Research Article

S. M. Patella*, F. Aletta, and L. Mannini

Assessing the impact of Autonomous Vehicles on urban noise pollution

Abstract: This paper presents the results of a noise emission study of Autonomous Vehicles (AVs) and their impact on the road network. By comparing the current situation with a future hypothetical scenario (100% AVs penetration), this study highlights the positive effect, in terms of noise pollution, of the adoption of AVs on a real road network (city of Rome). For this scope, a traffic simulation-based approach was used to investigate the effects of AVs on the network congestion. Results show that the full AVs penetration scenario leads to an improvement in the network performances in terms of travel time and average network speed. Moreover, the amount of Vehicle Kilometre Travelled (VKT) shows an 8% increase on longer extra-urban routes, due to the higher capacity impact of AVs on highways, with a consequent load reduction for intra-urban shortcutting routes. These results are also reflected in terms of noise emission. In fact, the central area would benefit from lower noise emission, whereas an increase in traffic volume and speed lead to worsened conditions for some specific highway links of the network. Overall, it was shown that a 100% AVs fleet would have a beneficial effect for the noise pollution, leading to a general reduction of noise emissions, which is more pronounced for intra-urban roads.

List of Abbreviations

AVs	Autonomous Vehicles
BEVs	Battery Electric Vehicles
BPR	Bureau of Public Roads
EVs	Electric Vehicles
HEVs	Hybrid Electric Vehicles
ICEVs	Internal Combustion Engine Vehicles
TTS	Total Time Spent
UE	User Equilibrium
VKT	Vehicle Kilometer Traveled

1 Introduction

Autonomous Vehicles (AVs) represent the biggest technological advance in the field of transportation. The AV (also called self-driving, driverless or robotic vehicle) is a vehicle that uses sensors to perceive the environment, artificial intelligence, and actuators for vehicle control to travel with little or no human input [1]. The National Highway Traffic Safety Administration [2] (NHTSA) defined six levels of automation. Beginning from zero (no automation), levels 1-3 still require a licensed driver, while fully automated vehicles (NHTSA, level 4-5) can self-drive in all situations. Fully automated vehicles are expected to produce a positive impact on the mobility system in terms of safety, sustainability, and congestion. A comprehensive review of the potential impact of AVs penetration can be found in [3–5]. It is expected a disruptive impact on drivers' behaviour as they will not need to pay attention on traffic, or even better they will be able to carry out any pleasure activity such as reading, using smartphones or tablet, sleeping [6, 7].

Although there is a considerable uncertainty about the future penetration of AVs, optimistic estimates predict that by 2050 around 90% of cars sold and almost 50% of the vehicle fleet could be autonomous, and it will take one or two more decades to dominate vehicle travel demand [8]. Moreover, Weiss *et al.* [9] observed that the automation can be seen as an accelerator of electrification and the introduction of AVs may by rapidly expediting the transition to transportation electrification.

In this light, there is a pressing need to understand the environmental impact of AVs. The recent literature is mainly focused on the emissions impact of AVs, which are normally modelled as battery electric vehicle (BEV)

***Corresponding Author: S. M. Patella:** Department of Engineering, Roma Tre University, Via Vito Volterra 62, Rome 00146, Italy; Email: sergiomaria.patella@uniroma3.it
F. Aletta: Institute for Environmental Design and Engineering, The Bartlett, University College London – 14 Upper Woburn Place, WC1H 0NN London, United Kingdom
L. Mannini: Department of Engineering, Roma Tre University, Via Vito Volterra 62, Rome 00146, Italy

with sensing and computing system [10]. As observed by many studies [11–18], the environmental implications of EVs strongly depend on each country's energy generation mix and an overview of the AVs environmental impact can be found in [19–23].

From the point of view of noise emissions, AVs also represent an important topic currently being debated in the research community. On one hand, it is important to reflect on the best modelling approach for these new road traffic sources [24]; on the other hand, there is still no clear consensus about the general implications that these new vehicles will have for the acoustic environments of future cities at a large scale [25].

The research presented in this paper aims at evaluating the noise performance in AV-regime at the mobility system level. To this end, we coupled a traffic simulation analysis to evaluate the impact of a full AV penetration scenario on a real road network (city of Rome), and a noise emission assessment based on the result of this simulation. This approach was used to compare the noise emission performance of the current state with a future hypothetical scenario characterized by a full adoption of AVs.

The paper is organized as follows: Section 2 outlines the materials and methods used both for the noise emission assessment and for the traffic simulation analysis; Section 3 presents and discusses the results of the study; Section 4 concludes and summarizes the paper, including a discussion on the assumptions of this study and future research needs.

2 Materials and methods

The methodology proposed in this study consists in two main steps: first we performed a traffic simulation to evaluate the impact of a full AV penetration scenario on a real road network (city of Rome); next, the output of the simulation (traffic flow and speed for each link of the network) are used as input parameters for the noise emission assessment. Assuming a 100% AV penetration scenario allowed us to simulate the traffic flow distribution taking into account the platooning effect (gain in road capacity). This led to a significant redistribution of traffic volumes on the network. A mixed fleet composition scenario (ICEVs, EVs, and AVs) or a 100% EVs scenario would not generate any significant variation in flow distribution.

2.1 Traffic simulation in AV-regime

A traffic simulation-based analysis was used to investigate the impact on the road network of a full AV-penetration scenario. If all vehicles on the road were fully autonomous, Friedrich [26] suggests a capacity gain of up to 80% for extra-urban roads (freeways and highways) and up to 40% for intra-urban roads. Such capacity impact might be seen as conservative, since Tientrakool *et al.* [27] suggest a capacity increase of up to 270% for extra-urban roads. Even more optimistically, Brownell [28] and Fernand and Nunes [29] proposed a capacity gain of up to 80% for intra-urban roads and 370% for extra-urban road. In the present work, in order to simulate the impact of a 100% fully-AVs penetration rate on the road network in terms of congestion (Vehicle Kilometer Traveled, Total Time Spent, and network average speed), we assumed the Friedrich's hypothesis. Regarding the volume-delay functions, this study used the BPR (Bureau of Public Roads) function [30]. As observed by Meyer *et al.* [4] it is still unclear whether the BPR also applies to the AVs homogeneous flow. Given the lack of more appropriate alternatives, the volume-delay function used for the simulation takes the form of a modified BPR function:

$$t_a = t_a^0 \cdot (1 + \alpha \cdot (\frac{q_a}{\gamma \cdot C_a})^\beta), \qquad (1)$$

$$\gamma = \begin{cases} 1.4 & \text{for urban roads} \\ 1.8 & \text{for highways} \end{cases}$$

where t_a^0 is the free-flow travel time of the road link a, α and β are road-type specific parameters, q_a is the load on the link a, C_a is the link's capacity, and γ is the capacity-gain factor. The current scenario was simulated by assuming a standard BPR function ($\gamma = 1$).

Concerning the demand, Lutin *et al.* [31] observed that as AVs do not require any driver; they allow car travel to people without a driving license (children, elderly, etc.). This leads to additional travel demand due to this new user groups. Moreover, AVs will lead to a reduction of travellers' value-of-time due to their occupants being able to perform non-driving activities [32–34]. This makes AV a very competitive modal alternative and a substantial mode shift from public transport towards AV is expected. Another possible consequence of the reduction of the generalized cost of travel could be a residential relocation from the city centre to cheaper suburban areas [5, 35], which translates into a redistribution of the trip matrix. Since this paper represents a first attempt to define an integrated approach to evaluate the noise emission of AVs at the urban mobility level, variations in travel demand (population growth, spatial distribution, mode choice, etc.) were not included. For

the scope of this study, we assumed that private vehicles owners are directly converted into AVs owners, and therefore all the current private car trips are made with AVs.

Both the current scenario and the AV-regime were simulated using EMME by INRO, which is a travel demand modelling software. EMME performs a static user equilibrium (UE) assignment and provides the traffic volume, the travel time, and the speed for every link of the road network [36]. The morning peak-hour (from 7:00 to 8:00 am) Origin-Destination (O-D) trip matrix of an average working day was loaded onto the traffic network of Rome, and the total amount of vehicle-trips assigned was 404,055. The network of Rome was modelled with 565 centroids (zones) and 6873 road links; of these, 5532 are intra-urban links.

Once these outputs are obtained, the noise emissions, regarding both the current and the 100% AVs scenario, can finally be estimated and compared.

2.2 Noise emission assessment

In this study, we considered specific noise emission factors related to different network conditions, *i.e.* intra-urban roads and highways, for each considered type of vehicle currently circulating in Rome. Table 1 shows the current fleet composition of Rome [37]. As shown in this table, the EVs diffusion amongst Roman households is quite limited. However, recent initiatives to promote sustainable mobility in the city of Rome have been reported by [38–41]. Most relevant factors and barriers affecting Italian consumers EV adoption intentions have been examined by Asdrubali *et al.* [42], and a general overview of consumer EV adoption behaviour can be found in [43].

Table 1: Fleet composition of Rome

Propulsion	Number of vehicles	%
Gasoline	1,424,986	49.45
Diesel	1,148,833	39.86
LPG	266,739	9.26
Natural Gas	21,235	0.74
Hybrid Electric Vehicles	19,460	0.68
Battery Electric Vehicles	703	0.02
Total n° of vehicles	2,881,956	-

In EU Member States, the noise emissions of internal combustion engine vehicles (ICEVs) are estimated in accordance with the Common Noise Assessment Methods in Europe (CNOSSOS-EU) [44]. Chapter III of the CNOSSOS-

EU document classifies the types of vehicles, provides the general equations and coefficients for the calculation of their sound power emission, and the reference conditions (and corrections for those), in terms of meteorology and traffic, under which those equations are valid. According to CNOSSOS-EU, the noise emission of a traffic flow on a single link of a network is represented by a line source characterized by its directional sound power per metre per frequency; this is in turn based on the sum of the sound emissions of individual vehicles in the traffic flow, taking into account the speed. Considering a traffic flow of Q_m vehicles of category m with an average speed v_m, the method defines the directional sound power per metre per frequency band of the line source $L_{W',eq,line,i,m}$ expressed in dB as:

$$L_{W',eq,line,i,m} = L_{W,i,m} + 10 \cdot \lg \left(\frac{Q_m}{1000 \cdot v_m} \right) \quad (2)$$

where $L_{W,i,m}$ is the instantaneous directional sound power of a single vehicle. The emission model of single vehicles is conceptualized as the energetic sum of two noise sources; namely: rolling noise (due to the tyre/road interaction) and propulsion noise (produced by the driveline: engine, exhaust, etc.).

The application of the general emission model proposed by CNOSSOS-EU to AVs might not be straightforward. In terms of vehicles type, the method defines four categories: light motor vehicles (1); medium heavy vehicles (2); heavy vehicles (3); powered two-wheelers (4). Thus, no category would fit AVs. Indeed, the CNOSSOS-EU states that "*a fifth category is foreseen as an open class for new vehicles that may be developed in the future and may be sufficiently different in their noise emission to require an additional category to be defined. This category could cover, for example, electric or hybrid vehicles or any futuristic vehicle. No data are available at this stage for vehicles in category 5*" [44]. A possible approach that has been previously proposed in literature is modelling electric vehicles (and therefore the AVs in this case) as sources made of a rolling component only, dismissing the propulsion noise [24]. To some extent, removing one of the two components (rolling or propulsion) from the emission model has also been considered as a viable solution within the CNOSSOS-EU itself for the Category 4 (powered two-wheelers), where only the propulsion noise is considered.

Within the context of this research, a number of assumptions were made: (a) AVs noise emissions were modelled as BEVs noise emissions, by considering the rolling noise component only, as suggested in the literature; (b) for the sake of representing the comparison between the AVs and ICEVs scenarios, a situation with Category 1 vehi-

Table 2: Simulation results:

(a) intra-urban and highways;

	INTRA-URBAN ROADS				HIGHWAYS			
	VKT (veh*km)	TTS (veh*h)	Avg. Flow (veh/h)	Network Speed (km/h)	VKT (veh*km)	TTS (veh*h)	Avg. Flow (veh/h)	Network Speed (km/h)
CURRENT (C)	2,204,596	179,033	817	12.3	2,029,259	40,267	854	50.4
100% AV (AV)	2,104,984	115,888	768	18.2	2,187,876	31,627	982	69.2
(AV-C)/C	−5%	−35%	−6%	+48%	+8%	−21%	+15%	+37%

(b) entire road network

	ENTIRE ROAD NETWORK		
	VKT (veh*km)	TTS (veh*h)	Network Speed (km/h)
CURRENT (C)	4,233,855	219,300	19.3
100% AV (AV)	4,292,860	147,515	29.1
(AV-C)/C	+1%	−33%	+51%

(VKT: Vehicle Kilometre Travelled; TTS: Total Time Spent)

cles only was simulated; (c) no corrections to the reference conditions for the calculation of the $L_{W,i}$ values were applied (regardless of the AVs of ICEVs scenario); (d) while $L_{W',eq,line,i}$ values were computed per frequency (63 Hz – 8 kHz), a single integrated broadband value $L_{W',eq,line}$ value will be considered for analysis; (e) since no actual noise propagation or mapping of the exposure will be approached in this study, the $L_{W',eq,line}$ values will be considered as the representative acoustic metrics for the links of the road network.

The traffic simulation procedure, described in the previous section, provided the flow (vehicles per hour) and speed (km/h) data for each link (intra-urban or highway) of the road network.

3 Results

3.1 Traffic simulation

The Rome AM peak O-D trip matrix was loaded onto the traffic network using EMME to estimate the link speeds, vehicle-kilometre, travel times, and average network speed. The full AV penetration scenario was simulated by assuming a capacity gain of 40% for intra-urban roads and 80% for highways. The travel demand for autonomous vehicle was assumed equal to the original (current) car demand. The simulation result of the AV scenario was compared to the current network performances (Table 2a, 2b). Clearly, in AV-regime, the Total Time Spent

(TTS) decreases (−35% for intra-urban road and −21% for highways) and the average network speed increases (48% for intra-urban road and 37% for highways) since no additional travel demand was loaded. The final amount of VKT increases for highways (8%) because the capacity gains of 80% (double that of intra-urban roads). Therefore, the assignment procedure leads to higher volumes on longer extra-urban routes by deducting load from intra-urban shortcutting routes.

Table 2b shows the entire network performances in the current state and in AV-regime. The VKT is almost the same, but the TTS drops by 33% and the average network speed increases by 51%. These results suggest that, under the assumption described in section 2.2., the full AV penetration scenario is likely to highly improve the network performances in terms of travel times, but not in terms of distance travelled. Figure 1 shows the difference in traffic volumes between the AV scenario (AV) and the current scenario (C). A thick red link means a rise in volumes (positive difference), while a green link means a reduction in volumes (negative difference). This figure clearly reveals that in AV-regime higher traffic volumes are expected in extra-urban high-capacity roads, whereas in intra-urban roads a reduction in volumes occurs (−5%). Higher increase in traffic volumes can be observed in the 'Grande Raccordo Anulare' (GRA, *i.e.* a ring-shaped, 68.2 kilometres long freeway that encircles Rome), and in the high-capacity roads connecting the GRA to the city centre. These results are reasonable since we assumed that at the extra-urban roadway level it is expected a greater capacity impact of AV.
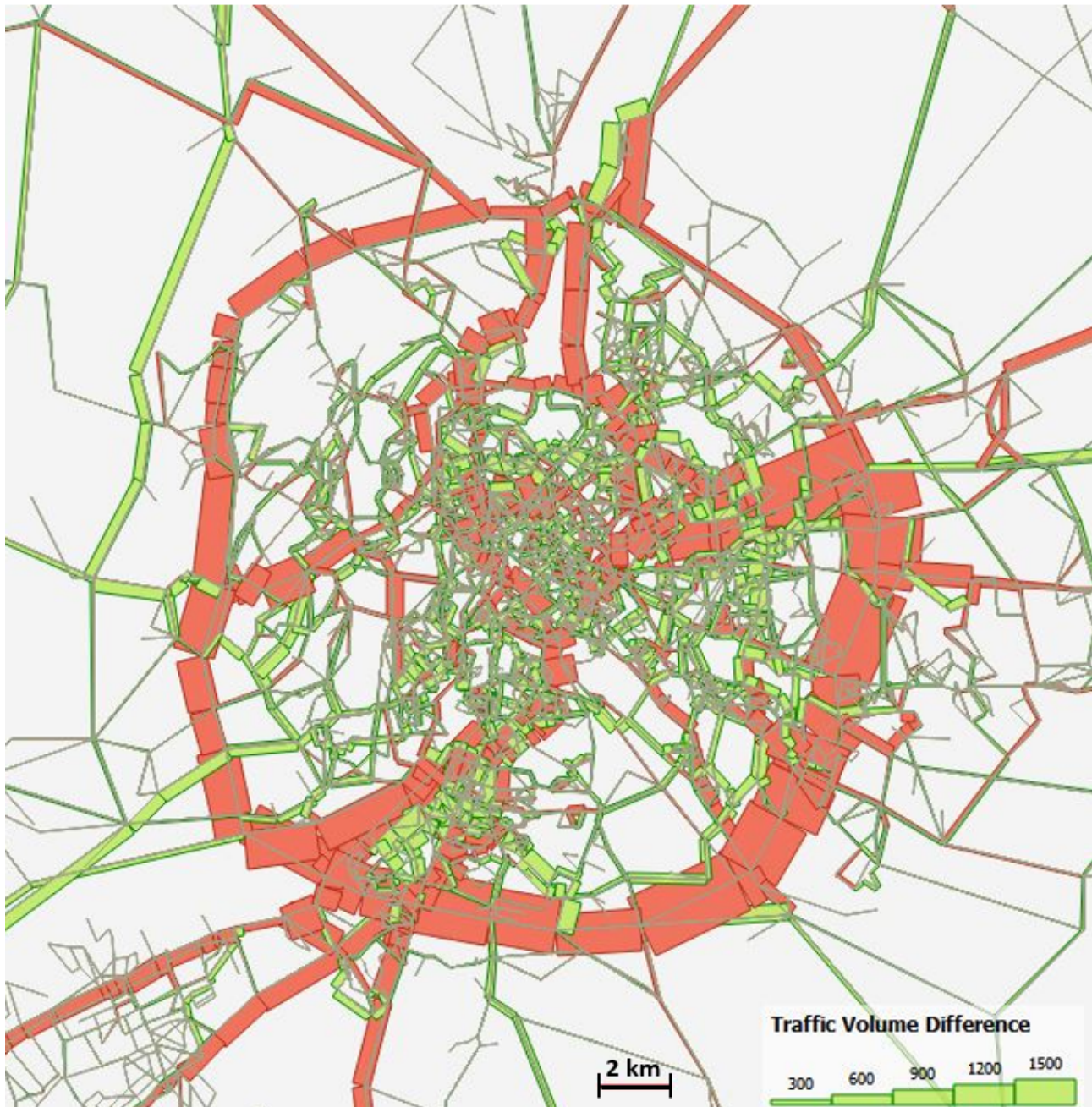
Figure 1: Traffic Volume difference (AV-C)

3.2 Current scenario and AV-regime noise emissions at the urban mobility level

A similar approach, as per the traffic simulation, was adopted for the comparison of the noise emissions of the current and the 100% AV traffic scenarios. Table 3 shows the sound power reduction achieved by implementing a full AV penetration on the entire road network, and depending on the link type (*i.e.*, intra-urban or highway). It is worth noting that considering the sum of dB values

in a cumulative way as it was done for the VKT and TTS does not correctly take into account the physics of the dB scale, nor any established method in current noise mapping practice; thus, one should not expect the percentage reduction to actually reflect a proportional reduction of the sound power magnitude, but rather a qualitative indicator of the decibels that could be "removed" from the network – thanks to AV penetration – in terms of noise emissions load. It seemed fair to assume that this kind of represen-
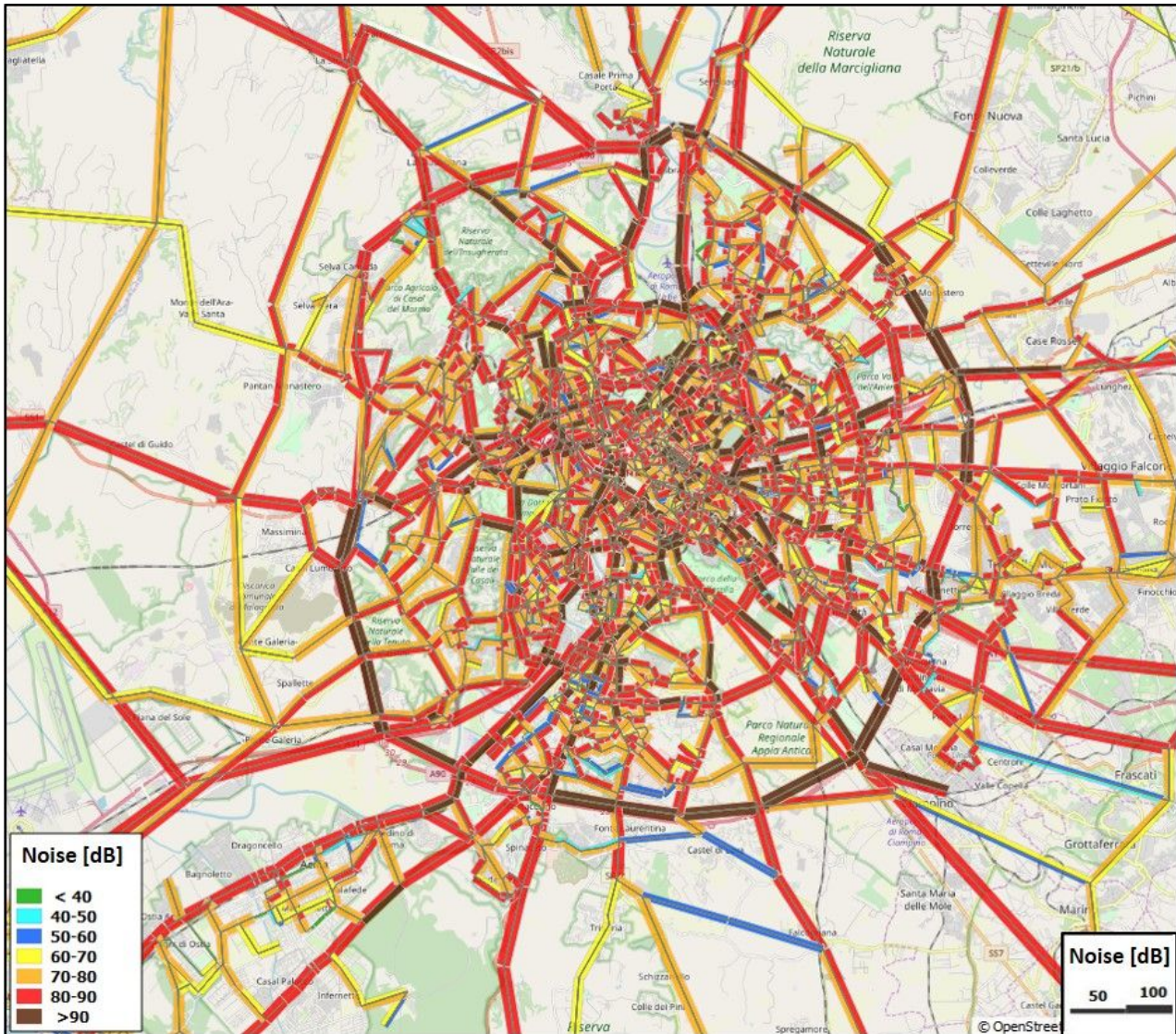
Figure 2: Noise emissions [dB], Current scenario

Table 3: Noise emissions comparison: 100% AV and current scenarios

	NOISE EMISSIONS (dBA)		
	INTRA-URBAN ROADS	HIGHWAYS	ENTIRE ROAD NETWORK
CURRENT (C)	349,275	77,016	426,291
100% AV (AV)	264,967	72,601	337,567
(AV-C)/C	−24%	−6%	−21%

tation would be meaningful when considered in combination with the traffic volume differences.

The overall noise emissions reduction effect on the entire network is considerable and it looks even stronger when considering intra-urban roads alone, while it is more marginal for highways. This is consistent with what one would expect from the noise emission models of the ICEVs and AVs as implemented in this study, since previous studies have shown that propulsion noise is only relevant below 30-40 km/h, whilst at higher speeds the rolling noise component becomes the main contribution for the total noise emission [24, 25].

Comparing Figure 2 and Figure 3 it can indeed be observed that large portions of the intra-urban roads network (inside the GRA) benefit of moving down the noise emissions scale for one or two 10-dB classes when transitioning from the current to the AVs scenario. This is a consequence of the different traffic flows distribution as obtained by the traffic simulation of the AV scenario. In fact, by assuming
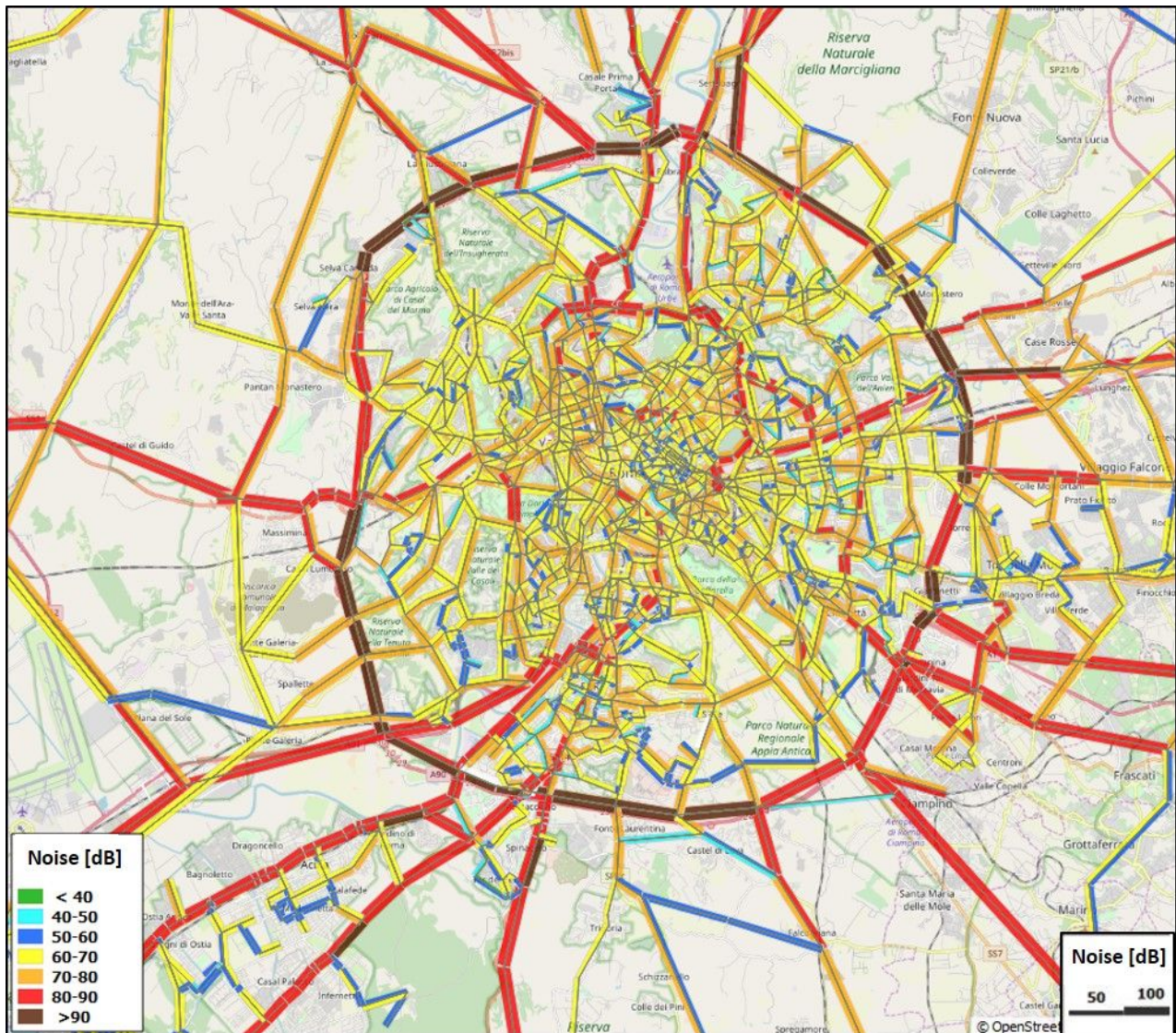
Figure 3: Noise emissions [dB], 100% AVs scenario

that the capacity-gain factor is higher for highways, the UE assignment procedure leads to a shift of traffic volumes from intra-urban routes to extra-urban routes. In particular, for the intra-urban part of the network, where a general −24% of emissions is estimated, many links would lower from the 80–90 dB class to the 60–70 dB class. This considerable reduction in terms of emissions would result also in significantly lower levels of exposure for receivers, especially in areas that are more likely to have higher residential densities (*i.e.*, intra-urban). For the highways type of links, the 6% estimated reduction does not seem to affect considerably the dB-classes of the interested parts of the network, which tend to stay in the in the 80–90 dB range; however, some benefits in terms of exposure are expected in this case too.

Figure 4 and Figure 5 offer further insights about the impact of the AVs fleet on the road network. Figure 4 shows the links where a proportional noise emission reduction is achieved, which is in most of cases, regardless of the extent of such effect. However, Figure 5 points out that for some specific network links (particularly for the highways type) implementing a 100% AVs scenario would result in higher noise emissions. A reasonable explanation for this effect is that higher increase in traffic volumes and speed are expected for highway (see Table 2), thus leading to higher noise emissions, as the CNOSSOS-EU model strongly depends on the traffic flow and speed.
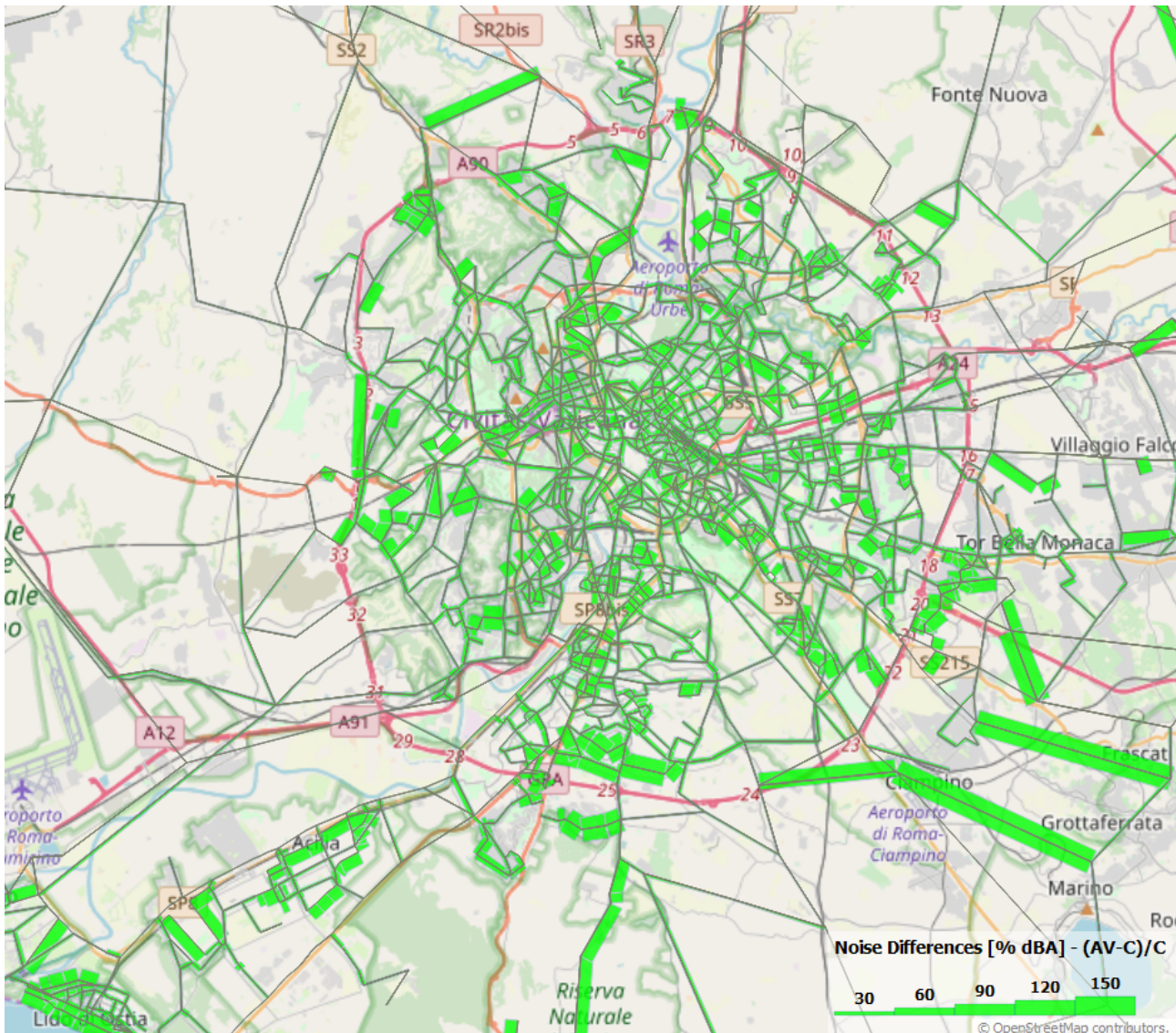
Figure 4: Noise pollution comparison: negative relative difference
(100% AVs emissions are lower than current scenario)

4 Discussion and Conclusions

This study presents a first attempt to define an integrated approach, which couples traffic simulation tools and a noise emission assessment, for evaluating the noise impact of AVs at the urban mobility level.

This work incorporates some assumptions, regarding both traffic simulation and noise emission assessment. First of all, AVs are assumed to be BEVs, but initial AV on the market are likely to be ICEVs or HEVs; this is an important assumption, and thus, the proposed approach should be used for further research to look comparatively at multiple future scenarios. As to the traffic simulation,

the volume-delay function used for the simulation was taken in the form of a modified BPR function, although it is not yet clear whether the BPR also holds for AVs homogeneous flow. Moreover, all the current private car trips were directly converted into AV-trips, and thus, variations in travel demand – population growth, spatial distribution, mode choice, ride sharing schemes, etc. – were not included; hence, future work should attempt to include a more realistic traffic simulation of AV-cities. As for the noise emission impact assessment, some assumptions were made too, both in terms of modelling strategy and descriptive approach of the variations between scenarios.

Traffic simulation results suggested that the full AV penetration scenario leads to an overall improvement in
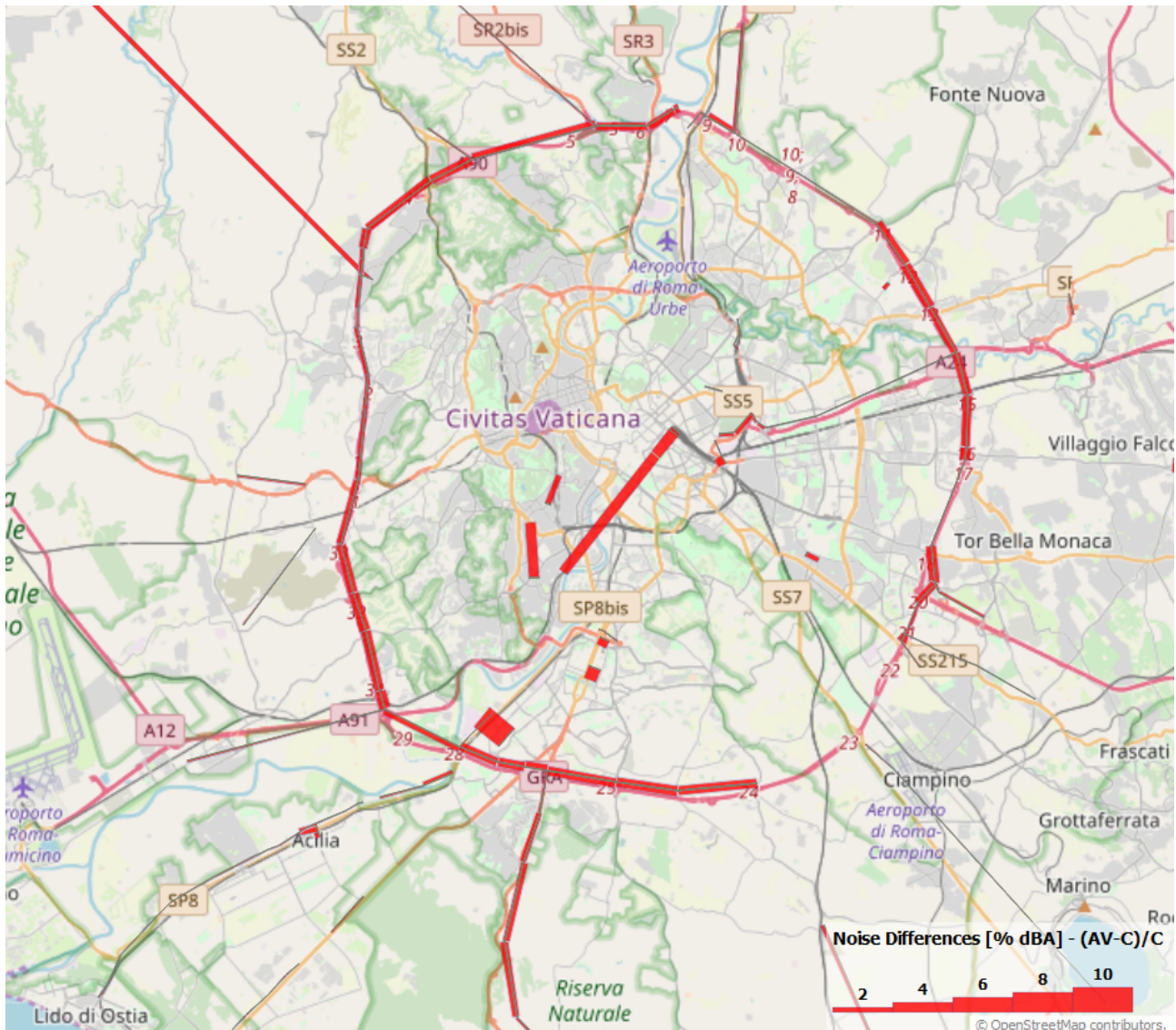
Figure 5: Noise pollution comparison: positive relative difference (100% AVs emissions are higher than current scenario)

the network performances in terms of travel time (−33%) and average speed network (+51%), whereas the total distance travelled increases for highways (8%) and decreases for intra-urban roads (−5%).

The noise emission assessment showed that a 100% AVs fleet would have a beneficial effect for the noise pollution, leading to a general reduction of noise emissions. This is promising, as from the noise emissions point of view, there seem to be better results than other traffic control and noise mitigation strategies (either related to the network and infrastructure, or to the fleet itself) are likely to achieve (see, for instance [45–47]). However, the analysis at a smaller scale also highlighted that an increase in traffic volume and speed lead to worsened conditions for some specific links of the network in terms of noise emissions. This suggests that locally on the network, some *ad hoc* noise control measures should be deployed to compensate for this side effect, and more generally it urges researchers and traffic planning and noise control practitioners to think more holistically about mobility networks.

References

[1]   Luettel, T., Himmelsbach, M., Wuensche, H.-J. (2012). Autonomous Ground Vehicles-Concepts and a Path to the Future. Proceedings of the IEEE, 100(Special Centennial Issue), 1831-1839.

[2] National Highway Traffic Safety Administration (NHTSA). (2013). U.S. Department of transportation releases policy on automated vehicle development. Webpage. Last accessed: 27.11.2018. https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety#issue-road-self-driving

[3] Fagnant, D. J., Kockelman, K. (2015). Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. Transportation Research Part A: Policy and Practice, 77, 167-181.

[4] Meyer, J., Becker, H., Bösch, M.P., Axhausen, K.W. (2017). Autonomous vehicles: The next jump in accessibilities? Research in Transportation Economics, 62, 80-91.

[5] Carrese, S., Nigro, M., Patella, S. M., & Toniolo, E. (2019). A preliminary study of the potential impact of autonomous vehicles on residential location in Rome. Research in Transportation Economics, 75, 55–61.

[6] Le Vine, S., Zolfaghari, A., Polak, J. (2015). Autonomous cars: The tension between occupant experience and intersection capacity. Transportation Research Part C: Emerging Technologies, 52, 1-14.

[7] Krueger, R., Rashidi, T. H., Rose, J. M. (2016). Preferences for shared autonomous vehicles. Transportation Research Part C: Emerging Technologies, 69, 343-355.

[8] Litman, T. (2018). Autonomous vehicle implementation predictions. Victoria, Canada: Victoria Transport Policy Institute.

[9] Weiss, J., Hledik, R., Lueken, R., Lee, T., Gorman, W. (2017). The electrification accelerator: Understanding the implications of autonomous vehicles for electric utilities. The Electricity Journal, 30(10), 50–57.

[10] Gawron, J. H., Keoleian, G. A., De Kleine, R. D., Wallington, T. J., Kim, H. C. (2018). Life Cycle Assessment of Connected and Automated Vehicles: Sensing and Computing Subsystem and Vehicle Level Effects. Environmental Science & Technology, 52(5), 3249-3256.

[11] Bollino, C., Asdrubali, F., Polinori, P., Bigerna, S., Micheli, S., Guattari, C., Rotili, A. (2017). A Note on Medium- and Long-Term Global Energy Prospects and Scenarios. Sustainability, 9(5), 833.

[12] Patella, S. M., Scrucca, F., Asdrubali, F., Carrese, S. (2019). Traffic Simulation-Based Approach for A Cradle-to-Grave Greenhouse Gases Emission Model. Sustainability, 11(16), 4328.

[13] Hawkins, T. R., Singh, B., Majeau-Bettez, G., Strømman, A. H. (2012). Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology, 17(1), 53-64

[14] Ellingsen, L. A.-W., Singh, B., Strømman, A. H. (2016). The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. Environmental Research Letters, 11(5), 054010.

[15] Canals Casals, L., Martinez-Laserna, E., Amante García, B., Nieto, N. (2016). Sustainability analysis of the electric vehicle use in Europe for CO2 emissions reduction. Journal of Cleaner Production, 127, 425–437.

[16] Woo, J., Choi, H., Ahn, J. (2017). Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: A global perspective. Transportation Research Part D: Transport and Environment, 51, 340–350.

[17] Kamiya, G., Axsen, J., Crawford, C. (2019). Modeling the GHG emissions intensity of plug-in electric vehicles using short-term and long-term perspectives. Transportation Research Part D: Transport and Environment, 69, 209–223.

[18] World Energy Outlook, 2018. Available at: https://www.iea.org/weo2018/scenarios/ (accessed on 19 August 2019).

[19] Brown, A., Gonder, J., Repac, B. (2014). An Analysis of Possible Energy Impacts of Automated Vehicles. Lecture Notes in Mobility, 137-153.

[20] Wadud, Z., MacKenzie, D., Leiby, P. (2016). Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. Transportation Research Part A: Policy and Practice, 86, 1-18.

[21] Vahidi, A., Sciarretta, A. (2018). Energy saving potentials of connected and automated vehicles. Transportation Research Part C: Emerging Technologies, 95, 822-843.

[22] Ross, C., Guhathakurta, S. (2017). Autonomous Vehicles and Energy Impacts: A Scenario Analysis. Energy Procedia, 143, 47-52.

[23] Patella, S.M., Scrucca, F., Asdrubali, F., Carrese, S. (2019). Carbon Footprint of Autonomous Vehicles at the urban mobility system level: a traffic simulation-based approach. Transportation Research Part D: Transport and Environment, 74, 189–200.

[24] Campello-Vicente, H., Peral-Orts, R., Campillo-Davo, N., Velasco-Sanchez, E. (2017). The effect of electric vehicles on urban noise maps. Applied Acoustics, 116, 59-64.

[25] Maffei, L., Masullo, M. (2014). Electric Vehicles and Urban Noise Control Policies. Archives of Acoustics, 39(3), 333-341.

[26] Friedrich, B. (2015). VerkehrlicheWirkungautonomerFahrzeuge. AutonomesFahren, 331-350.

[27] Tientrakool, P., Ho, Y.-C., Maxemchuk, N. F. (2011). Highway Capacity Benefits from Using Vehicle-to-Vehicle Communication and Sensors for Collision Avoidance. 2011 IEEE Vehicular Technology Conference (VTC Fall).

[28] Brownell, C. K. (2013). Shared Autonomous Taxi Networks: An Analysis of Transportation Demand in NJ and a 21st Century Solution for Congestion. Princeton University, April.

[29] Fernandes, P., Nunes, U. (2010). Platooning of autonomous vehicles with intervehicle communications in SUMO traffic simulator. 13th International IEEE Conference on Intelligent Transportation Systems.

[30] Bureau of Public Roads. (1964). Traffic assignment manual. Washington, D.C: U.S. Dept. of Commerce, Urban Planning Division.

[31] Lutin, J. M., Kornhauser, A. L., Lerner-Lam, E. (2013). The revolutionary development of self-driving vehicles and implications for the transportation engineering profession. Institute of Transportation Engineers. ITE Journal, 83(7), 28-32.

[32] Gucwa, M.(2014). Mobility and energy impacts of automated cars. Presentation at Automated Vehicles Symposium, July 15-17th, 2014, San Francisco. Conference co-sponsored by Transportation Research Board and Association for Unmanned Vehicle Systems International.

[33] Bhat, C., Howard, C., 2014. Regional Planning and Modeling Implications of Driverless Cars. Published Agenda of jointly-organized breakout session, Automated Vehicles Symposium 2014, July 15-17th, 2014, San Francisco. Conference co-sponsored by Transportation Research Board and Association for Unmanned Vehicle Systems International.

[34] Cairns, S., Harmer, C., Hopkin, J., Skippon, S. (2014). Sociological perspectives on travel and mobilities: A review. Transportation Research Part A: Policy and Practice, 63, 107-117.

[35] Bansal, P., Kockelman, K. M., Singh, A. (2016). Assessing public opinions of and interest in new vehicle technologies: An Austin perspective. Transportation Research Part C: Emerging Technologies, 67, 1-14.

[36] Florian, M., Hearn, D. (1995). Chapter 6 Network equilibrium models and algorithms. Network Routing, 485–550.

[37] Agenzia per l'Italia Digitale (AGID). https://www.dati.gov.it/dataset/parco-circolante-dei-veicoli (accessed on 1 July 2019)

[38] Carrese, S., Giacchetti, T., Patella, S. M., Petrelli, M. (2017a). Real time ridesharing: Understanding user behavior and policies impact: Carpooling service case study in Lazio Region, Italy. 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS).

[39] Carrese, S., Giacchetti, T., Nigro, M., Patella, S. M. (2017b). An innovative car sharing electric vehicle system: An Italia experience. Urban Transport XXIII.

[40] Patella, S. M., Sportiello, S., Petrelli, M., Carrese, S. (2019). Workplace relocation from suburb to city center: A case study of Rome, Italy. Case Studies on Transport Policy, 7(2), 357–362.

[41] Gatta, V., Marcucci, E., Nigro, M., Patella, S., Serafini, S. (2018). Public Transport-Based Crowdshipping for Sustainable City Logistics: Assessing Economic and Environmental Impacts. Sustainability, 11(1), 145.

[42] Asdrubali, F., Carrese, S., Patella, S. M., Sabatini, L. (2018). Development of Electric Urban Mobility: Comparative Research and Preliminary Survey. European Journal of Sustainable Development Research, 2(3).

[43] Rezvani, Z., Jansson, J., Bodin, J. (2015). Advances in consumer electric vehicle adoption research: A review and research agenda. Transportation Research Part D: Transport and Environment, 34, 122-136.

[44] Kephalopoulos, S., Paviotti, M., Anfosso-Lédée, F. (2012). Common Noise Assessment Methods in Europe (CNOSSOS-EU). Luxembourg: Publications Office of the European Union.

[45] Kirrian Fiedler, P. E., Trombetta Zannin, P. H. (2015). Evaluation of noise pollution in urban traffic hubs—Noise maps. Environmental Impact Assessment Review, 51, 1-9.

[46] Sorrentino, F., Aletta, F., Maffei, L., Kang, J., & Masullo, M. (2015). Effects of different urban traffic mitigation actions on cities' noise levels. Rivista Italiana di Acustica, 39(4), 23-41.

[47] Alves, S., Estévez-Mauriz, L., Aletta, F., Echevarria-Sanchez, G. M., & Puyana Romero, V. (2015). Towards the integration of urban sound planning in urban development processes: the study of four test sites within the SONORUS project. Noise Mapping, 2(1), 57-85.