also known as the "Environmental Noise Directive").

The Italian "framework law" defines the concepts of noise emission and immission limit values. Emission limit values refer only to a specific source (for example, road traffic), while immission limit values refer to all sources present in the environment.

The EU Directive 2002/49/CE [23] (the European "Environmental Noise Directive") defines the "acoustic descriptor day-evening-night", L_{den} as in Equation (1):

$$L_{den} = 10 \cdot \lg \frac{1}{24} \left(12 \cdot 10^{\frac{L_{day}}{10}} + 4 \cdot 10^{\frac{L_{evening}+5}{10}} + 8 \cdot 10^{\frac{L_{night}+10}{10}} \right) \tag{1}$$

The reference threshold values, currently valid in Italy, for the establishment of the acoustic capacity of a road infrastructure are the following:

- the emission limit values and the immission limit values established by the DPCM 14 November 1997 [14];
- the immission limit values in the pertinence range of the road infrastructure established by the DPR no. 142 of 2004 [24].

The position of the receiver for the calculation of noise emissions was defined by the European Commission Recommendation of 6 August 2003 [15] and by the UNI standard no. 11,143 of 2005 [26]. According to the Recommendation [15], the receiver must be placed at 7.5 m horizontal distance from the vehicle trajectory and at 1.2 m height. According to the UNI standard [26], the receiver must be placed on the side of the road and at 1.5 m height.

The position of the receiver for the calculation of noise immissions was defined by the DM of 16 March 1998 of the Italian Ministry of Environment [22] and by the European Commission Recommendation of 6 August 2003 [15]. The receiver must be placed at 1 m horizontal distance from the most exposed façade of the buildings and at a height of 4 ± 0.2 m from the ground.

The calculation method of the acoustic descriptors L_{den}, L_{day}, $L_{evening}$, and L_{night} was provided by the European Union Directive no. 2015/996/EU of 2015 [27], and adopted in Italy by the Legislative Decree no. 42 of 17 February 2017 [28].

3. Materials and Methods

Noise modeling due to road traffic is obtained through a two-step process:

- modeling of noise emissions by road traffic; and
- modeling of noise propagation in the surrounding of the investigated area.

To model both noise emission and noise propagation, in the present research, the "classical" Harmonoise model was used (Nota et al. [29]; Salomons et al. [17]). A model which provides good results, and whose application is not too demanding, is the CNOSSOS-EU methodology, which is essentially a simplification of the Harmonoise model. However, we decided to use the "full" Harmonoise model, because it is implemented in the SUMO software (the simulation model used in the European project LIST Port).

3.1. The Harmonoise Emission Model

To compute the noise emissions generated by traffic, the Harmonoise model considers two models in sequence: the vehicular model and the traffic model. The vehicular model receives as input the average speed and acceleration for each vehicle category, and allows the calculation of the sound power emitted by each vehicle. The sound power emissions by each vehicle (and, more precisely, by each sub-source) are the input of the traffic model, which combines them, and computes the level of sound power emitted per meter of length of the vehicular stream.

In the Harmonoise model, the road source is modeled as a set of point sources, the vehicles. Each one of these point sources is characterized by position, sound power level, and direction of movement.

The trajectory of a moving source is modeled as a "source line". The traffic source line could be approximated as a set of 1 m long segments, which are "active" when the vehicle occupies the road section.

3.1.1. Some Fundamental Definitions for the Calculation of Noise Emissions

Source line: the trajectory of a moving noise source. It is pointed out by the dashed red line in Figure 1. The source line, in the case of noise due to vehicular traffic, can be approximated with a set of segments, each one 1 m long. Each source line segment, 1 m long (pointed out in black in Figure 1), is modeled by a point source. At a given time instant, the point source is active when the road section modeled by the point source is crossed by a vehicle, and it is inactive when it is not crossed by any vehicle.

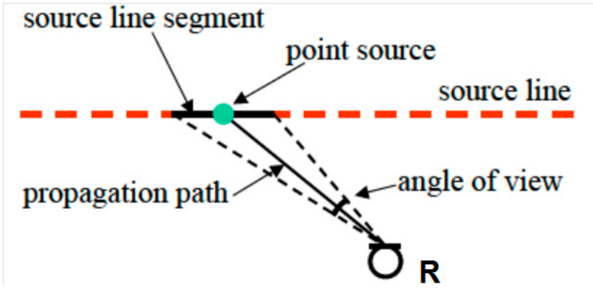

Figure 1. Source line, source line segment, and point source. The source line is shown by the red dashed line. The point source is shown by the green dot. The propagation path is the segment connecting the point source to the receiver (indicated by R) (source: Nota et al. [29]).

Point source: models a segment of source line. A point source is "active" only when the road section modeled by the point source is crossed by a vehicle.

Propagation sector: the triangular portion of the plane between the receiver and the two extremities of the 1 m long source line segment. In Figure 1, it is limited superiorly by the source line segment (shown in black) and laterally by the black dashed lines.

Propagation path: in Figure 1, it is the segment connecting the point source with the receiver.

3.1.2. The Harmonoise Vehicular Model

In the vehicular model, each vehicle is modeled by three sub-sources, located at different heights from the road surface.

The localization of the sub-sources varies with the vehicle type. Indeed, the noise generated by each vehicle could be categorized into rolling and propulsion noise.

The rolling noise is mainly (80%) generated by the lowest source, at 1 cm from the road surface, for both cars (or light vehicles) and medium and heavy vehicles, while the remaining 20% is attributable to the higher of the two sources: at 30 cm and 75 cm for light vehicles and for medium and heavy vehicles, respectively. Vice versa, the propulsion noise is attributable by 20% to the lowest source (at 1 cm) and by 80% to the two highest ones (at 30 and 75 cm).

The only exception is constituted by the motorcycles, for which the rolling noise is negligible and the only generated noise is the propulsion one, fully attributable to the source located at 30 cm from the road surface. See Figure 2.

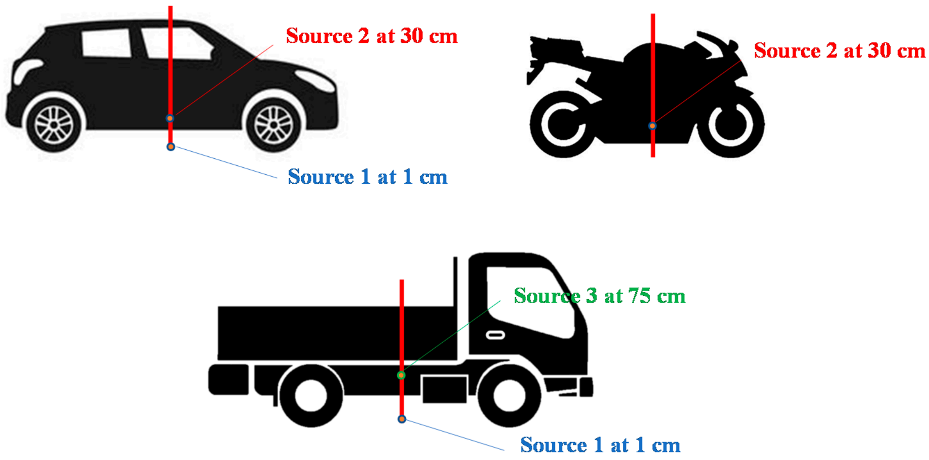

Figure 2. Localization of the three noise sub-sources (at 1, 30, and 75 cm) for the different vehicle types (source: Nota et al. [29]).

The Harmonoise vehicular model takes into account several categories of vehicles: see Table 2. In Table 2, each vehicle category is divided into sub-categories: for example, sub-category 1a refers to cars with an internal combustion engine, while sub-category 1c refers to electric vehicles.

However, in the practical implementations of Harmonoise, only a few categories listed in Table 2 are taken into account. Indeed, the coefficients for the calculation of noise emissions are not provided for all vehicle categories of Table 2, but only for a few of them. In particular, the sub-categories m = 1a, m = 1b, m = 1c, and m = 1d are not taken into account in the practical implementations of Harmonoise, but a single category m = 1, which groups all light vehicles, is considered. The same applies to the categories m = 2 (medium heavy vehicles) and m = 3 (heavy vehicles). In addition, category 4 (other heavy vehicles) is assimilated to category 3 (heavy vehicles), while category 5, two-wheelers, is partly assimilated to category 1.

Indeed, for two-wheelers (category 5), only the sub-source 2, at 30 cm above the road surface, is taken into account whose acoustic emissions are calculated taking into account the same coefficients of light vehicles; instead, the sub-source 1 is neglected. However, this approximation may lead to remarkable mistakes: indeed, motorcycles usually produce more noise than cars, therefore, if we consider only one sub-source and in addition with the same coefficients as cars, this leads to an underestimation of the acoustic emissions of two wheelers.

Table 2. Vehicles' categorization according to the Harmonoise model (source: Nota et al. [29]).

Main Type	m	Example of Vehicle Types	Notes
Light vehicles	1a	Cars (incl. MPVs up to 7 seats)	2 axles, max 4 wheels
	1b	Vans, SUV, pickup trucks, RV, car + trailer or car + caravan, MPVs with 8–9 seats	2–4 axles, max 2 wheels per axle
	1c	Electric vehicles	
	1d	Hybrid vehicles	
Medium heavy vehicles	2a	Buses	2 axles (6 wheels)
	2b	Light trucks and heavy vans	2 axles (6 wheels)
	2c	Medium heavy trucks	2 axles (6 wheels)
	2d	Trolley buses	2 axles (6 wheels)
	2e	Low noise design	2 axles (6 wheels)

Table 2. *Cont.*

Main Type	m	Example of Vehicle Types	Notes
Heavy vehicles	3a	Buses	3–4 axles
	3b	Heavy trucks	3 axles
	3c	Heavy trucks	4–5 axles
	3d	Heavy trucks	≥6 axles
	3e	Low noise design	≥3 axles
Other heavy vehicles	4a	Construction trucks (partly off-road use)	
	4b	Agr. tractors, machines, dumper trucks, tanks	
Two-wheelers	5a	Mopeds, scooters	Include also 3-wheel motorcycles
	5b	Motorcycles	

In synthesis, in practical applications of the Harmonoise model, the following vehicle categories are taken into account:

Category 1, divided into two sub-categories:

(1a) cars: two sub-sources at 1 cm and 30 cm above the road surface.

(1b) two wheelers: a single sub-source placed at 30 cm above the road surface whose coefficients are the same as the sub-source at 30 cm of the category 1a ("cars").

Category 2, medium heavy vehicles: two sub-sources at 1 cm and 75 cm above the road surface.

Category 3, heavy vehicles: two sub-sources at 1 cm and 75 cm above the road surface.

Category 4 of Table 2 is always assimilated to category 3 in the practical applications of Harmonoise.

In the Harmonoise vehicular model, the sound power level emitted by each vehicle is calculated as the logarithmic sum of the sound power levels due to traction and rolling, as shown in Equation (2):

$$L_{W,h,m,i} = L_{WRN,h,m,i} \oplus L_{WTN,h,m,i} \tag{2}$$

where:

- $L_{W,h,m,i}$ is the sound power level L_W of the sub-source h, emitted by the vehicle of the m category, at frequency i [dB];
- $L_{WRN,h,m,i}$ is the sound power level, caused by rolling (RN means "rolling noise"), of the sub-source h, emitted by the vehicle of the m category, at frequency i [dB];
- $L_{WTN,h,m,i}$ is the sound power level, caused by traction (TN means "traction noise"), at the sub-source h, emitted by the vehicle of the m category, at frequency i [dB].
- $\oplus$ stands for logarithmic sum.

All details for the calculation of $L_{WRN,h,m,i}$ and of $L_{WTN,h,m,i}$ are reported in Nota et al. [29], pp. 19–24. These quantities are calculated separately for each vehicle category (1, 2 and 3) and depend on the average speed of each vehicle category v_m, the sound frequency i, the average acceleration of the vehicle stream a_m, and the slope of the road.

3.1.3. The Harmonoise Traffic Model

The vehicular model provides as output, by Equation (2), the sound power level emitted by each single vehicle, keeping the sub-sources separate and considering three vehicle categories m. In addition, the vehicular model provides as output a different sound power level for each noise frequency i.

The output of the vehicular model is therefore $L_{W,h,m,i}$, that is: the sound power level of a given sub-source h, related to a single vehicle of category m, and to the noise frequency i.

$L_{W,h,m,i}$ is the sound power level emitted by a single vehicle: it is provided as input to the traffic model.

The traffic model at first calculates separately, for each sub-source h, the sound power level $L'_{W,h,m,i}$, emitted by a stream of vehicles, of category m and at a noise frequency i, per meter of source line.

$L'_{W,h,m,i}$ is calculated as follows:

$$L'_{W,h,m,i} = L_{W,h,m,i} + 10 \cdot \lg\left(\frac{Q_m}{1000 \cdot \overline{v}_m}\right) \tag{3}$$

- $L'_{W,h,m,i}$ = explained above (Watt/m)
- $L_{W,h,m,i}$ = explained above (Watt)
- Q_m = traffic flow, related to the vehicle category m, taken as constant (veh/h)
- $\overline{v}_m$ = average speed of vehicles of category m (km/h)

3.1.4. Calculation of the Equivalent Sound Pressure Level

In this sub-section, we describe how we pass from the sound power level $L'_{W,h,m,i}$ of each sub-source h, emitted by a stream of vehicles of category m and at a noise frequency i, per meter of source line, to the equivalent sound pressure level at a receiver. In particular, we describe how they are combined with each other: the sound power levels of different vehicle categories m, the emissions of the three sub-sources h at 1 cm, 30 cm, and 75 cm in height, and the emissions at the different noise frequencies i.

The sound power levels of different vehicle categories m are combined using Equation (4):

$$L'_{W,h,i} = 10 \lg \sum_m 10^{\frac{L'_{W,h,m,i}}{10}} \tag{4}$$

The sound power levels, calculated for every sub-source h, are combined using Equation (5):

$$L'_{w,i} = 10 \cdot \lg\left(10^{L'_{W,1,i}/10} + 10^{L'_{W,2,i}/10} + 10^{L'_{W,3,i}/10}\right) \tag{5}$$

In order to "pass" from the sound power level L'_i (in dB) emitted by a linear incoherent source, per meter of source line, to a sound pressure level (in dB), at a receiver point placed at a distance of r meters from the linear source, we can use Equation (6) (Farina, [30], De Vos [31]):

$$L_{p,i} = L'_{w,i} - 10 \cdot \lg(\mathrm{r}) - 6 \tag{6}$$

The sound pressure levels $L_{p,i}$ at the ith frequency should be weighted ("A weighting") and summed by means of the Equation (7). The result of this calculation is the total sound pressure level, in dBA.

$$L_p = 10 \lg \sum_{i=1}^{27} 10^{(L_{p,i} + A_{f,i})/10} \tag{7}$$

where $A_{f,i}$ is the A-weighting coefficient and is determined from the A-weighting curve.

The sound pressure level obtained by Equation (7) is instantaneous. It is therefore possible to obtain an equivalent sound pressure level using the well-known Equation (8):

$$L_{eq} = 10 \cdot \log\left[\frac{1}{T}\int_0^T 10^{L_p} dt\right] \mathrm{dB} \tag{8}$$

3.2. The Harmonoise Propagation Model

The Harmonoise propagation model determines how the sound power level, generated by a sound source, propagates into the environment. This value will be compared to the threshold value, set by the current European standards.

The sound pressure propagation in the environment could be defined using the following equation:

$$L_{p,h,j,i} = L_{w,h,j,i} - A_{div} - A_{atm,i} - A_{excess,i} - A_{refl,i} - A_{scat,i} \tag{9}$$

where:

- $L_{p,h,j,i}$ = instantaneous sound pressure level, introduced at a given receiver point, generated by the sub-source h, from the source line segment j, at the frequency i;
- $L_{w,h,j,i}$ = sound power level (in dB), generated by the sub-source h, from the source line segment j, at the frequency i. This value is computed by the Equation (10) reported in the following;
- A_{div} = attenuation term due to geometrical divergence;
- $A_{atm,i}$ = attenuation term due to sound absorption through the atmosphere;
- $A_{excess,i}$ = attenuation term due to ground reflection;
- $A_{refl,i}$ = attenuation term due to the sound energy loss into reflection;
- $A_{scat,i}$ = attenuation term due to the sound dispersion caused by the surrounding vegetation (trees, bushes, hedges etc).

All these terms are expressed in dB(A).

$L_{W,h,j,i}$ is calculated as follows:

$$L_{W,h,j,i} = L'_{W,h,j,i} + 10\lg(l) \tag{10}$$

where:

- $L'_{W,h,j,i}$ = output of the emission model, calculated from Equation (3), i.e.: the sound power level emitted by each sub-source h, on a source line segment j (which represents a road section) 1 meter long, at a sound frequency i (dB/m).
- l = length of the source line segment taken into account in the propagation model (m).

In the emission model, the source line segments all have the same length, equal to 1 m, but in the propagation model source line segments could have a different length (e.g., 1.2 or 0.8 meters), because of the geometry of the ground between the source and the receiver.

The "instantaneous" sound pressure level is then converted into an equivalent sound pressure level using the Equation (8). In the applications to road transport networks it is considered, as T, usually 1 h, because road networks are generally studied for the daytime peak hour. However, standards define limit values over longer time periods: for example, the entire daytime period. Peak hour values can be compared with the daytime limit values. Acting in this way, we are in favor of safety, because noise emissions are over-evaluated. Otherwise, it is necessary to determine the noise pollution in other conditions, for example in low demand periods, and determine the average noise emissions level on a longer time period, for example 8 h. In this way, we obtain a complete estimation of L_{day}.

For the determination of the road noise due to vehicular traffic, Equation (9) must be applied for each sub-source h (i.e., at 1 cm, 30 cm, and 75 cm above the road surface), and for each segment of source line j.

The distinction for each sub-source h is necessary because the propagation differs according to the quota above the road surface, in particular because of obstacles which screen off the three sub-sources in a different way.

To mix up the sound pressure levels immitted by the three sub-sources at the receiver, an equation similar to Equation (5) is used. To combine the equivalent sound pressure level immitted at the various frequencies i, an equation similar to Equation (7) is adopted.

In the following, the calculation of each component of Equation (9) will be briefly described.

3.2.1. Attenuation Due to Geometrical Divergence

The geometrical divergence is due to the dispersion of the acoustic energy, emitted by the noise source, in the environment. It is independent from the frequency and is calculated according to the following equation:

$$A_{div} = 20\lg(r) + 11 \tag{11}$$

r = distance from the source to the receiver [m].

3.2.2. Attenuation Due to Atmospheric Absorption

The attenuation term due to atmospheric absorption is calculated as follows:

$$A_{atm,i} = \alpha_{atm,i} \cdot r \cdot (1.0053255 - 0.00122622 \cdot \alpha_{atm,i} \cdot r)^{1.6} \quad (12)$$

where:

- $\alpha_{atm,i}$ = coefficient of atmospheric attenuation, in (dB/m). It is calculated according to Nota et al. [29], p. 38. $\alpha_{atm,i}$ is a function of temperature (K), relative humidity (%), atmospheric pressure (kPa), and wind speed (km/h).
- r = distance from the source to the receiver (m).

3.2.3. Excess Attenuation Due to the Diffraction and to the Ground Reflection

The diffraction phenomenon occurs when a sound wave encounters an obstacle on its way: due to the obstacle, the wave path is no longer straight. It is as if the wave is broken and is recomposed beyond the obstacle. This happens, however, when the sound wave has a wavelength greater than (or almost equal to) the size of the obstacles it encounters. In fact, a wave is able to "go around" an obstacle if the size of the obstacle is smaller (or comparable) to the wavelength. In any case, due to diffraction, the noise loses energy and therefore the sound pressure level decreases.

Sound reflection occurs when the size of the obstacle is much greater than the wavelength of the sound wave. This occurs, for example, when the sound wave meets the surface of the ground and, therefore, is reflected. This is the case, for example (but there are obviously others), of a flat surface.

The way to calculate both terms of the excess attenuation, due to diffraction and reflection, is reported in Nota et al. [29], pp. 39–41.

3.2.4. Attenuation Due to Reflection

The loss of acoustic energy due to reflection, $A_{refl,i}$, is calculated according to Equation (13):

$$A_{refl,i} = 10\log(\rho_\varepsilon) + 20\log\left(S_{refl,i}/S_{Fz,i}\right) \quad (13)$$

- ρ_ε = reflection coefficient which is a function of the reflecting surface;
- $S_{refl,i}$ = projection of the reflection surface over the Fresnel zone;
- $S_{Fz,i}$ = total area of Fresnel zone.

The Fresnel zone is a well-known acoustic concept and is described in detail in Nota et al. [29], p. 33.

3.2.5. Attenuation Due to Sound Dispersion Caused by Vegetation A_{scat}

The calculation of A_{scat} is described in Nota et al. [29], p. 48. A_{scat} depends on:

- average diameter of trees;
- length of the sound path across the wooden areas;
- average height of trees;
- noise frequency.

3.2.6. Synthesis of the Harmonoise Sound Propagation Model

The Harmonoise propagation model receives as input the noise emissions of the road source, in terms of sound power level (first term of the right-hand side of Equation (9), obtained by Equation (10)) and provides in output the sound pressure level detected at a receptor point.

If the receiver is located near the source, for example at the roadside, the noise attenuation terms, reported in Equation (9), are all null, except the attenuation due to geometric divergence A_{div} (Equation (11)).

To assess the noise emissions, the European laws (Recommendation of 6 August 2003 [15], Section 3.1.1, page L212/58) establish that the receiver must be placed at 7.5 m of horizontal distance from the vehicle (source) trajectory.

To evaluate the noise immissions to be compared with the limit values, provided for the "range of acoustic pertinence" of the road by the D.P.R. no. 142 of 2004, or provided for each zonal class by the DPCM 14 November 1997, the receiver must be placed 4 m above the ground and 1 m (horizontally) from the most exposed façade of the buildings (as reported in the Ministerial Decree of 16 March 1998).

If the receiver is far from the source, then the sound pressure level detected by the receiver will be attenuated. The attenuations are calculated by means of the coefficients of Equation (9): $A_{atm,i}$, $A_{excess,i}$, $A_{refl,i}$, $A_{scatt,i}$.

The attenuation terms depend on the geometric characteristics of the ground and of the obstacles present between the source and the receiving point, and the meteorological characteristics of the air (temperature, relative humidity). However, this dependence is very complex to calculate. It appears therefore necessary, in complex situations, to use a specific software to evaluate the noise immissions. Several professional softwares already exist, a very popular one is iNoise—Predictor LimA [32].

The propagation model provides in output the "instantaneous" sound pressure level $L_{p,h,j,i}$ entered at a given receptor point, distinguished for each sub-source h (at different height), each segment of source line j, and each sound frequency i.

To mix up the sound pressure levels introduced by the three sub-sources h (at the three different heights of 1 cm, 30 cm, and 75 cm above the ground) at the receptor point, an equation such as (5) is used. An equation such as (7) is used to combine the sound pressure levels entered at the different frequencies i.

To compare the calculated sound immission level with the limit value according to the regulations, the equivalent sound pressure level must be calculated over a time interval T (Equation (8)).

3.3. The Concept of "Acoustic Capacity" and Capacity Constraints

As reported in the introduction, the acoustic capacity of a link of a transport network is the maximum flow that can travel without the noise pollution exceeding the tolerance threshold established by the legislation.

To determine the "acoustic capacity" in this paper, we make use of the Harmonoise model.

3.3.1. Synthesis on the Calculation of the Acoustic Emissions Using the Harmonoise Emission Model

The Harmonoise emission model receives as input:

- the vehicle flow by vehicle category on each road section;
- the average speed and the average acceleration for each vehicle category flow. The average acceleration, when using SUMO, is automatically calculated by the software. In the practice of use, in particular in the LIST Port project, three categories of vehicles were considered: cars, motorcycles, and heavy vehicles.

The Harmonoise emission model provides as output:

- the sound power level $L'_{W,h,m,i}$ emitted, for each sub-source h, by a stream of vehicles, of category m and at a noise frequency i, per meter;
- the sound pressure level L_p (in dBA) at a receiver point, placed at a distance of r meters (normally 7.5 meters) from the trajectory of the vehicle flow (Equation (7)).
- The equivalent sound pressure level over a period T, at a receptor point (Equation (8)), due to the vehicle flow. Normally, in traffic applications, T is considered equal to one hour. This pressure level must be compared with the limit values established by regulations.

3.3.2. Synthesis of the Calculation of the Acoustic Immissions Using the Harmonoise Propagation Model

- The Harmonoise propagation model receives as input: the sound power level emitted by a vehicular flow per meter of source line, calculated using the emission model: $L'_{W,h,m,i}$.
- The Harmonoise propagation model provides as output: the sound pressure level detected by a given receiver at a receptor point. This sound pressure level is compared to the limit values given by regulations (law 447/95, DPCM 14 November 1997 and DPR 142/2004 in Italy).

A synthesis of the input and output data of the Harmonoise emission and propagation models is shown in Figure 3.

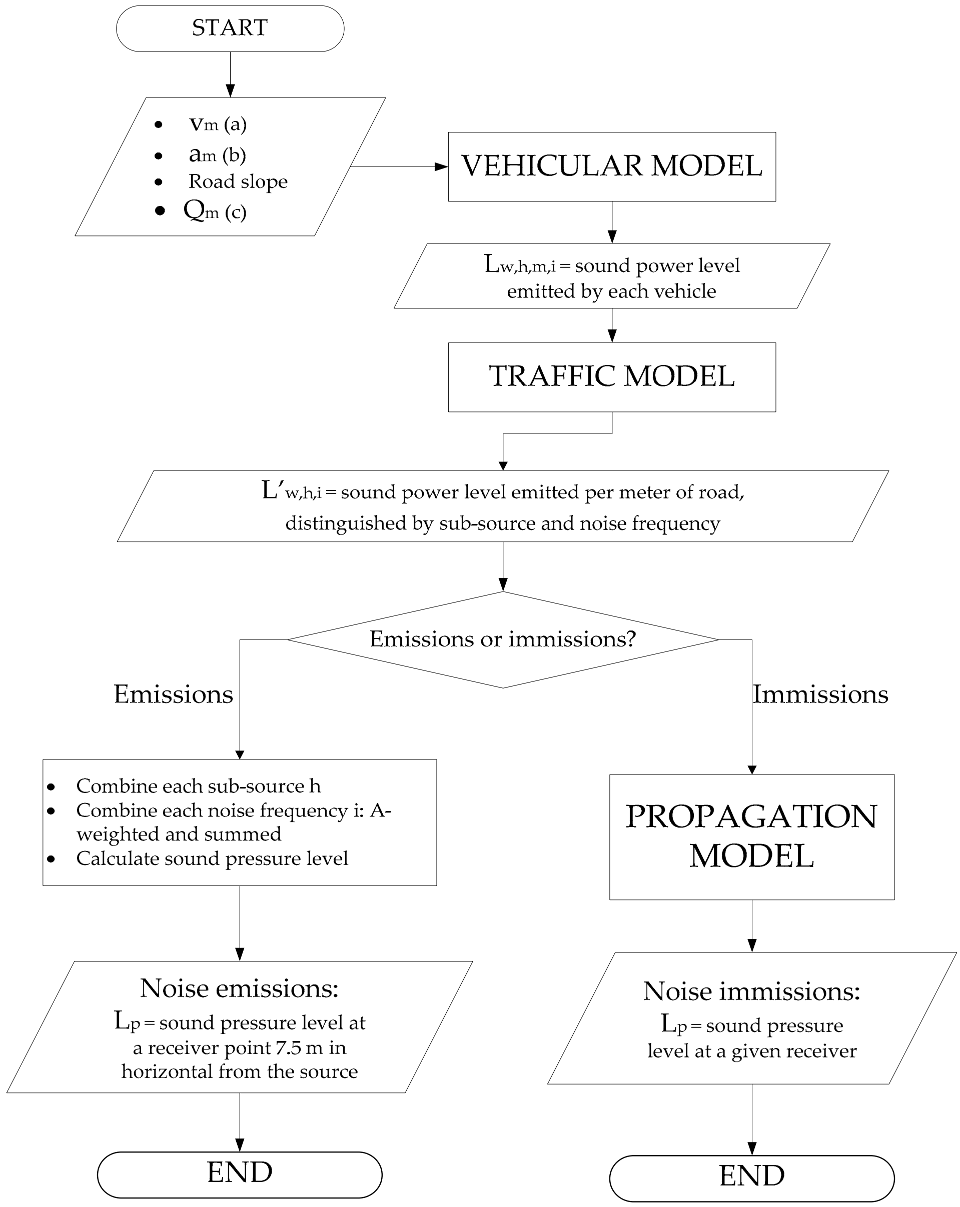

Figure 3. Scheme of the Harmonoise emission and propagation model, showing the input and the output data of vehicular, traffic, and propagation models. (a) Average speed for each vehicle category *m*. (b) Average acceleration for each vehicle category *m*. (c) Traffic flow for each vehicle category *m*.

3.3.3. Verification of Capacity Constraints

As reported in the literature review section, the Law no. 447/95 [20] and the DPCM 14 November 1997 [14] establish two types of limit values:

- Emission limit value: i.e., the sound pressure level detected by a receiver placed near the sound source/road (for example: blue dot in Figure 4). The height of the receiver point is 1.5 m (1.2 according to the European Commission Recommendation of 2003 [15]). However, the Italian standards are imprecise as to the receiver's horizontal position, and report generically "on the side of the road", while European standards report, more precisely, that the receiver must be placed at 7.5 m horizontally from the vehicle trajectory (point "RE" in Figure 5). In particular, the receiver is placed at 7.5 m from the road centerline if the road is composed of two lanes, and from the center of the lane if the road is composed by only one lane; see: [33–35].
- Immission limit value: i.e., the sound pressure level detected at a sensible receiver point. The Presidential Decree no. 142 of 30 March 2004 establishes limit values for noise immissions at a point, as for example the green dot in Figure 4, in the acoustic pertinence range of the road infrastructure (green line in Figure 4). In this case, the noise immissions are measured at 1 m from the most exposed façade, of the most sensitive building/receiver, and at a height of 4 m above the ground (point "RI" in Figure 5). In any case, also outside the pertinence range, road traffic contributes, together with other kind of noise sources, to the immission value detected at a sensible receiver in any point of the municipal territory (Law no. 447/95 and the DPCM 14 November 1997), and in particular at a receiver point, again located 4 m above the ground and 1 m from the most exposed façade: for example, the red dot in Figure 4.

The Ministerial Decree of 16 March 1998 (Annex C, paragraph 2) specifies that in the absence of buildings, the measurement must be carried out "in correspondence to the position occupied by the sensible receptors".

When calculating the acoustic capacity on the basis of the emission limit values (law 447/95 and DPCM 14 November 1997), generally, reference is made exclusively to the road section on which the receiver is located (blue dot in Figure 4). However, even in this simple case, it is not a problem of capacity of one link, but of a capacity constraint that involves the two-way traffic flow accommodated by the road section.

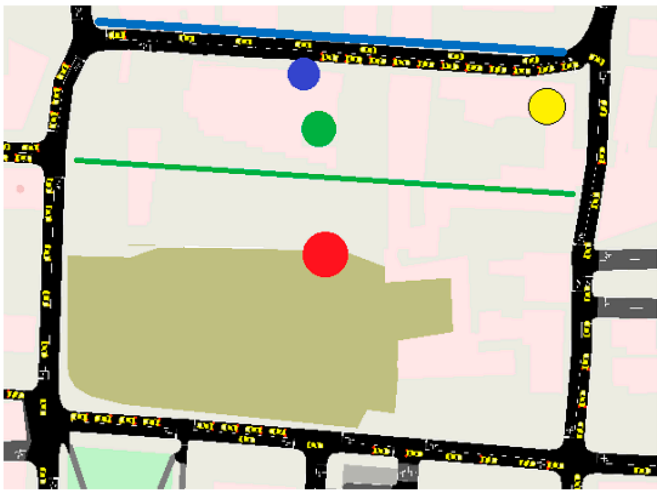

Figure 4. Acoustic capacity of the road section indicated by the blue line. The pertinence range of the road is limited by the green line (source: own elaboration).

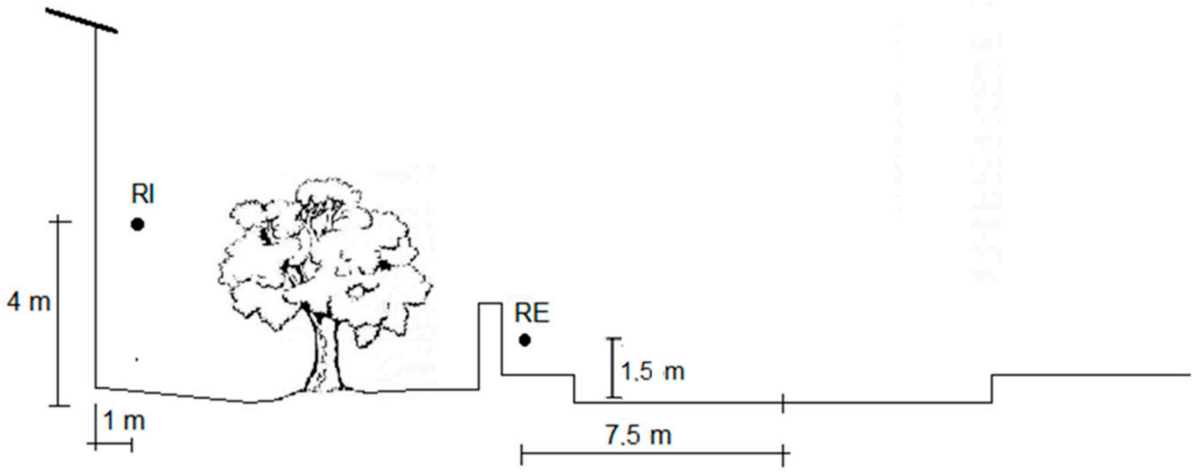

Figure 5. Position of the receivers for the purpose of measuring noise emissions (RE) and noise immissions (RI) (source: own elaboration).

The Harmonoise model directly calculates the noise emissions taking into account the vehicular flows in both directions. The software SUMO, on the other hand, calculates the noise emissions link by link: therefore, in a two-way traffic road, the noise emissions of the two links in the two directions must be added together in order to compare them with the limit values imposed by the legislation.

When, on the other hand, reference is made to the immission limit value (law 447/95, DPCM 14 November 1997, DPR no. 142 of 30 March 2004), all road links close to the receiver must be considered; for example, in Figure 4, the four roads that limit the block (the environmental sector) on which the red dot is located. Again, this is a capacity constraint, but more complex than the previous one. In fact, in general, all the links surrounding the block (the environmental sector) contribute to the sound immission at the receiver point represented by the red dot.

In Figure 4, different situations are depicted: a receiver placed along a road (blue dot); a receiver in the acoustic pertinence range of a road (green dot); a receiver placed at the intersection of two roads (yellow dot); and a receiver placed in the center of a block (red dot).

The receiver indicated by the green dot in Figure 4 belongs to a single pertinence range, therefore the limit value of noise immissions measured at this receiver determines a constraint for the traffic flow of a single road section. However, also in this case, as already mentioned, we have a capacity constraint, involving the two flows on the links that circulate in each direction of the road section.

In the case of the receiver located near an intersection, such as the one indicated by the yellow dot in Figure 4, the limit values of both noise emissions and immissions determine a constraint for the flows of several road sections.

4. Results

In the following, two application examples of the proposed methodology on a test network will be shown.

For the calculation of noise emissions, the SUMO software was used, as the Harmonoise emission model is implemented in this software.

SUMO provides, for each road link, the noise emissions (in terms of sound power level) of each vehicle present in the link in each simulation time instant. However, this software provides a single emission value for each vehicle, without distinguishing the three sub-sources (at the three heights) or the sound frequencies.

In any case, it was necessary to use SUMO to perform this analysis, as it was adopted in the LIST Port project, because it is open source: in the project LIST Port it was mandatory to use an open source software to perform traffic and noise analyses.

4.1. First Application Example

The proposed methodology was applied to a test network. SUMO provides, for each road link, the noise emissions (in terms of sound power level) of each vehicle present in the link in each simulation time instant. As reported before, SUMO provides a single emission value for each vehicle, without distinguishing the three sub-sources (at the three heights) and the noise frequencies.

The test network is shown in Figure 6. The transport demand was completely trial and was provided to the software for a period of 1.5 h, of which we took the first half an hour as the initial simulation transitory, while the remaining 1 h was the period of analysis. The transport demand consisted of only cars and it was varied iteratively, until traffic flow values corresponding to the acoustic capacity constraints were reached.

We aimed at determining the acoustic capacity of the road section indicated in light blue (Figure 6). Both emission and immission limit values must be satisfied.

We hypothesized (in this sample case) that no obstacles were placed between the noise source and the receiver (see Figure 6), the ground was flat, and there was no vegetation. Under this hypothesis, for the calculation of noise immissions, the following attenuation terms are neglected:

- $A_{excess,i}$ = attenuation term due to ground reflection and diffraction: neglected as there are no obstacles from the source to the receiver and the ground is flat;
- $A_{refl,i}$ = attenuation term due to the sound energy loss in reflection: neglected as there are no obstacles from the source to the receiver and the ground is flat;
- $A_{scat,i}$ = attenuation term due to the sound dispersion caused by the surrounding vegetation (trees, bushes, hedges, etc.): neglected as there is no vegetation between the source and the receiver.

The attenuation term due to sound absorption through the atmosphere, that is $A_{atm,i}$, is also neglected, as the receiver is close to the source, therefore the attenuation due to the atmospheric absorption is low.

In the hypothesis of a single type of vehicle, considering that the noise source, that is the road link, is a linear source, the equivalent sound power level per meter can be calculated according to Equation (14):

$$L'_w = L_{w,1\ \mathrm{veic}} - 10\ \mathrm{lg}d \tag{14}$$

$$d = \frac{1}{k} = \left(\frac{1000 \cdot \overline{v}}{Q}\right) \tag{15}$$

- d = average distance among the vehicles (m) (a single type of vehicle was considered);
- k = density (veh/m), that is, the number of vehicles present in the road link under study, in the given time instant;
- Q = traffic flow (veh/h);
- $\overline{v}$ = average speed (km/h);
- $L_{w,1\ \mathrm{veic}}$ = equivalent sound power level emitted by a single vehicle (dB(A));
- L'_w = equivalent sound power level per meter, emitted by the linear noise source (dB(A)/m).

Considering only the attenuation term due to geometrical divergence, the equivalent sound pressure level is calculated according to Equation (16), valid for a linear source:

$$L_p = L'_w - 10\ \mathrm{lg}r - 6 \tag{16}$$

where:

- L_p = equivalent sound pressure level, measured at the receiver (dB(A));
- L'_w = explained above (dB(A)/m);
- r = distance between the noise source and the receiver (m). For the calculation of noise emissions, a receiver located at 7.5 m from the middle of the carriageway was taken

into account. For the calculation of noise immissions, the most sensible receiver was taken into account.

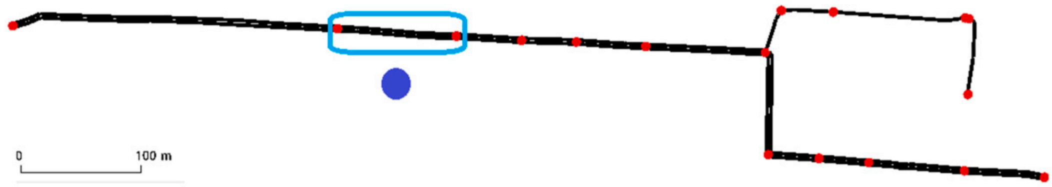

Figure 6. The test network. The road section under study is circled in light blue. The most sensible receiver near the road section under study is shown by the violet dot (source: own elaboration).

The SUMO software provides as output, in each simulation time instant:

- the equivalent sound power level emitted by each vehicle; and
- the position of each vehicle: that is, the link where the vehicle is, and the position of the vehicle in the link.

For each time instant, the following are calculated:

- $L_{w,1\ \text{veic}}$, of Equation (14), as the average ("logarithmic average", Equation (17)) of the sound power levels emitted by all vehicles present in the link under study in each simulation time instant (which is not provided directly by SUMO);
- the density k, calculated as the number of vehicles present in the link in each time instant, divided by the link length in m. From the density, d = 1/k was calculated, that is the average space among vehicles in meters.

The calculation of the logarithmic average was performed as follows. Suppose that, at a given simulation time instant and in a given link, there are n vehicles, having respectively the emission values of $L_{w,1}$, $L_{w,2}$ … and $L_{w,n}$. The logarithmic average is calculated according to Equation (17):

$$L_{W,1\ \text{veic}} = 10 \cdot \lg\left(\frac{10^{L_{W,1}/10} + 10^{L_{W,2}/10} + \ldots\ldots + 10^{L_{W,n}/10}}{n}\right) \tag{17}$$

L'_w, i.e., the equivalent sound power level per meter of source line, was calculated for each simulation time instant applying the Equation (14).

After, the equivalent sound power level L'_w over 1 h of simulation, was calculated.

Finally, for the calculation of the emission limit value, the receptor, shown by the violet dot in Figure 6, placed at a distance of r = 7.5 m from the center of the road, was considered. Applying the Equation (16), the equivalent sound pressure level, emitted by the road link in 1 h of simulation was calculated.

In a two-way road, in order to calculate the acoustic capacity, in the hypothesis of using SUMO, it was necessary to calculate the noise emissions of the two links in both directions, L_1 *e* L_2, and to sum them as mutually incoherent sources ("logarithmic sum": sign $\oplus$).

$$L_1 \oplus L_2 = 10\lg_{10}\left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}}\right) \tag{18}$$

The first constraint to the acoustic capacity consists of noise emission limit values.

Noise emission limit values according to the DPCM 14 November 1997 (Italian law) are reported in Table 3. We consider that the road network under study is in a "mainly residential area", that is class II, and that we were in the daytime period; therefore the limit value for noise emissions is equal to 50 dB(A): see Table 3.

Table 3. Emission limit values (dB(A)) established by the Italian DPCM 14 November 1997 (source: English translation of [14]).

Land Use Destination Class	Reference Times	
	Daytime (6:00–22:00)	Night (22:00–6:00)
I—particularly protected areas	45	35
II—mainly residential areas	50	40
III—mixed type areas	55	45
IV—area of intense human activity	60	50
V—mainly industrial areas	65	55
VI—exclusively industrial areas	65	65

We make the assumption of having the same traffic flow in both directions. Under this assumption, the acoustic capacity, taking into account only noise emissions, is reached for a traffic flow of about 1300 veh/h per direction.

The procedure for the assessment of the traffic flow, corresponding to the acoustic capacity, is iterative. Each iteration is composed of the following steps:

1. Departing from a given value of traffic demand, SUMO automatically calculates traffic flows on each link of the test network, and noise emissions of each vehicle in each simulation time instant.
2. For the road section circled in blue in Figure 6, and for each simulation time instant, we calculated: the value of vehicle density k, and the average noise emissions of all vehicles present in the link at the given time instant, that is $L_{w,1\ \mathrm{veic}}$.
3. Applying Equation (14), for each simulation time instant, we calculated the "instantaneous" L'_w value.
4. We calculated the equivalent sound power level L'_w over 1 h of simulation.
5. We calculated the equivalent sound pressure level L_p from L'_w by means of Equation (16) considering a distance of 7.5 m from the road centerline.

As the points (2) and (3) are very demanding in terms of number of calculations (in 1 h, there are 3600 simulation time instants), a script in Matlab which implements points 2 and 3 was developed.

To a traffic flow of about 1300 veh/h per direction corresponds an average L'_w of 64.6 dB(A)/m, which, applying Equation (16), provides an L_p of 49.85 dB(A).

It must be noticed that the physical capacity, i.e., the capacity due to traffic congestion, is, based on the Highway Capacity Manual (HCM) of 2016 [36], about 1900 veh/h per lane (that is per direction in a two-lane road). This, however, is valid if there is no interaction between the two traffic streams in the two directions (that is, overtaking is not allowed or virtually impossible as it usually occurs in urban congested areas).

The second constraint is relative to the immission limit values. It consists of the limit values in the acoustic pertinence range of the road infrastructure, established by the DPR (Decree of the President of the Italian Republic) no. 142 of 2004. The limit values are provided for each road typology and for the two cases of new and existing infrastructures. As the road infrastructure under study is supposed to be already existing, we considered the table of immission limit values related to existing infrastructures, that is Table 2, page 9, of the Official Gazette of Italian Republic no. 127 of 1 June 2004. A selection of this table, concerning only urban roads, is provided in Table 4.

We hypothesized that the most sensible receiver, represented by the violet dot in Figure 6, is a hospital or a school. It is located at 21.5 m from the side of the carriageway, that is at 25 m from the road centerline, for a Type E road (lane width of 3 m and a road quay width of 0.5 m) [37], that is, an urban collector. As a result, the receiver indicated by the violet dot (Figure 6) was placed in the pertinence range (wide 30 m) of the road section circled in light blue.

The national laws do not provide a limit value for a Type E road (Table 4), but report that the values are defined by municipalities. Let us consider, for this example, the same limit value of the type D infrastructure (urban expressway or arterial street), that is 50 dB(A).

Noise emission limit values take into account only one source, in this case a road section traveled by road vehicles, but noise immission limit values consider all noise sources present in the area, for example, a jackhammer or a railway. We hypothesize, for simplicity, that the only noise source present in the area is the road.

From Equation (16) we obtain:

$$L_{p25} = L_{p7.5} - 10\lg(25) + 10\lg(7.5) = L_{p7.5} - 10\lg\left(\frac{25}{7.5}\right) = 49.8 - 5.2 = 44.57 \quad (19)$$

Applying Equation (19), for a distance of the receiver equal to 25 m, the equivalent sound pressure level at the receiver is equal to 44.57 dB(A), which is below the noise immission limit value of 50 dB(A).

As a result, in this first example, the most binding capacity constraint consists of noise emission limit values.

Table 4. Width of the infrastructure's pertinence range (m) and immission limit values (dB(A)) as equivalent sound pressure level, for existing infrastructures, established by the DPR no. 142 of 2004 [24]. Selection for only urban roads (source: English translation of [24]).

Road Type	Road Sub-Type	Pertinence Range Width [m]	Schools and Hospitals		Other Receivers	
			Daytime dB(A)	Night dB(A)	Daytime dB(A)	Night dB(A)
D—arterials	Da (separate carriageways)	100	50	40	70	60
	Db (other arterials)	100	50	40	65	55
E—urban collectors		30	Defined by Municipalities, according to the acoustical zoning of the urban area.			
F—locals		30				

The comparison between physical and acoustic capacity is provided in Table 5. The hypothesis of traffic flow equally distributed in the two directions was made.

Table 5. Comparison between physical and acoustic capacity. The road section under study is circled in light blue in Figure 6. The road section is composed of two links, in the two directions: it is hypothesized that traffic flows are the same in the two directions (source: own elaboration).

Acoustic Capacity	Physical Capacity
1300 veh/h per direction	1900 veh/h per direction

4.2. Second Application Example

A second example is provided herewith, and it concerns an intersection. The three branches of the intersection are circled in light blue, orange, and green in Figure 7. The branches circled in light blue and orange are two-way ones, the branch circled in green is one-way towards the intersection.

This example was studied because the acoustic capacity constraint involves several traffic flows.

Figure 7. The test network. This second example consists of the intersection between the road sections circled in light blue, green, and orange. It is an unsignalized intersection with three branches (source: own elaboration).

As far as noise emissions are concerned, the receiver must be placed at 7.5 m from the road centerline if the road is composed of two lanes, or from the center of the road if it is composed of only one lane. In case of a four-branch crossroads, four receivers are necessary. In case of the crossroads of Figures 7 and 8, two receivers are necessary, and their positions are shown by the violet and green dots in Figure 8. The noise emissions on both receivers were evaluated and the larger one was taken.

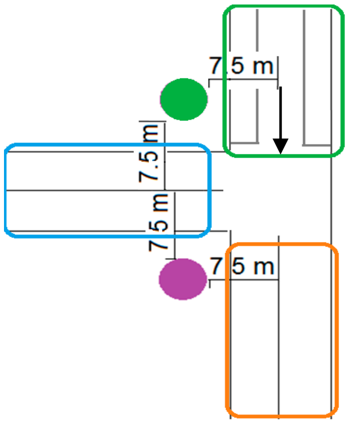

Figure 8. The position of the receivers for the evaluation of noise emissions. The receiver represented by the violet dot will be referred to in the text as the "1st receiver", the one represented by the green dot will be referred as the "2nd receiver". The road circled in green is one-way towards the intersection (as shown by the arrow) (source: own elaboration).

The first receiver, represented by the violet dot of Figure 8, is located at 7.5 m from the centerline of the two road sections circled in light blue and in orange. The second receiver, represented by the green dot of Figure 8, is located at 7.5 m from the centerline of the road section circled in light blue, and at 7.5 m from the center of the unique lane of the road section circled in green.

The roads circled in light blue and orange are type E ones (lane width of 3 m and a road quay width of 0.5 m) [37]; therefore, the first receiver was placed at 4 m from the edge of the carriageway of the two sections circled in light blue and orange. The road circled in green is a type F, with a lane wide 3 m and two parking spaces, at the two edges of the lane, wide 2 m each. As a result, the carriageway is wide 7 m and the second receiver was placed again at 4 m from the edge of the carriageway of the section circled in green.

The road sections in exam are located in a residential area, that is, the emission limit value is 50 dB(A) (see Table 3). The set of traffic flows which respect the acoustic capacity constraints are the following:

- road section circled in light blue: 1050 veh/h in both directions;
- road section circled in orange: 1065 veh/h in exit from the intersection and 850 veh/h towards the intersection;
- road section circled in green: 215 veh/h, only one way, towards the intersection.

This analysis was performed with the help of the SUMO software. SUMO provides in output, in each simulation time instant:

- the equivalent sound power level emitted by each vehicle;
- the link where each vehicle is located, and the position of the vehicle in the link.

For each time instant, the following was calculated:

- the average ("logarithmic average", Equation (17)) of the sound power levels emitted by all vehicles present in the link in each simulation time instant: that is, $L_{w,1\ \mathrm{veic}}$ of Equation (14) (which is not provided directly by SUMO);
- the density k, described in the previous Section 4.2. (which is not provided directly by SUMO).

After, applying Equations (14) and (15), the equivalent sound power emission per meter, L'_W, was calculated.

The L'_W values of the three road sections are the following:

- road section circled in light blue: 62.2 dB(A)/m
- road section circled in orange: 60.8 dB(A)/m
- road section circled in green: 47.5 dB(A)/m

In the Guide du Bruit of 1980 [16], page 134 (and schéma 4.16) and page 137 (and schéma 4.20), the road sections and the traffic flows to be taken into account for the evaluation of noise emissions and immissions at a given receiver (at a given position) are shown.

If the first receiver (violet dot) is considered, four traffic flow values must be taken into account: two traffic flows (in the two directions) of the road section circled in light blue (one per direction) and two traffic flows (in the two directions) of the road section circled in orange.

If the second receiver (green dot) is considered, three traffic flow values must be taken into account: two traffic flows (in the two directions) of the road section circled in light blue (one per direction) and one traffic flow of the road section circled in green (it is a one-way road).

For the evaluation of noise emissions, we took into account only the 1st receiver (violet dot of Figure 8) as it registers higher noise emissions than the 2nd one. This receiver is 7.5 meters from the noise sources of the road sections circled in light blue and orange.

Considering only the attenuation term due to geometrical divergence, the equivalent sound pressure level was calculated according to Equation (20):

$$L_p = L'_w - 10\,\mathrm{lg}r - 6 \tag{20}$$

where r (distance between the noise source and the receiver) was taken as equal to 7.5 m from the middle of the carriageway of the two sections circled in light blue and orange.

Applying Equation (20), we obtained the following values of L_p:

- road section circled in light blue: 47.45 dB(A);
- road section circled in orange: 46.05 dB(A).

The logarithmic sum of the two noise emissions provides 49.8 dB(A), which is just below the noise emission limit value.

Consequently, the set of traffic flow values reported above satisfies the acoustic capacity constraint.

However, it must be noticed that there are other possible solutions satisfying the capacity constraint: that is, there are different sets of traffic flow values which provide a total noise emission just below the maximum value allowed by regulations.

As far as noise immissions are concerned, we assumed that the most sensible receiver is located at a distance of about 10 m from the edge of the carriageway, of the two sections circled in light blue and in orange in Figure 9: it is shown by the red dot of Figure 9. Therefore, supposing the two road sections "Type E" ones, the most sensible receiver was placed at a distance of 13.5 m from the centerline of them. It is in the pertinence range of the two road sections circled in blue and in orange. We hypothesized that the most sensible receiver is a school.

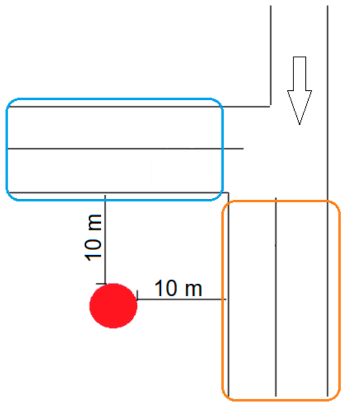

Figure 9. The position of the most sensible receiver (shown by the red dot) for the evaluation of noise immissions. The receiver is 10 m from the edge of the carriageways of the road circled in blue and in orange, that is 13.5 m from the centerline of the two road sections.

We hypothesized that the only noise source in the area is the road traffic.

In order to calculate noise immissions, due to the two road sections, we applied the following Equations: (21a) for the road section circled in light blue in Figure 9, and (21b) for the road section circled in orange in Figure 9.

$$L_{p13.5}(\text{light blue}) = L_{p7.5}(\text{light blue}) - 10\text{lg}(13.5) + 10\text{lg}(7.5) = 44.9\ \text{dB(A)} \quad (21a)$$

$$L_{p13.5}(\text{orange}) = L_{p7.5}(\text{orange}) - 10\text{lg}(13.5) + 10\text{lg}(7.5) = 43.5\ \text{dB(A)} \quad (21b)$$

Summing the immissions of the two road sections (logarithmic sum) circled in light blue and in orange, the noise immission of 47.27 dB(A) was obtained. This value is below the limit value in the pertinence range (Table 4) for schools, hospitals, and nursing homes, which is 50 dB(A).

For the calculation of the physical capacity of the links, we made reference to the Highway Capacity Manual (HCM) 2010, Book 3 “Interrupted flow” [38], as it is more detailed than the HCM 2000.

The intersection under exam is unsignalized.

The road section circled in light blue (Figures 8 and 10) is two ways: the link directed towards the intersection is indicated as link 1 in Figure 10, the link in the opposite direction is indicated as link 2 in Figure 10.

The road section circled in orange (Figures 8 and 10) is also two ways: the link directed towards the intersection is indicated as link 3 in Figure 10, the link in the opposite direction is indicated as link 4 in Figure 10.

The road section circled in green (Figures 8 and 10) is one-way, towards the intersection, therefore it is modeled only by one link, in the direction of the intersection. This link is indicated as link 5 in Figure 10.

From link 1, it is only possible to turn right towards link 4. From link 3, it is only possible to turn left towards link 2. Both links 1 and 3 have right of way.

From link 5, it is possible: to turn right to link 2, for this movement, it is necessary to give way to the flow of link 3; to go through to link 4, for this movement it is necessary to give way to both flows of links 1 and 3. The movement from link 5 to link 4, geometrically speaking, is a “minor through”, but it can be assimilated to a left turn in a three-branch intersection, because it consists of crossing a main vehicular stream (coming from link 3 and directed to link 2) and of an immission into another main vehicular stream (coming from link 1 and directed to link 4).

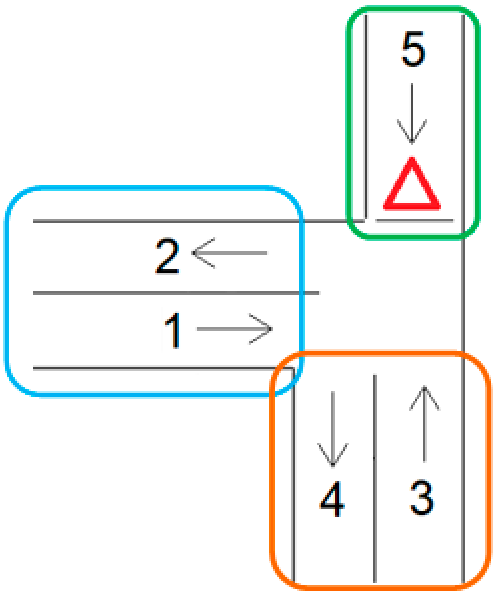

Figure 10. Intersection scheme to determine the physical capacity. From link 1, it is only possible to turn right towards link 4. From link 3, it is only possible to turn left towards link 2. Both links 1 and 3 have right of way. From link 5, it is possible to turn right to link 2 and to turn left to link 4, but for both movements, it is necessary to give way to links 1 and 3.

The movements modeled by links 1 and 3 are called "of rank 1" in the HCM 2010 [38] because they do not have to give way to any other movement.

The capacity of rank 1 movements can be calculated according to Equation (22) (HCM 2010 [38], Volume 3, page 15–17):

$$C_{th} = 1800\ (N_{th} - 1 + p^*_{0,j}) \tag{22}$$

- C_{th} = through-movement capacity (veh/h) of rank 1 movements,
- N_{th} = number of through lanes (shared or exclusive). In this example, it is always equal to 1, for both road sections circled in light blue and in orange, because they have only one lane per direction (see Figure 9).
- $p^*_{0,j}$ = probability that there will be no queue in the inside through lane. The probability $p^*_{0,j}$ is equal to 1.0 if no left turn (having to give way to vehicles coming from the opposite direction) is allowed from the major street. In this example, $p^*_{0,j}$ is equal to 1.0 because vehicles coming from link 1 are obliged to turn right to link 4; vehicles coming from link 3 and turning left to link 2 do not have to give way.

However, Equation (22) is related to a rank 1 movement of crossing, while the rank 1 movements in this example concern a right turn and a left turn. The right turn and left turn maneuvers have a lower capacity than crossing maneuvers, because vehicles take more time to turn left and especially to turn right than to simply go straight.

This specific layout of the intersection is not clearly reported in any of the examples shown in the HCM 2010 [38] or in the HCM 2016 [36]. However, the right turn movement from link 1 towards link 4 can be assimilated to a "major street right-turn movement", which has a saturation flow (and therefore a capacity) of 1500 veh/h: HCM 2010 [38], chapter 19 (Volume 3), page 19–21.

The left turn movement from link 3 towards link 2 can be assimilated to a "major street left-turn movement" but without any conflicting flow. The HCM 2010 [38], chapter 32 (Supplementary volume), page 32-1, exhibit 32-1, shows that the capacity of a major street left-turn movement, in the case of zero conflicting flow, is equal to about 1700 veh/h.

Both physical capacity flows were considerably higher than the acoustic capacity ones, but this occurs because vehicles coming from both links 1 and 3 do not have to give way. If vehicles coming from either link 1 or 3 had to give way, the physical capacity would not be so high.

As regards link 5 of Figure 10, two maneuvers share the same lane, that is the right-turn and the left-turn (“assimilated to a left turn” as previously specified). In this case, the capacity depends on conflicting volumes, critical gaps, and follow-up times.

For the right turn, the conflicting volume is 850 veh/h (traffic volume of link 3); for the crossing, which was assimilated to a left turn, it is 850 (traffic volume of link 3) + 1050 (traffic volume of link 1) = 1900 veh/h.

The equations for calculating critical gap, follow-up time, and capacity are reported in pages 15–19, 19–16, 19–18, and 19–25 of volume 3, HCM 2010.

Applying these equations, the capacity of link 5 was equal to 224 veh/h.

A comparison between the physical and the acoustic capacity is provided in Table 6. In the comparison, link 5 is not reported as far as the acoustic capacity is concerned, because it is not considered for the calculation of noise emissions at the most disadvantaged receiver (represented by the violet dot in Figure 8).

Table 6. Comparison between physical and acoustic capacity for the links of the intersection under study. The numbering of the links is displayed in Figure 10. The acoustic capacity of the link 5 is not reported, because link 5 was not considered for the calculation of noise emissions at the most disadvantaged receiver.

Link	Acoustic Capacity (veh/h)	Physical Capacity (veh/h)
Link 1 (section in light blue)	1050	1500
Link 2 (section in light blue)	1050	1900
Link 3 (section in orange)	850	1700
Link 4 (section in orange)	1065	1900
Link 5 (section in green)	-	224

5. Discussion

As mentioned before, the physical capacity can be defined as “the maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental or control conditions; usually expressed as vehicles per hour, passenger cars per hour, or persons per hour” (page 5-2, Chapter 5 “Glossary” of HCM 2000 [1])

In the case of a motorway with separate carriageways or of an urban road, where overtaking is not allowed or virtually impossible, the physical capacity involves the flow on only one link.

In a rural road, with a two-lane carriageway, the physical capacity depends on the vehicular flows in the two directions: it is a capacity constraint that involves traffic flows on several links (in this case two).

The capacity of an urban street is 1900 veh/h per lane, which corresponds to a saturation flow headway of 1.9 s (HCM 2000 [1] (pp. 8–27)).

The capacity of a traffic stream, traveling on a group of lanes at an urban intersection, could involve again traffic flows on several links, therefore it is again a capacity constraint.

The environmental capacity, considering only atmospheric pollutants, of a road section, is the maximum flow that can travel without the concentrations of pollutants in the atmosphere exceeding the tolerance threshold established by the legislation. Also in this case, most of the time, it is a capacity constraint, that is an inequality involving several vehicular flows.

Similarly, the acoustic capacity of a link of a transport network is the maximum flow that can travel without the noise pollution exceeding the tolerance threshold established by the legislation (both in terms of emissions and immissions). However, also in this case, actually it is almost always a capacity constraint.

In a mono-directional road, noise emissions depend only on the traffic flow in a single direction, therefore the link capacity (according to only noise emissions) can be easily determined. In a bi-directional road, noise emissions depend on flows in the two directions, therefore it is not a question of capacity of only one link, but of a capacity constraint that involves the two flows on the links in both directions of the given road section. In the case of an intersection, noise emissions depend on traffic flows in all the intersection branches: therefore, again, it is a problem related to a capacity constraint, as shown by the second example of this paper.

Finally, it should be remembered that the regulations in force require that, in order to compare with the limit values imposed by laws, the acoustic descriptors L_{day}, $L_{evening}$, and L_{night} be calculated over the entire reference period. For example, L_{day} is an equivalent sound level calculated using Equation (8), where T is the entire diurnal period. However, within the reference period (for example L_{day}), peaks in noise emissions may occur. Therefore, for example, it could happen that the equivalent sound level, calculated over the entire daytime period, is lower than the limit value established by the legislation, while the equivalent sound level calculated during the morning peak hour is very high, much higher than the daytime limit value. Nevertheless, the value of the hourly limit is not normalized (at least currently).

Similarly, it could happen that the equivalent sound level calculated over the entire night period is lower than the limit value, but a particularly intense sound level may occur at an hour of the night (for example, in the case of the LIST Port project, because the vehicles are unloaded during an hour of the night period from a very large ship).

As a result, in order to calculate the acoustic capacity of a road infrastructure, it is appropriate to perform not only the calculation of L_{day}, $L_{evening}$, and L_{night} over the entire reference period, but also the calculation related to the peak hours (daytime and night). However, current regulations do not provide the calculation of noise pollution and related emission and immission limit values for peak hours.

The limitation of the proposed methodology is the fact that the combination of traffic flows, respecting the acoustic capacity constraint, is not unique. However, this is actually also the case for the capacity of the link flows involved in the physical capacity constraint of a traffic stream (a lane group) at an intersection. This limitation also concerns the environmental capacity due to atmospheric pollutants at an intersection. In particular, it is possible that the acoustic capacity constraint is respected in a scenario where one road is heavily congested, while the other roads have a low traffic level.

The relationship between the acoustic capacity and the environmental one due to air pollutants depends on the specific scenario. Indeed, it is possible that, in some applicative case studies, the acoustic capacity is less than the environmental one due to air pollutants, while in other scenarios the acoustic capacity is greater. In general, the variables determining the acoustic and the environmental capacity due to air pollutants are different. The environmental capacity due to air pollutants depends strongly on meteorological factors such as the velocity of the wind, the height of the dilution volume of the total urban area, and the height of the buildings along the road (canyon effect). The velocity of the wind is also taken into account in the emission and propagation acoustic model, but it is not as significant as in the case of the atmospheric one. Indeed, the velocity of the wind relevantly changes the environmental capacity due to air pollutants (Ferrari [6]).

6. Conclusions

In this paper, a new methodology for the assessment of the so-called "acoustic capacity" of a road infrastructure is proposed. This aspect is very important in the field of transportation planning; currently, the capacity of a road link is usually assessed only in term of physical capacity; sometimes also the environmental capacity, but due to only atmospheric pollutants, is taken into account. The acoustic capacity instead is usually completely neglected.

The proposed procedure makes use of the Harmonoise emission and propagation model, which is one of the most remarkable models in Europe, but it is also recognized in non-European countries.

As limit values, for noise emissions and immissions, for the sake of example, those established by European and Italian laws were taken into account. These laws provide three type of limit values: emission limit values, immission limit values in the pertinence range of the road infrastructure, and immission limit values according to the classification of the municipal land.

The proposed procedure was applied to a test network. The results of the application case study show that, when almost all noise is generated by road traffic, the most binding constraint concerns noise emissions, but when other relevant noise sources are present in the area, e.g., a jackhammer or a railway, noise immissions could be more binding. Indeed, emission limit values are generally lower than immission ones, and in the case of noise emissions, the position of the receiver established by laws is closer to the source, therefore the sound pressure level measured at the receiver is higher. However, emission values involve only the road traffic source, while immission ones involve all noise sources present in the area.

Currently, road infrastructures are verified only in terms of physical capacity, but the reported examples showed that, usually, the acoustic capacity is relevantly lower than the physical one. In the first application case study, for example, the acoustic capacity was 1300 veh/h per direction, against 1900 veh/h per direction for the physical capacity. As regards the links of the second application case study, the acoustic capacity was over 40% less than the physical one. The acoustic capacity could become even lower if important noise sources, aside from road traffic, are present in the area, for example, a railway. As a result, not only the physical capacity of road infrastructures, but also the environmental capacity, due to both atmospheric and noise pollution, must be taken into account in network transportation planning and design.

However, the two examples reported in this paper are a kind of worst situation, because it was hypothesized that no obstacles were present between the noise source and the receiver. Indeed, in the real situations, when the noise is too high, noise barriers are placed, but barriers can reduce only noise immissions, while emissions remain unaltered. However, citizens and administrations provide a great importance to noise immissions and take into account noise emissions only to a lesser extent.

In addition, the regulations in force require that, in order to compare with the limit values imposed by standards, the acoustic descriptors L_{day}, $L_{evening}$, and L_{night}, are calculated as an average over the entire reference period. However, within the reference period (for example, L_{day} but also L_{night}), peaks in traffic noise emissions and immissions may occur. Therefore, it is appropriate to perform not only the calculation of L_{day}, $L_{evening}$, and L_{night} over the entire reference period, but also a calculation relating to peak hours (daytime and night).

Finally, the application of the study shows that the acoustic capacity is actually a capacity constraint which involves several traffic flows. This occurs in particular in the case of an intersection, because all traffic flows in all the intersection branches are involved. However, this also occurs if a two-lane, two-way road is taken into account, because the flows in both directions of the road are involved.

In any case, additional studies about acoustic capacity will be performed in the future of this research in order to further develop the proposed model. In particular, it will be necessary to apply the proposed model not only to a test network but also to an urban network of a real town.

Author Contributions: Conceptualization, M.L.; methodology, A.F.; software, C.P.; validation, M.L.; formal analysis, A.F.; investigation, A.F. and C.P.; data curation, C.P.; writing—original draft preparation, A.F.; project administration, M.L.; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European project LIST Port (Limitazione Inquinamento Sonoro da Traffico nei Porti commerciali), funding Programme Interreg Italy—France Maritime 2014–2020, 2nd call, grant agreement no. I53I18000030006.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are very grateful to the Transport group of the University of Cagliari (the LIST Port project leader) for their precious support.

Conflicts of Interest: The authors declare no conflict of interest.

References and Notes

1. Transportation Research Board. *Highway Capacity Manual 2000*; Transportation Research Board, National Research Council: Washington, DC, USA, 2000.
2. Ferrari, P. Road pricing and network equilibrium. *Transp. Res. Part B* **1995**, *29*, 357–372. [CrossRef]
3. Buchanan, C. *Traffic in Towns*; H.M.S.O.: London, UK, 1963.
4. Sharpe, C.P.; Maxman, R.J.; Voorhees, A.M. *A Methodology for the Compilation of the Environmental Capacity of Roadway Networks. Highway Research Record*; Highway Research Board: Washington, DC, USA, 1972; pp. 33–40. Available online: https://onlinepubs.trb.org/Onlinepubs/hrr/1972/394/394-004.pdf (accessed on 23 October 2021).
5. Holdsworth, J.; Singleton, D. Environmental capacity of roads. In Proceedings of the 5th Australian Transport Research Forum, Canberra, Australia, 18–20 April 1979; pp. 219–238.
6. Ferrari, P. *Fondamenti di Pianificazione dei Trasporti*; Pitagora Editrice: Bologna, Italy, 2001.
7. Zachariadis, T.; Samaras, Z. An Integrated Modeling System for the Estimation of Motor Vehicle Emissions. *J. Air Waste Manag. Assoc.* **1999**, *49*, 1010–1026. [CrossRef] [PubMed]
8. Emisia, S.A. COPERT—Computer Programme to Calculate Emissions from Road Transport. 2018. Available online: http://emisia.com/ (accessed on 23 October 2021).
9. Wang, F.; Xie, Z.; Liang, J.; Fang, B.; Piao, Y.; Hao, M.; Wan, Z. Tourmaline-Modified $FeMnTiO_x$ Catalysts for Improved Low-Temperature NH_3-SCR Performance. *Environ. Sci. Technol.* **2019**, *53*, 6989–6996. [CrossRef] [PubMed]
10. Ouyang, J.; Zhao, Z.; Yang, H.; Zhang, Y.; Tang, A. Large-scale synthesis of sub-micro sized halloysite-composed CZA with enhanced catalysis performances. *Appl. Clay Sci.* **2018**, *152*, 221–229. [CrossRef]
11. Wang, X.; Fu, H.; Lu, J.; Han, S. Study on road section environmental traffic capacity model and algorithm under double constraints. *Transp. Res. Part D* **2016**, *48*, 14–19. [CrossRef]
12. Koorey, G.; Chesterman, R. Assessing the environmental capacity of local residential streets. In Proceedings of the 12th World Conference on Transport Research, Lisbon, Portugal, 11–15 July 2010.
13. Distefano, N.; Leonardi, S. *La Capacità Ambientale come Indicatore di Qualità delle Infrastrutture Stradali*; Working Paper of Stradelandia; University of Catania: Catania, Italy, 2005.
14. Official Gazette of the Italian Republic, Decree of the President of the Council of Ministers (DPCM) of 14 November 1997.
15. Official Journal of the European Union, European Commission Recommendation no. 2003/613/EC, of 6 August 2003.
16. Ministére de l'environnement et du cadre de vie et Ministére des Transports. *Guide du Bruit des Transports Terrestres: Prévision des Niveaux Sonores*; CERTU: Lyon, France, 1980.
17. Salomons, E.; Van Maercke, D.; Defrance, J. The Harmonoise sound propagation model. *Acta Acust. United Acust.* **2011**, *97*, 62–74. [CrossRef]
18. LIST Port Project. Available online: http://interreg-maritime.eu/web/listport/progetto (accessed on 23 October 2021).
19. Official Gazette of the Italian Republic, Decree of the President of the Council of Ministers (DPCM) of 1 March 1991.
20. Official Gazette of the Italian Republic, Law no. 447 of 26 October 1995.
21. CERTU; SETRA; LCPC; CSTB. NMPB-Routes-96. In *Bruit des Infrastructures Routières, Méthod de Calcul Incluant les Effets Météorologiques*; CERTU: Lyon, France, 1997.
22. Official Gazette of the Italian Republic, Decree of the Ministry of the Environment of 16 March 1998.
23. Official Journal of the European Union, Directive no. 2002/49/CE of the European Parliament and of the Council, of 25 June 2002.
24. Official Gazette of the Italian Republic, Decree of the President of the Council of Ministers (DPCM) of 30 March 2004, no. 142.
25. Official Gazette of the Italian Republic, Legislative Decree (D.Lgs.) no. 194 of 19 August 2005.
26. UNI. Metodo per la Stima dell'Impatto e del Clima Acustico per Tipologia di Sorgenti—Parte 2. In *Rumore Stradale*; Standard No. 11143 of 2005; UNI: Cedar Falls, IA, USA, 2005.
27. Official Journal of the European Union, Directive (EU) no. 2015/996 of the European Commission, of 19 May 2015.
28. Official Gazette of the Italian Republic, Legislative Decree (D.Lgs.) no. 42 of 17 February 2017.
29. Nota, R.; Barelds, R.; Van Maercke, D. *Harmonoise WP 3 Engineering Method for Road Traffic and Railway Noise after Validation and Fine-Tuning*; Technical Report HAR32TR-040922-DGMR20; Harmonoise Project: Brussels, Belgium, 2005.

30. Farina, A. Acustica ambientale—La propagazione del suono in campo libero e gli effetti dell'ambiente, del rumore e delle sue sorgenti. In Proceedings of the RCF Audio Academy, Reggio Emilia, Italy, 10 January 2016.
31. De Vos, P.; Beuving, M.; Verheijen, E. *Harmonised Accurate and Reliable Methods for the EU Directive on the Assessment and Management of Environmental Noise*; Final Technical Report; Harmonoise Project, 2005; Available online: https://cordis.europa.eu/project/id/IST-2000-28419 (accessed on 23 October 2021).
32. Noise, Predictor-LimA. Available online: https://dgmrsoftware.com/products/predictor/ (accessed on 23 October 2021).
33. Farina, A. Modelli numerici per il rumore da traffico stradale e ferroviario in aree urbane. In Proceedings of the Conference "Rumore? Ci Stiamo Muovendo—Secondo Seminario sull'Inquinamento Acustico" (Noise? We Are Moving—Second Seminar on the Acoustic Pollution), Rome, Italy, 26–27 October 1998.
34. Calejo Rodrigues, R. Traffic noise and energy. In Proceedings of the 6th International Conference on Energy and Environment Research, Aveiro, Portugal, July 22–25 2019; pp. 177–183.
35. De Leon, G.; Fidecaro, F.; Cerchiai, M.; Reggiani, M.; Ascari, E.; Licitra, G. Implementation of CNOSSOS-EU method for road noise in Italy. In Proceedings of the 23rd International Congress on Acoustics, Aachen, Germany, 9–13 September 2019.
36. Transportation Research Board. *Highway Capacity Manual 2016*; Transportation Research Board, National Research Council: Washington, DC, USA, 2016.
37. Gazzetta Ufficiale della Repubblica Italiana, Ministry Decree no. 6792 of 5 November 2001, Norme funzionali e geometriche per la costruzione delle strade.
38. Transportation Research Board. *Highway Capacity Manual 2010*; Transportation Research Board, National Research Council: Washington, DC, USA, 2010.