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Abstract: The use of strategic noise maps as a means for estimating population exposure to environmental noise and defining action plans to mitigate its effects on human health has become a reality since the publication of the European Noise Directive. In this context, it is known that some differences can be found between the values obtained for sound indicators through simulation and measurements due to different causes. One of these factors is the presence of elements in urban environments not currently considered in calculation methods but certainly present in validation measurements. This paper presents an assessment of the acoustic shielding effect due to parked vehicles on urban streets using computational methods. First of all, a process of validation of the software model by means of different simulation methods and in situ measurements was carried out. Then, a study was developed varying different variables related to urban planning and noise modelling, as well as considering different typologies of real streets according to a categorisation method. Broadband results show that this shielding effect can be significant in common configurations in urban environments, even to receiver heights of 4 m considered as a reference in strategic noise maps. The magnitude of this effect varied depending on the distances between the building façade, parked vehicles and sound sources, as well as the receiver height. Differences up to 4 dBA in sound levels were found in several configurations between situations without and with cars parked at 4 m, although in some specific cases it reached up to 8 dBA. Therefore, results of this study indicated that parking lane shielding effect should be considered in calculations and validation measurements for strategic noise maps in order to obtain an adequate estimation of population exposure to road traffic noise.

Response to Reviewers: The authors would like to thank the reviewers for their comments and suggestions because they have contributed to improve the work. Please find below the suggestions of the reviewer followed by our comments describing the changes made or answering them.

Effect of parking lanes on assessing the impact of road traffic noise on building façades

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ABSTRACT

The use of strategic noise maps as a means for estimating population exposure to environmental noise and defining action plans to mitigate its effects on human health has become a reality since the publication of the European Noise Directive. In this context, it is known that some differences can be found between the values obtained for sound indicators through simulation and measurements due to different causes. One of these factors is the presence of elements in urban environments not currently considered in calculation methods but certainly present in validation measurements. This paper presents an assessment of the acoustic shielding effect due to parked vehicles on urban streets using computational methods. First of all, a process of validation of the software model by means of different simulation methods and in situ measurements was carried out. Then, a study was developed varying different variables related to urban planning and noise modelling, as well as considering different typologies of real streets according to a categorisation method.

Broadband results show that this shielding effect can be significant in common configurations in urban environments, even to receiver heights of 4 m considered as a reference in strategic noise maps. The magnitude of this effect varied depending on the distances between the building façade, parked vehicles and sound sources, as well as the receiver height. Differences up to 4 dBA in sound levels were found in several configurations between situations without and with cars parked at 4 m, although in some specific cases it reached up to 8 dBA. Therefore, results of this study indicated that parking lane shielding effect should be considered in calculations and validation measurements for strategic noise maps in order to obtain an adequate estimation of population exposure to road traffic noise.

Keywords: environmental pollution; sound propagation; measurement uncertainty; noise mapping; health.

1. INTRODUCTION

The World Health Organization (WHO) considers environmental noise as a major risk to human health [1]. Evidence suggests that long-term exposure to noise has a negative impact on human well-being and health, as it relates this pollutant to effects on cardiovascular and metabolic systems [2,3], cognitive faculties [4,5], sleep disturbance [6,7], annoyance [8,9], mental health [10,11], hearing system [12] and birth outcomes [13]. In this context, the WHO strongly recommends reducing noise levels produced by noise sources in order to diminish adverse effects on sleep and health [1].

The European Noise Directive (END) is the legislative reference in Europe for the management and assessment of environmental noise [14]. It proposes strategic noise maps as a key instrument for assessing population exposure to environmental noise [15–17], which provide the basis to relevant authorities to improve people's way of life by the development of action plans for mitigation [18–20]. The END also points to the need to protect quiet areas in agglomerations or open country from the increase of noise [21–23].

Concerning road traffic noise, although the prevailing trend is to carry out strategic noise maps by computation, in situ measurements are necessary for verifying noise models [24]. Recent researches proposed the use of an artificial intelligence based ensemble model and an emotional artificial neural network for prediction of vehicular traffic noise [25,26]. In this regard, uncertainty arises between the values obtained for sound indicators through simulations and in situ measurements due to different factors such as anomalous events or sound sources not considered in models [27,28], speed and type of vehicles [29,30], spatial sampling and interpolation process [31], etc. Another uncertainty factor between sound indicators obtained through measurements and simulations is the presence of elements in urban environments not considered in models. Since parking areas available to residents are also taken into consideration in the urban planning phase of cities, it is common to find parking spaces on the sides of streets in residential areas. But these obstacles are not currently considered in noise mapping due to reasons such as the increase in computational cost and the associated uncertainties due to the facts that these parking areas do not always have the same occupancy rate and the size of parked vehicles can be variable over time. However, this factor should be considered in measurements for static noise model verification, as well as in real-time measurements for dynamic noise models [32,33] to correct the recorded sound levels according to the height of the receivers and their position with respect to the building façade [34–37].

The starting hypothesis of the acoustic shielding effect due to parked vehicles was initially suggested from an experimental study carried out by means of measurements in different urban environments [37]. Subsequently, a new approach to the problem was made through simulations with the Boundary Element Method (BEM) [38]. However, that research was limited by the fact that the gap between parked vehicles could not be considered due to the use of a two-dimensional model. Therefore, when considering a continuous barrier [39,40] instead of a barrier with discontinuities, the values obtained for acoustic shielding could be overestimated. This paper proposes a new approach to the problem with two essential differences. First, no numerical methods such as BEM were used in this case, but calculation methods commonly used for strategic noise maps such as CNOSSOS-EU [41], NMPB-08 [42], CRTN [43] and NORD2000 [44] were used. Secondly, a three-dimensional model of the urban environment was carried out, which made it possible to produce a more realistic model for considering the space between parked vehicles.

In view of the above, the objective of this study was to estimate the differences in sound indicators between receivers located at different heights with and without parked vehicles in order to know the consequences that parking lanes, so common in the streets of cities, may have on the results of the strategic maps produced or in progress and on their validation procedure through measurements. For this purpose, the study of the dependence of the shielding effect with the distances between the façade, parked vehicle and sound source; the orientation of parked vehicles; the number of sound sources and the street profile was carried out. In addition, the possible relationship of the shielding effect with the categorisation method [45,46] was analysed by simulating some real cases.

2. METHODOLOGY

First, this section describes the validation process of simulations. Secondly, the methodology used to carry out the study of the different variables and aspects related to the acoustic shielding effect due to parked vehicles is shown.

2.1 Noise model validation

Prior to the assessment of the effect of parking lanes on sound level measured at different heights, it was considered necessary to verify whether the computational model developed can reproduce the shielding effects measured experimentally in a controlled situation in order to achieve the objectives set out in this work.

First, a measuring environment was selected in Don Benito (Spain) next to a road (EX-206) with an average traffic flow of approximately 20,000 vehicles/day [47]. This road joins the municipalities of Don Benito and Villanueva de la Serena (Spain) and is connected to the EX-A2 highway (Fig. 1). As can be seen, in the selected environment there is a row of vehicles, between the building façade and the sound source, parked in a perpendicular direction with respect to the building façade. It was therefore considered as an interesting urban configuration to assess the acoustic shielding effect caused by parked vehicles.

To carry out this part of the study, three microphones were placed at different heights above the ground on the building façade. The microphones — two 2260 and one 2250L Brüel & Kjær type 1 analyzers — were placed at heights of 1.5, 4.0 and 7.3 m on the building façade in accordance with the ISO 1996-2 standard [48–50]. A verification of the calibration of the measuring instruments was performed before and after the measurement session using a Bruel and Kjaer 4231 sound calibrator. In addition, checks were made before the measurements to ensure that both microphones had similar readings for a common position. The measurements were carried out in the day period on a working day, during which an approximate traffic volume of 1210 ± 47 vehicles/hour was recorded.

Fig. 1: Measuring environment (by https://satellites.pro)

Secondly, a model of this urban environment was made by CadnaA software v.2018. Some of the most commonly used methods so far in Europe for noise mapping were considered in simulations in this verification process in order to compare them and contrast the results with the experimental values. Methods such as CNOSSOS-EU [41], NMPB-08 [42], CRTN [43], NORD2000 [44] were employed. For this purpose, a linear sound source was used for each of the four traffic lanes in this stretch of the EX-206 road. These sources were located in the centre of the corresponding lane at a height of 0.05 m above the ground [41]. The traffic flow and speed of the vehicles used as input data in the simulations were according to those registered during in situ measurements. On the other hand, dimensions of parked vehicles in this scenario and separation between them were taken during the measurement. So, rectangular blocks of dimensions 4.5 × 1.5 × 1.5 m (length × width × height) were positioned in the direction perpendicular to the building façade to simulate the parked vehicles. A gap of 0.5 m between them was taken into account. Their surfaces were considered fully reflective, as were the surfaces of the building and the ground. According to the guidelines of Annex II of the END [41] for those cases in which possible multiple reflections may occur, a unique reflection of sound in vertical obstacles was considered in simulations [51,52]. Finally, three receivers were placed on the building's façade at heights of 1.5, 4 and 7.3 m, according to the heights of the microphones used in the in situ measurements. Results of this model verification procedure are shown in Section 3.1.

2.2 Variability of urban configurations and vehicle layout

A study of the impact of different variables on the acoustic shielding effect due to vehicles parked in urban environments was developed by simulations. In order to assess the magnitude of this effect, the difference in broadband for equivalent sound level (ΔL_{eq}) without and with parked vehicles was analysed depending on the height of the receivers. Taking into account common real situations in cities, Fig. 2 shows a general scheme of the considered urban environment in which a building and some vehicles parked parallel to the building façade were drawn. In this figure, the red line represents the linear sound source located in the centre of all traffic lanes. The distances — façade to parked vehicles (d_{FV}), parked vehicles to sound source (d_{VS}) and façade to sound source (d_{FS}) — are also detailed. Finally, some receivers were placed on the façade in vertical arrays at heights between 1.5 and 8 m above the ground. A total of six arrays with a distance between them of 1.5 m were used for the study in order to make a spatial average of the sound levels.

In this regard, configurations close to reality were simulated by using variables such as the distances between the sound source, the parked vehicles and the building façade; the orientation of the parked vehicles; the number of linear sound sources; and street profiles. Results of this study are structured in different sections. Section 3.2 includes those related to urban configuration variables, while Section 3.3 shows the results related to noise modelling variables. Lastly, the acoustic shielding effect of parked vehicles in real scenarios on streets of Cáceres with diverse functionality is analysed in Section 3.4. For this purpose, different streets were selected according to the categorisation method, which classifies the streets of a city into five types depending on their functionality as a means of connection [53].

Finally, some points must be highlighted. First, parked vehicles were placed parallel to the building façade considering a gap of 0.5 m between them (d_{VV}), except in Section 3.2.4 where two parking directions were studied. The number of parked vehicles and their location was enough to ensure a screening of all the receivers of a minimum horizontal viewing angle of 60° with respect to the linear sound sources [48]. Regarding the general configuration employed in Sections 3.2 and 3.3, widths of 2 and 3 m were used, respectively, for parking and traffic lanes. It should also be pointed that an L profile street was considered in these sections, except in Section 3.2.3 in which the influence of U and L profiles on the shielding effect was investigated. And, obviously, real widths for parking and traffic lanes and street profiles were selected in Section 3.4.

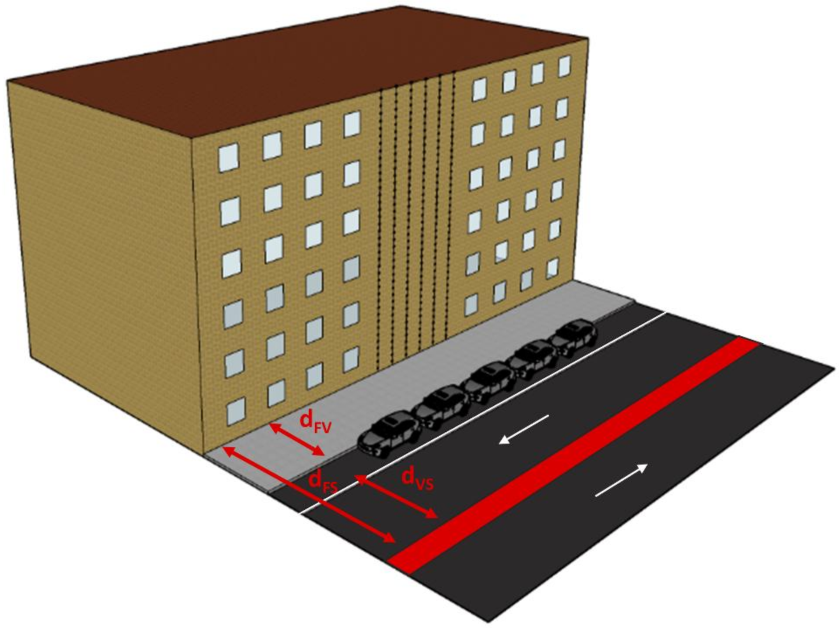


Fig. 2: General scheme of the urban environment considered in the noise model

3. RESULTS

3.1 Computational model verification

A verification procedure of the computational model was initially carried out by comparing the results obtained from in situ measurements with those obtained from simulations with different calculation methods. On the one hand, five 10-minute measurements were made with three microphones located on the façade of a building at heights of 1.5, 4.0 and 7.3 m above the ground. The heights of 1.5 and 4.0 m are indicated in the END [14] and the ISO 1996-2 standard [48]. The height of 7.3 m is used as an option for in situ measurements to assess the impact of environmental noise in two or more storey buildings. Table 1 shows the broadband results for the difference of the equivalent sound level registered by pairs of microphones in each measurement (ΔL_{eqM}), as well as the averaged values and the associated standard deviation.

	$\Delta L_{eqM\ 1.5–4.0m}$ (dBA)	$\Delta L_{eqM\ 4.0–7.3m}$ (dBA)	$\Delta L_{eqM\ 1.5–7.3m}$ (dBA)
Meas. 1	6.0	−0.1	6.1
Meas. 2	5.9	−0.2	6.1
Meas. 3	5.9	−0.1	6.1
Meas. 4	5.6	0.0	5.6
Meas. 5	5.3	−0.1	5.3
Average	5.7	−0.1	5.8
St. Dev.	0.3	0.1	0.4

Table 1: Differences in equivalent sound level between pairs of microphones for in situ measurements

On the other hand, concerning the verification process of the model, simulations of the measurement environment were carried out. For this purpose, the vehicle flow counted during in situ measurements was considered as input data, as well as the speed limit established for that section of the road (50 km/h) [29]. Table 2 shows the obtained values for the difference between pairs of receivers (ΔL_{eqE}). Results for the differences in measured and estimated sound levels in Tables 1 and 2 respectively show good agreement in many cases, and the CNOSSOS method is the one that gets closer to the experimental results.

	$\Delta L_{eqE\ 1.5–4.0m}$ (dBA)	$\Delta L_{eqE\ 4.0–7.3m}$ (dBA)	$\Delta L_{eqE\ 1.5–7.3m}$ (dBA)
CNOSSOS-EU	5.4	0.1	5.3
NMPB-08	5.2	0.1	5.1
CRTN	4.3	−0.5	4.8
NORD2000	5.3	0.2	5.1

Table 2: Differences in equivalent sound level between pairs of receivers for simulations with different methods

Thus, considering the results of Tables 1 and 2 and that CNOSSOS-EU method was established for strategic noise mapping by computational methods in the recent modification of Annex II of the END [41], the following sections include a study by simulations with the CNOSSOS-EU method of different variables related to urban planning and noise modelling that may have relevance to the aforementioned shielding effect.

3.2 Variables related to urban configuration

3.2.1 Parked vehicle to source distance (d_{VS})

The influence of the variation in the distance between the parked vehicles and the sound source (dvs) on the acoustic shielding effect of parked vehicles is evaluated according to the different urban configurations present in cities. A common sidewalk width of 2 m was considered (d_{FV} = 2 m), and three street configurations with different number of traffic lanes (1, 2 and 4) were studied. For this purpose, the sound source was placed in the centre of all traffic lanes, meaning that the distance between the parked vehicles and the sound source varies according to the number of traffic lanes (Table 3).

d_{FV} (m)	Parking lane width (m)	Traffic lane width (m)	No. of traffic lanes	No. of linear sources	d_{VS} (m)
			1		2.0
2.0	2.0	3.0	2	1	3.5
			4		6.5

Table 3: Values of the variables in the considered setups for the study of d_{VS} influence

Fig. 3 shows the difference in broadband for equivalent sound level in each of the three configurations depending on the height of the receivers. Fig. 4 presents the calculated value for sound indicator with (Fig. 4a) and without vehicle obstacles (Fig. 4b) for the case d_{VS} = 2 m at a receiver height of 4 m. Results found in these three common street configurations reveal different remarkable aspects related to calculated noise maps or the use of the measures as a system to evaluate the impact of urban noise on population or for validation of noise maps based on calculations.

To analyse these aspects, two factors must be taken into account. The first factor is the height of the receivers at which the calculations or measurements are made. In this regard, the reference heights are 1.5 and 4.0 m. The second factor is the type of building on which the noise doses received are estimated, making a distinction between single-storey dwellings and multi-storey buildings.

The screening effect of vehicles at 1.5 m height (reference for single-storey dwellings) is predicted by the model. In any of the cases studied, differences greater than 8 dBA were found when considering or not a parking lane in the model. Therefore, the current absence of these elements in noise models would lead to an overestimation of the doses received by the population in the case of one-storey dwellings. In case of measurements carried out at a height of 1.5 m, these would be adequate for estimating exposure in single-storey dwellings. On the other hand, if measurements at 1.5 m were used as indicators of the reference height of 4 m [14], the presence of parked vehicles would involve a screen effect, meaning that the noise doses to which the population is exposed would be underestimated.

On the other hand, for a microphone height of 4 m, the effect of the parking lanes on the sound level is predicted by the model in the case of single-lane streets, in the fairly common configuration of a sidewalk and a parking lane 2 m wide. This fact is of relevance for the current validation of noise maps, since validation measurements take into account the actual situation of the presence of parked vehicles and the estimations of the calculation models do not. These findings show differences of about 4 dB. This would have implications for the accurate estimation of the noise doses received on building façades not only at this height but also at greater heights. On the other hand, in the case of two- and four-lane streets for the analysed configurations, measurements at 4 m can be used for the validation of strategic noise maps, and calculations at 4 m can serve as estimators of sound levels at greater heights in case of buildings with two or more storeys. In addition, if calculations or measurements were made at 4 m in the three configurations studied (1, 2 and 4 lanes), the values obtained would overestimate the impact on the population if they were used to assess the noise doses received on the ground floors of detached houses.

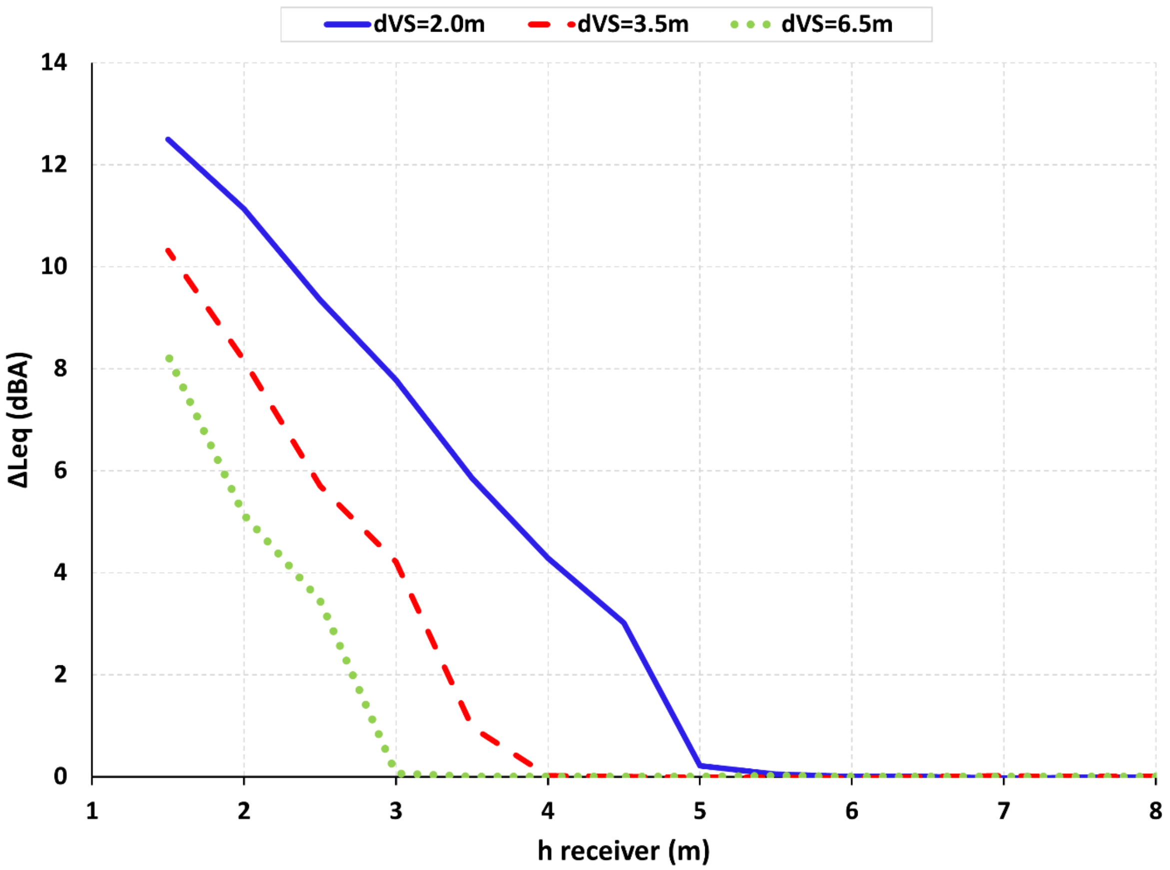


Fig. 3: ΔL_{eq} between situations without and with parked cars depending on receiver height for different distances between parked vehicles and sound source (d_{VS})

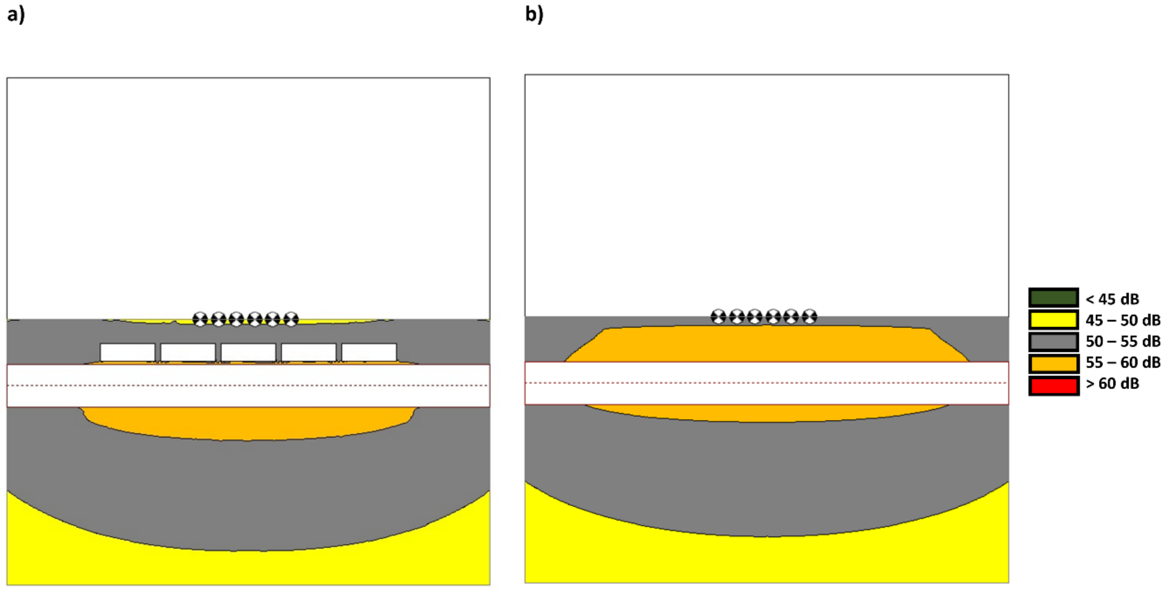


Fig. 4: Sound field distribution at a height of 4 m a) with and b) without parked vehicles for d_{VS}=2 m

3.2.2. Façade to parked vehicle distance (d_{FV})

Given the wide variety of street configurations in cities, it is also interesting to study the influence of the distance between the building façade and the parked vehicles (d_{FV}) on the acoustic shielding effect. Usually, this variable is directly related to the width of the sidewalk of each street, which varies from narrow streets to wide avenues. For this, four urban configurations were studied, in which a fixed distance of 2 m between the parked vehicles and the sound source (d_{VS} = 2 m) was considered (Table 4).

d_{FV} (m)	Parking lane width (m)	Traffic lane width (m)	No. of traffic lanes	No. of linear sources	d_{VS} (m)
1.0 2.0 4.0 8.0	2.0	3.0	1	1	2.0

Table 4: Values of the variables in the considered setups for the study of d_{FV} influence

Fig. 5 shows the difference in broadband for equivalent sound level in each of the four configurations depending on the height of the receivers. When a linear sound source located at a fixed distance from parked vehicles is considered, the shielding effect generally increases as the distance between the façade and parked vehicles increases. In cases where street sidewalks were narrow (d_{FV} = 1 m), a shielding effect was observed that should be taken into account for receiver heights lower than 4 m. While for higher d_{FV} values, a relevant shielding was detected at the height of 4 m recommended for strategic noise mapping. Fig. 6 shows in detail the results at a height of 4 m with parked vehicles for: a) d_{FV} = 1 m; b) d_{FV} = 2 m, c) d_{FV} = 4 m and d) d_{FV} = 8 m. It can be verified that the case d_{FV} = 8 m is the one in which the parked vehicles have the greatest impact on the sound level recorded by the receivers located on the building façade.

Consequently, in the configurations analysed in which d_{VS} was set as fixed and d_{FV} (sidewalk width) varied, the calculation models indicate the presence of a screening effect of vehicles parked on the sides of streets and, furthermore, a dependence of this effect on height. The involvement of these findings will be analysed again, taking into account the reference heights of the European Directive and the height of the buildings on which it is desired to evaluate the noise doses to which they are exposed.

First, in streets with parking lanes, at the reference height of 1.5 m, only in situ measurements would allow to estimate the actual doses received in single-storey dwellings, whereas calculation models currently carried out would overestimate the noise doses. In addition, these in situ measurements should not be used in buildings with two or more storeys in order to estimate the doses received by the inhabitants, even if they are normalised to 4 m.

Concerning the reference height of 4 m, the results indicate that only in the case of a very narrow sidewalk (d_{FV} = 1 m), calculations or measurements at 4 m are representative of the impact of traffic noise on the façade on the first floor and above; furthermore, only in this urban configuration, measurements can be compared with estimations from computational models for the validation of noise maps. In the remaining configurations, which are generally closer to the urban reality of cities, it is not convenient to use a height of 4 m as a reference for noise mapping, given the effects that parking lanes have on the incident sound field on the façade. If the validation were carried out with measurements at 4 m in these urban configurations in the current calculation models, the noise doses received by the citizens living on the upper floors of the buildings would be underestimated.

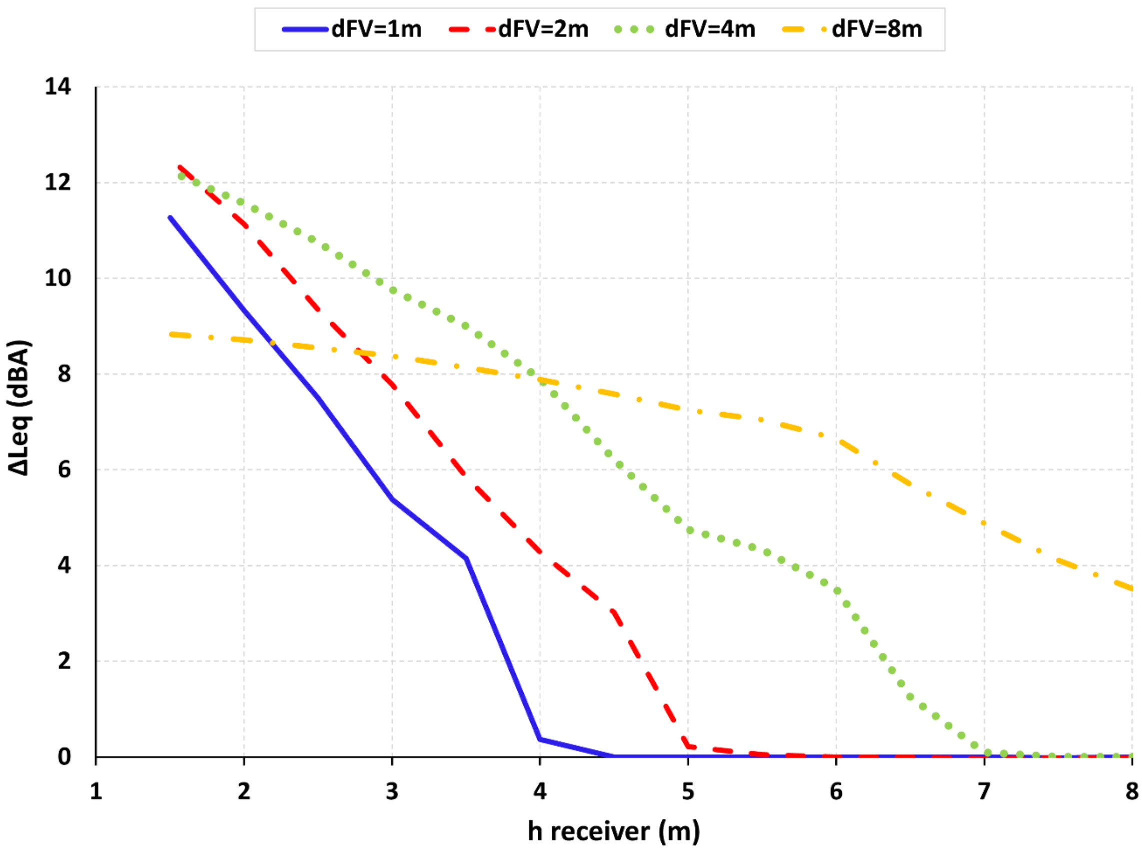


Fig. 5: ΔL_{eq} between situations without and with parked cars depending on receiver height for different distances between building façade and parked vehicles (d_{FV})

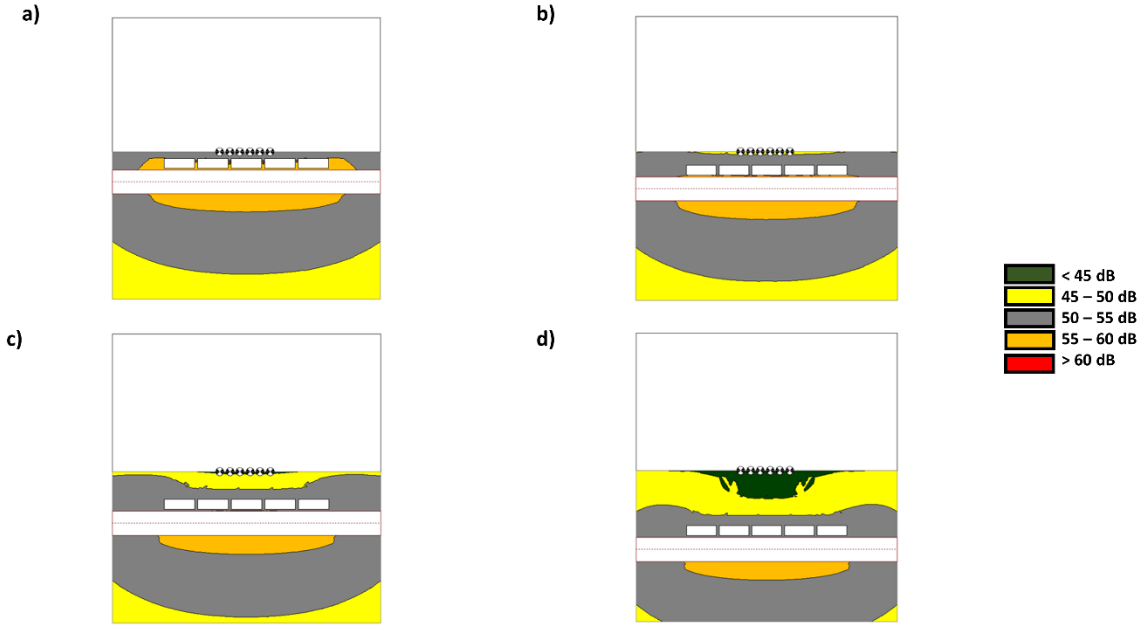


Fig. 6: Sound field distribution at a height of 4 m with parked vehicles for: a) d_{FV} = 1 m, b) d_{FV} = 2 m, c) d_{FV} = 4 m and d) d_{FV} = 8 m.

3.2.3. Street profile

This section presents a study of the shielding effect of parked vehicles based on two common configurations in urban environments: with reflective walls on one side of the street (L profile) and with reflective walls on both sides of the street (U profile). A frequent configuration of a street with two traffic lanes was considered, where a linear sound source was placed in the centre of all traffic lanes. Two different street configurations were assessed according to the sidewalk width: a) d_{FV} = 2 m and b) d_{FV} = 8 m (Table 5).

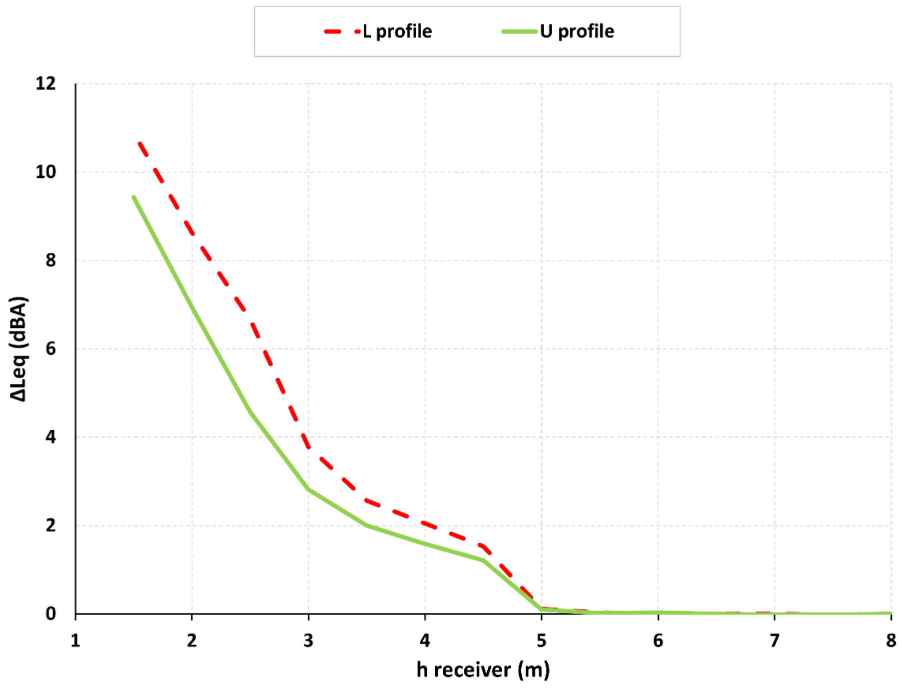
d_{FV} (m)	Parking lane width (m)	Traffic lane width (m)	No. of traffic lanes	No. of linear sources	d_{VS} (m)
2.0 8.0	2.0	3.0	2	1	3.5

Table 5: Values of the variables for the study of street profiles

Fig. 7 shows the difference in broadband for the equivalent sound level without and with parked vehicles depending on the height of the receivers for the two street configurations studied. Thus, the total width of the street was 14 m in case a) and 26 m in case b). Results obtained through the CNOSSOS-EU method in the two urban configurations (Fig. 7a and Fig. 7b) showed that the acoustic shielding effect was lower on streets with reflective buildings on both sides of the street (U profile) than when the buildings were only on one side (L profile). This weakening of the shielding effect is due to the contribution of the sound reflections in the opposite façade to the one in which the receivers are located. The difference in the shielding effect between the two street profiles (U and L) decreased as the height of the receiver increased. This was explained by the fact that the receiver became less shielded by parked vehicles as its height above the ground was higher. A further aspect to be noted is that the difference in the shielding effect produced by parked vehicles between U and L profile streets was smaller when the streets were narrower. On the one hand, this effect for both street profiles is due to the increase in the distance between the façade and the parked vehicles (d_{FV}) already detected in Fig. 5. In addition, it must be taken into account for U profile streets that that the waves reflected in the opposite façade become more intense as the width of the street is reduced, which contributes to a more homogeneous sound field in the area of the receivers.

In any case, results indicate that the shielding effect of parking lanes on U profile streets remains significant and that their weakening or softening with respect to L profile streets is less important than the shielding values found. Thus, although not numerically, the effects and conclusions obtained in L profile streets are valid for U profile ones.

a)



b)

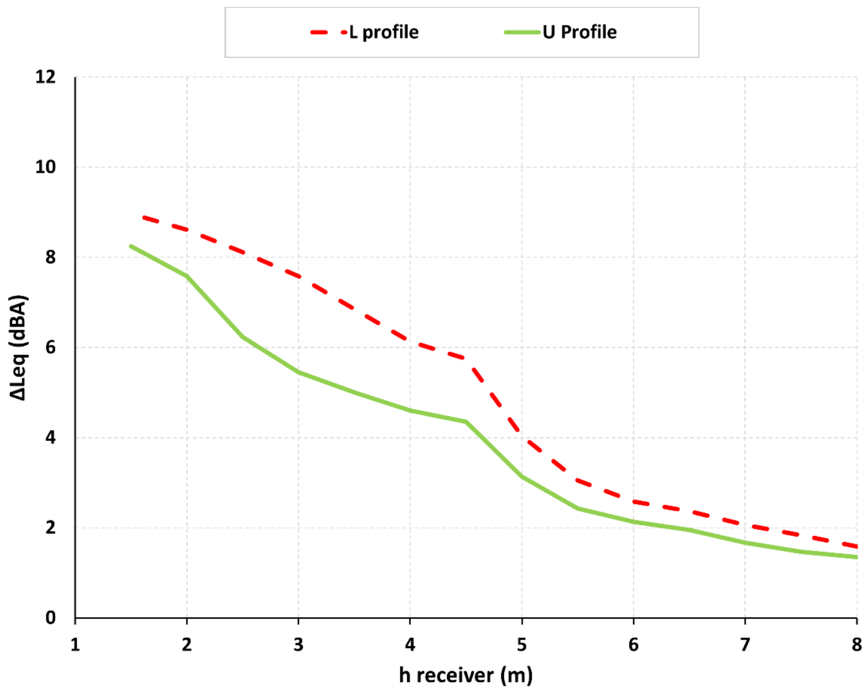


Fig. 7: ΔLeq between situations without and with parked cars depending on receiver height in different streets configurations for: a) d_{FV} = 2 m and b) d_{FV} = 8 m

3.2.4. Direction of parked vehicles

The direction in which vehicles are parked with respect to building façade in real urban environments is another variable to be addressed in the study due to its possible influence on the aforementioned acoustic shielding effect according to the shape of the obstacles and the structure in which they are positioned. In this regard, two configurations of parked vehicles with respect to the building façade that are common in the streets of urban areas were studied: parallel and perpendicular. Table 6 shows the details of the configurations considered in this analysis.

d_{FV} (m)	Parking direction	Parking lane width (m)	Traffic lane width (m)	No. of traffic lanes	No. of parking lanes	d_{VS} (m)
2.0	Par.	2.0	3.0	1	1	2.0
2.0	Perp.	5.0				

Table 6: Values of the variables for the studied parking setups

Fig. 8 shows the difference in broadband for the equivalent sound level without and with parked vehicles as a function of the height of the receivers for the two considered parking configurations of vehicles with respect to the building façade. In this regard, Fig. 9 shows the sound field distribution for a receiver mesh at 4 m height with both configurations of parked vehicles. In the case where vehicles are parked parallel to the façade (Fig. 9a), a lower acoustic shielding effect is observed than in the case of the perpendicular parking configuration (Fig. 9b). Therefore, a change in the configuration of vehicles parked on the sides of streets from the most common in urban environments such as parallel to the façade to the perpendicular configuration would generally imply an increase in the resulting screening effect. In any case, qualitatively, the implications on the validation of the noise maps are similar in both configurations, so that the results in the previous sections were confirmed. That is, with respect to the reference height of 1.5 m, only measurements allow a proper valuation. Regarding the case of using 4 m as a validation or reference height to evaluate the impact of traffic noise on the building, care and attention must be paid to the presence of parking lanes in front of the façade of the building in question, given the shielding effects that would take place.

Results by the CNOSSOS-EU method revealed that the acoustic shielding effect was quite similar in both parking configurations for a receiver height of up to 2 m. However, from this height, a greater acoustic shielding effect was found when the parked vehicles were oriented perpendicular to the façade. This difference between the two configurations increased gradually with the height of the receiver up to a height of approximately 5 m, where the difference reached a maximum value of 5 dB. From this point on, the shielding effect tended to decrease in both cases, but even at a height of 7 m, differences between the two cases of more than 2 dB were detected.

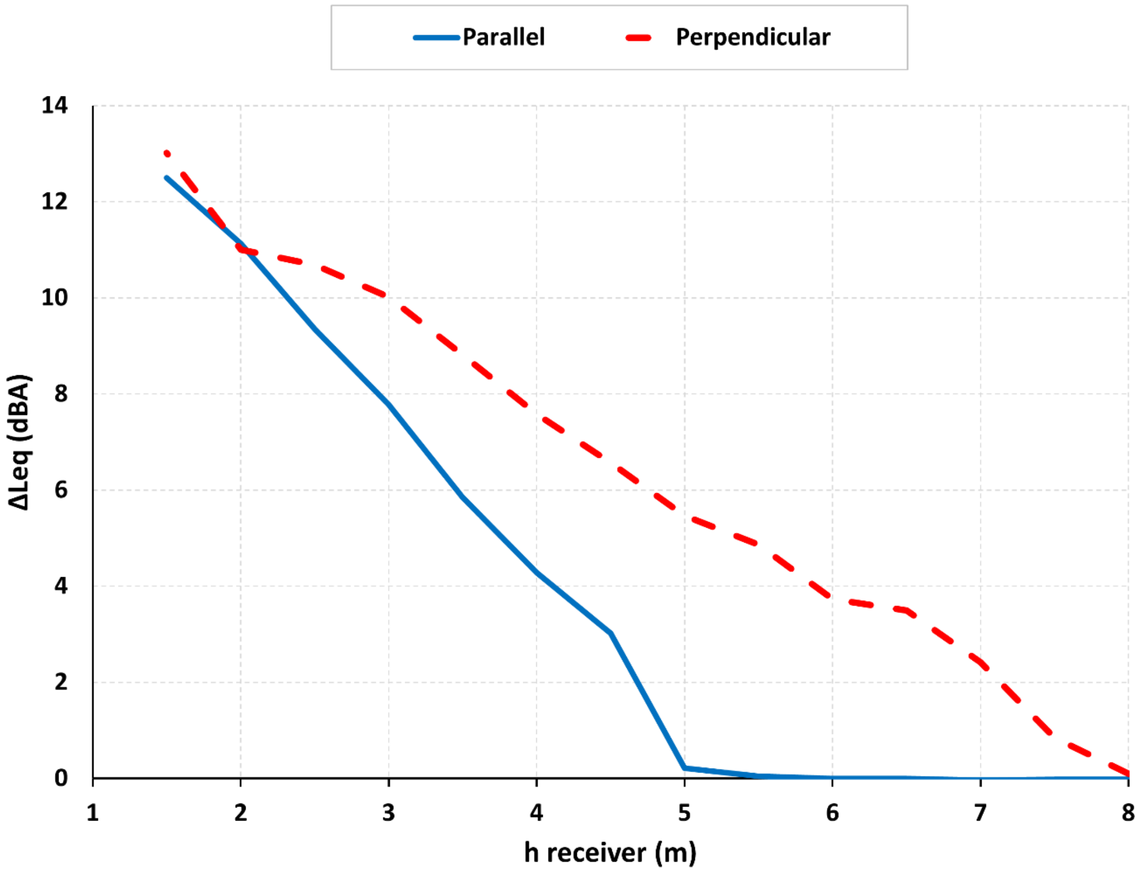


Fig. 8: ΔL_{eq} between situations without and with parked cars depending on receiver height for different parking configurations

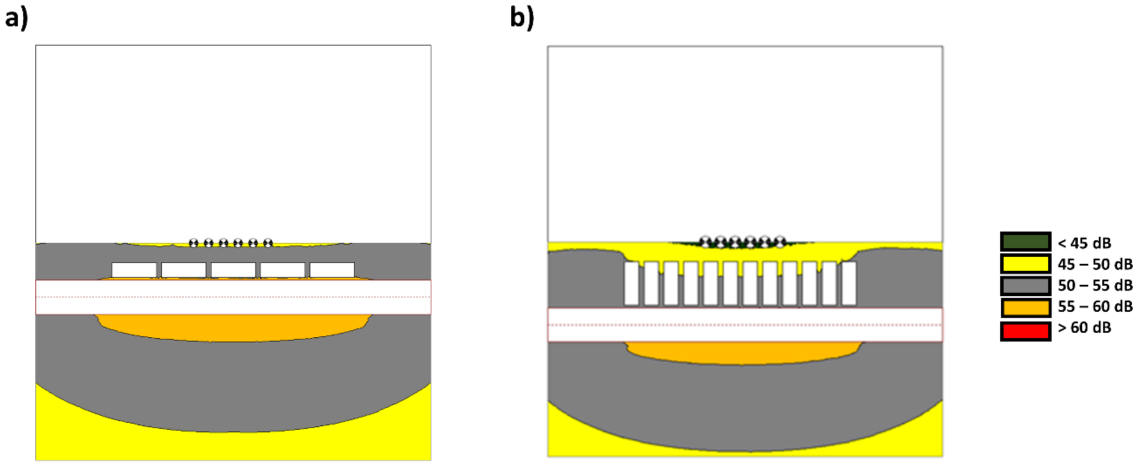


Fig. 9: Sound field distribution at a height of 4 m for different parking configurations: a) parallel and b) perpendicular

3.3 Variables related to noise modelling

3.3.1. The number of linear sources

Another interesting aspect in the process of producing strategic noise maps is the number of linear sources used to simulate traffic noise on urban streets. In relation to this issue, it is considered interesting to evaluate the impact of considering a different number of linear sources on multi-lane streets on the acoustic shielding effect. To this end, this section proposes a study of three street configurations with four traffic lanes (two for each direction) considering three cases: one linear source (in the centre of all lanes); two linear sources (in the centre of each traffic direction); and four linear sources (in the centre of each traffic lane). These three street configurations were evaluated for a sidewalk width (d_{FV}) of 2, 4 and 8 m

(Table 7). The d_{VS} column shows the distance(s) between parked vehicle and linear sound source(s).

d_{FV} (m)	Parking lane width (m)	Traffic lane width (m)	No. of traffic lanes	No. of linear sources	d_{VS} (m)
				1	6.5
2.0	2.0	3.0	4	2	3.5/9.5
				4	2.0/5.0/8.0/ 11.0
				1	6.5
4.0	2.0	3.0	4	2	3.5/9.5
				4	2.0/5.0/8.0/ 11.0
				1	6.5
8.0	2.0	3.0	4	2	3.5/9.5
				4	2.0/5.0/8.0/ 11.0

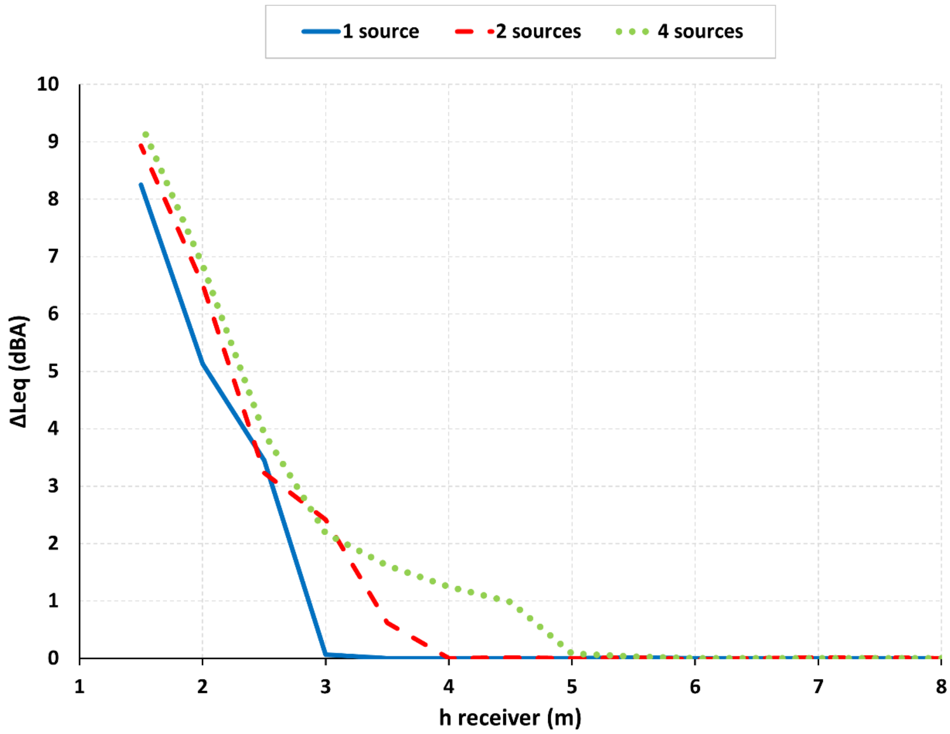
Table 7: Values of the variables for the studied setups

Fig. 10 shows the difference in broadband for the equivalent sound level without and with parked vehicles depending on the height of the receivers for three different street configurations: a) d_{FV} = 2 m; b) d_{FV} = 4 m; c) d_{FV} = 8 m. In the setup considered in Fig. 10a (d_{FV} = 2 m), a similar shielding effect was observed in the three cases up to a microphone height of 2.5 m above the ground, regardless of the number of linear sources involved. As the microphone height increased, a higher shielding effect was observed in the case where four linear sources were considered, probably due to the greater proximity of one of the linear sources to parked vehicles, in accordance with the results shown in Fig. 3. A similar trend was noted in the remaining cases (Fig. 10b and Fig. 10c). Also, as the distance between the building façade and parked vehicles (d_{FV}) grew, the height of the receivers up to which similar values of the acoustic shielding effect were obtained regardless of the number of sources progressively increased. Finally, in congruence with the results obtained in Fig. 5, an increase in the shielding effect was detected as the distance between the building façade and parked vehicles (d_{FV}) became greater.

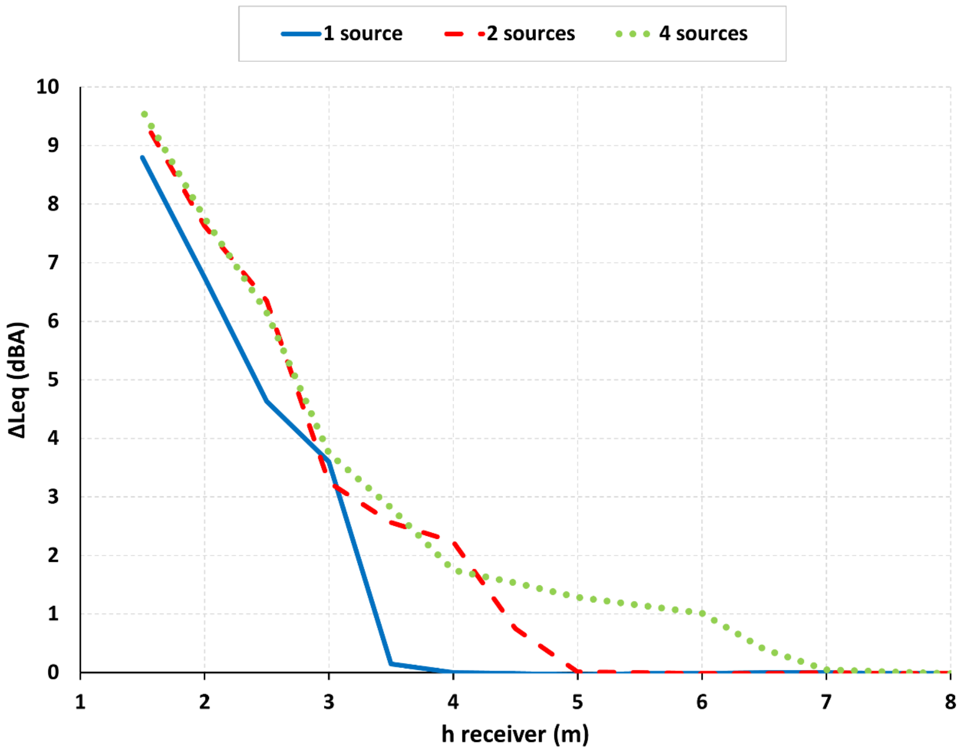
Therefore, for the three configurations analysed, results indicate that the increase in the number of linear sources to represent four traffic lanes does not involve significant variations in the screening effect of the parking lanes predicted by the computational model at the reference height of 1.5 m. On the other hand, if the height of 4.0 m is considered, the calculations show some differences in the shielding effect depending on the number of linear sources.

For the situation of 2 m wide sidewalks, some differences appeared in case of using four linear sources. For 4 m wide sidewalks, the settings with two and four linear sources lead to similar and different results to the use of a single linear source. And finally, for 8.0 m wide sidewalks, results at 4.0 m show no relevant differences depending on the number of traffic lanes used in the model. It can also be observed that in receivers located at greater heights, in the cases of sidewalks 4.0 and 8.0 m wide, there are differences depending on the number of lanes used, but these heights are no longer used in the verification of calculation models. In summary, regarding the assessment of the acoustic shielding effect of vehicles parked on the side of streets, the consideration of a greater number of linear sources to represent the traffic lanes does not play a major role in the final result. Consequently, the findings from Sections 3.2.1 and 3.2.2, where the study of the shielding effect of parking lanes for the different urban configurations existing in our cities was performed, were confirmed.

a)


1 source
2 sources
4 sources
ΔLeq (dBA)
h receiver (m)
0
1
2
3
4
5
6
7
8
9
10
1
2
3
4
5
6
7
8

b)


1 source
2 sources
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ΔLeq (dBA)
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c)

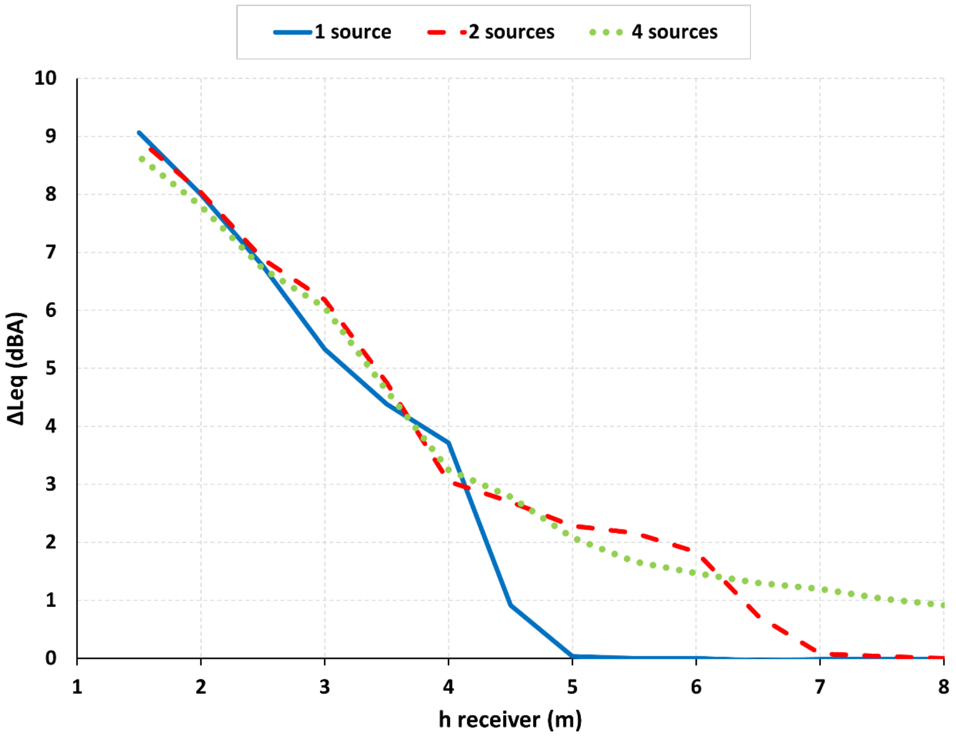

Fig. 10: ΔL_{eq} between situations without and with parked cars depending on receiver height for different distances between building façade and parked vehicles: a) d_{FV} = 2 m; b) d_{FV} = 4 m; c) d_{FV} = 8 m

3.4 Variation of urban street types

The effect of parking lanes on the urban design of a city is studied in this section. Moreover, in order to obtain a view over a wide range of street types, it was deemed useful to make the selection according to the functionality of the streets by applying the categorisation method. Two streets were selected from each of the five categories of the method with different features regarding the distance between building façade, parked vehicle and the sound source; the number of traffic lanes; and the street profile. Table 8 shows the urban characteristics of the chosen streets for the different categories. In this table, the considered values of the distance between parking lane and source (dvs) in each street correspond to those of each linear source. One sound source was located in the centre of each traffic lane. Pictures of these streets are shown in Fig. 11.

Cate gory	**Street name**	**d_{FV} (m)**	**Parking lane width (m)**	**Traffic lane width (m)**	**No. of traffic lanes**	**No. of linear sources**	**d_{VS} (m)**	**Street profile**
1	Alemania Av.	6.0	3.0	4.0	4	4	3.5/7.5/13.5/17.5	U
	Her.Cortés Av.	3.0	2.0	3.0	4	4	2.0/5.0/9.0/12.0	L
2	Cervantes Av.	4.0	2.5	4.0	4	4	3.0/7.0/12.0/16.0	U
	Vadillo Rd.	1.0	2.0	3.0	2	2	2.0/5.0	L
3	Ant. Hurtado Av.	4.0	2.0	3.0	4	4	2.0/5.0/8.0/11.0	U
	Carmen Rd.	2.0	2.0	3.0	1	1	2.0	U
4	Barrerón St.	2.0	2.0	3.0	2	2	2.0/5.0	U
	Italia St.	3.0	2.0	3.0	1	1	2.0	U
5	León Leal St.	2.0	2.0	3.0	1	1	2.0	U
	Toledo St.	1.0	2.0	3.0	1	1	2.0	U

Table 8: Values of the variables for the studied streets

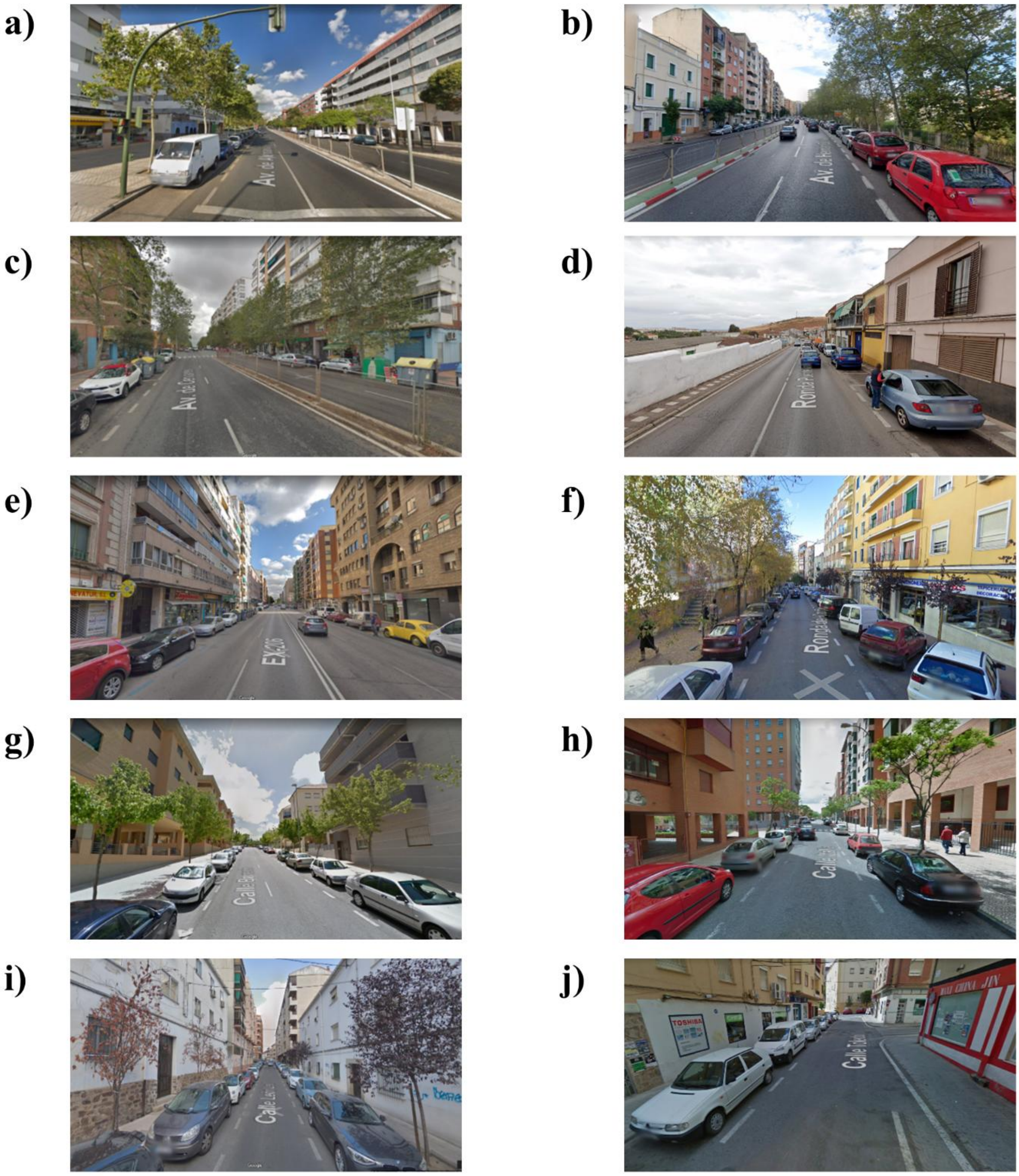

Fig. 11: Pictures of streets from different categories in Cáceres: Alemania Av. (a), Hernán Cortes Av. (b), Cervantes Av. (c), Vadillo Rd. (d), Antonio Hurtado Av. (e), Carmen Rd. (f), Barrerón St. (g), Italia St. (h), León Leal St. (i), and Toledo St. (j) (by Google Maps)

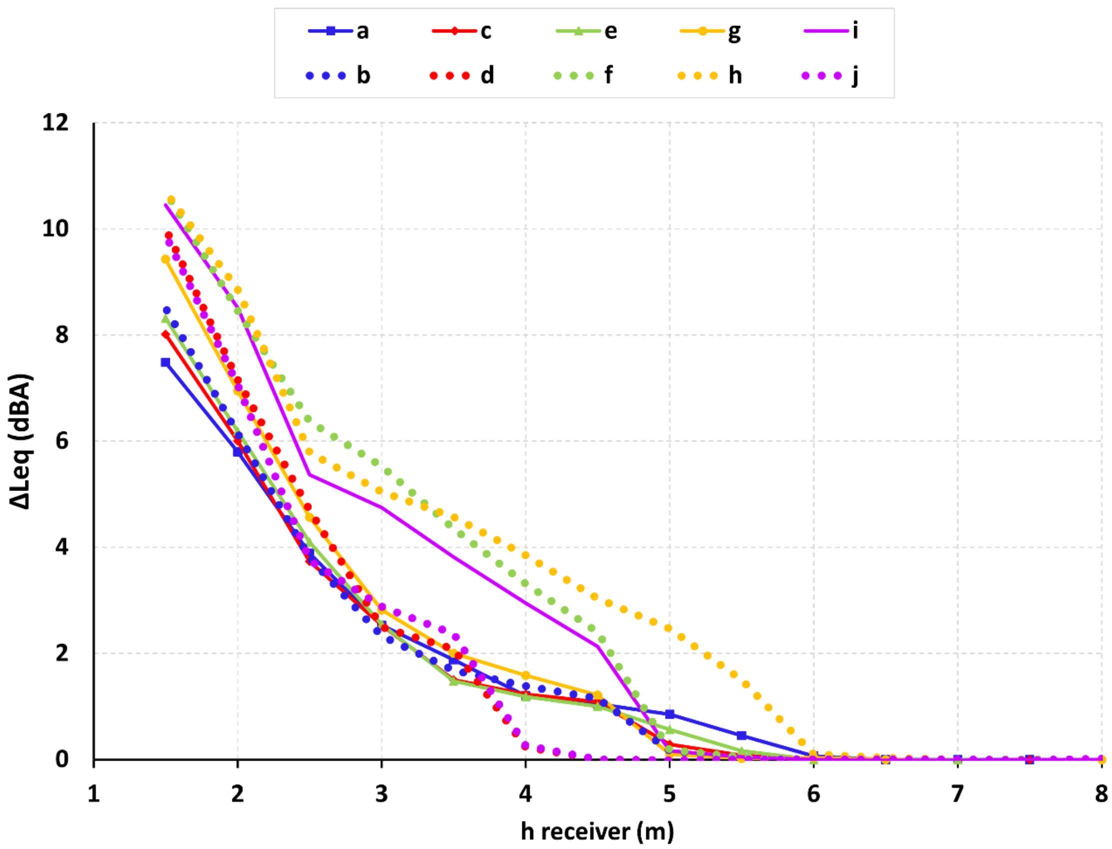

Fig. 12. ΔL_{eq} between situations without and with parked cars in street categories with different urban characteristics

Fig. 12 shows the difference in broadband between calculated sound levels without and with parked vehicles depending on the height of the receivers located on building façade in different streets of Cáceres. First, it can be seen that single-lane streets (f, h and i in Fig. 11 and Fig. 12) presented the greatest shielding effect. This is due to the proximity of the sound source to the parked vehicles, a result congruent with the trend shown in Fig. 3 of Section 3.2.1. However, a single-lane street such as Toledo St. (j in Fig. 11 and Fig. 12) shows a lower degree of shielding. This could be due to its urban configuration. First, the distance between the building façade and the parking lane (d_{FV}) was 1 m, similar to the first configuration shown in Fig. 5. In addition, it was the narrowest street, so that reflections from the opposite façade were more intense and the barrier effect could be smoothed. In the same respect, it only contains one parking lane, which means that the sound field was less disturbed when reflected on the opposite wall.

Another effect shown in Fig. 12 is the reduction of shielding by increasing the number of lanes to two and four, as a consequence of the greater distance between linear sound sources and parked vehicles (same trend as in Fig. 3 of Section 3.2.1). Fig. 12 shows that the behaviour of this group of streets with more than one traffic lane is relatively similar. However, if the figure is analysed in detail, two findings of interest can be seen depending on the height of the receivers. On the one hand, two-lane streets present the most significant screening effect at lower heights (1.5 m) as a result of shorter d_{VS} distance on them. On the other hand, the screening effect is extended to greater heights on four-lane streets, according to the results found in Section 3.2.2. Finally, if a comparison is made between category 1 streets with the same number of lanes, such as U profile Alemania Av. (a in Fig. 11 and Fig. 12) with a higher d_{FV} but with a lower d_{VS} than L profile Hernán Cortés Av. (b in Fig. 11 and Fig. 12), the shielding effects were quite similar but are extended to higher heights in the first one due to a greater distance d_{FV}.

As a result of the analysis carried out, it can be deduced that the differences in the urban characteristics of the streets are those which fundamentally influence the degree of shielding regardless of street category. The number of traffic lanes, the distance between source and vehicle, the distance between façade and vehicle, and the street profile, as already shown in the results of previous sections, are responsible for the differences in this acoustic shielding effect.

In addition, the following aspects must be taken into account considering the acoustic shielding shown by the streets of different categories in Fig. 12. The results at a height of 1.5 m when parked vehicles exist show differences of more than 7 dB with respect to urban situations without parking lanes. The shielding decreases with height, and therefore using these sound values as a reference to calculate the sound exposure at other heights (4 m) involves an error of underestimation. In case of making assessments at 4 m height, the parking lanes generally produce a disturbance in the propagation of the road traffic noise sound field that would imply differences between approximately 1 and 4 dBA. This fact should therefore be considered in single-lane streets.

4. CONCLUSIONS

This paper presents an assessment through computational methods of the influence of vehicles parked on streets in estimating the impact of road traffic noise on population. Different variables related to urban planning and noise modelling were considered to study the acoustic screening effect generated by parking lanes. In order to evaluate this effect in real environments, it was also investigated in some streets of Cáceres (Spain) taking into account the different street functionalities established in the categorisation method.

The following general conclusions are drawn from the results of this study:

- The acoustic screening effect of vehicles parked on the sides of the streets in cities is predicted by the computational model in all cases studied. In most of the urban configurations analysed, it is detected up to heights even higher than the reference height of 4 m used in the strategic maps made in accordance with European Noise Directive.
- If the dependence of the shielding effect with the urban variables is considered, it is generally observed that for a receiver located at all heights between 1.5 and 4 m and higher, the acoustic shielding increased as the distance between the parked vehicles and the sound source (d_{VS}) decreased, just as when the distance between the building façade and these obstacles (d_{FV}) increased.

- Considering modelling variables on streets with multiple traffic lanes, results at the reference height of 1.5 m for the shielding effect showed minor changes when the number of linear sound sources used in the model was varied. However, this effect increased at a height of 4 m or higher when linear sources were closer to parking lanes.
- The previous conclusions were confirmed in real streets in the city of Cáceres. If urban variability was considered by the use of the different categories established according to the categorisation method, the results indicate that attention should be paid if measurements for noise mapping validation are made on streets with parked vehicles for microphone heights of 1.5 m. This aspect should also be considered up to microphone heights of 4 m, especially on single-lane streets.

Considering the applications of these results in connection with strategic noise maps, some conclusions can be reached if the evaluated streets have parking lanes near the building façade:

- The current absence of parking lanes in the strategic maps would imply that in general the models predict an overestimation of the doses received by the population, at least between the reference heights of 1.5 to 4 m. Under a population protection approach, this would not be particularly problematic.
- If in situ measurements at 1.5 m were used as indicators of the reference height of 4 m (corrected for that equivalent height) according to the indications of the European Noise Directive, the noise dose estimates to which the population is exposed would be underestimated.
- The necessary process of validation of the strategic maps by means of measurements carried out at the height of 4 m, recommended in the European Directive, must be done with special care to the presence of parked vehicles because the doses of noise received by citizens on second and upper floors of buildings would be underestimated.

Considering that computational methods used in this work for noise mapping are based on ray-tracing models in accordance with European Directive recommendations, future lines of research based on in situ measurements and numerical computational methods that allow to verify these results in different urban configurations are open.

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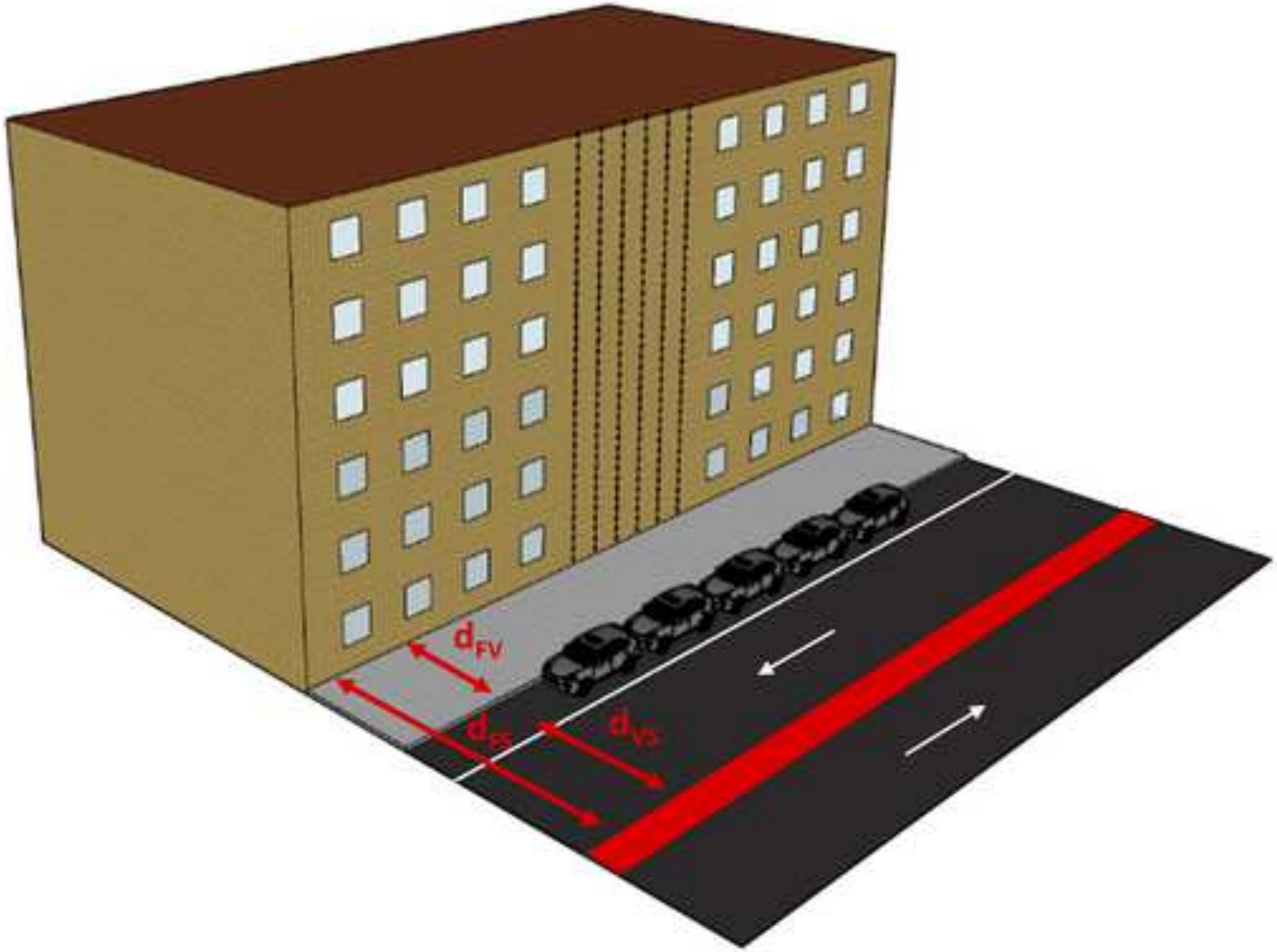

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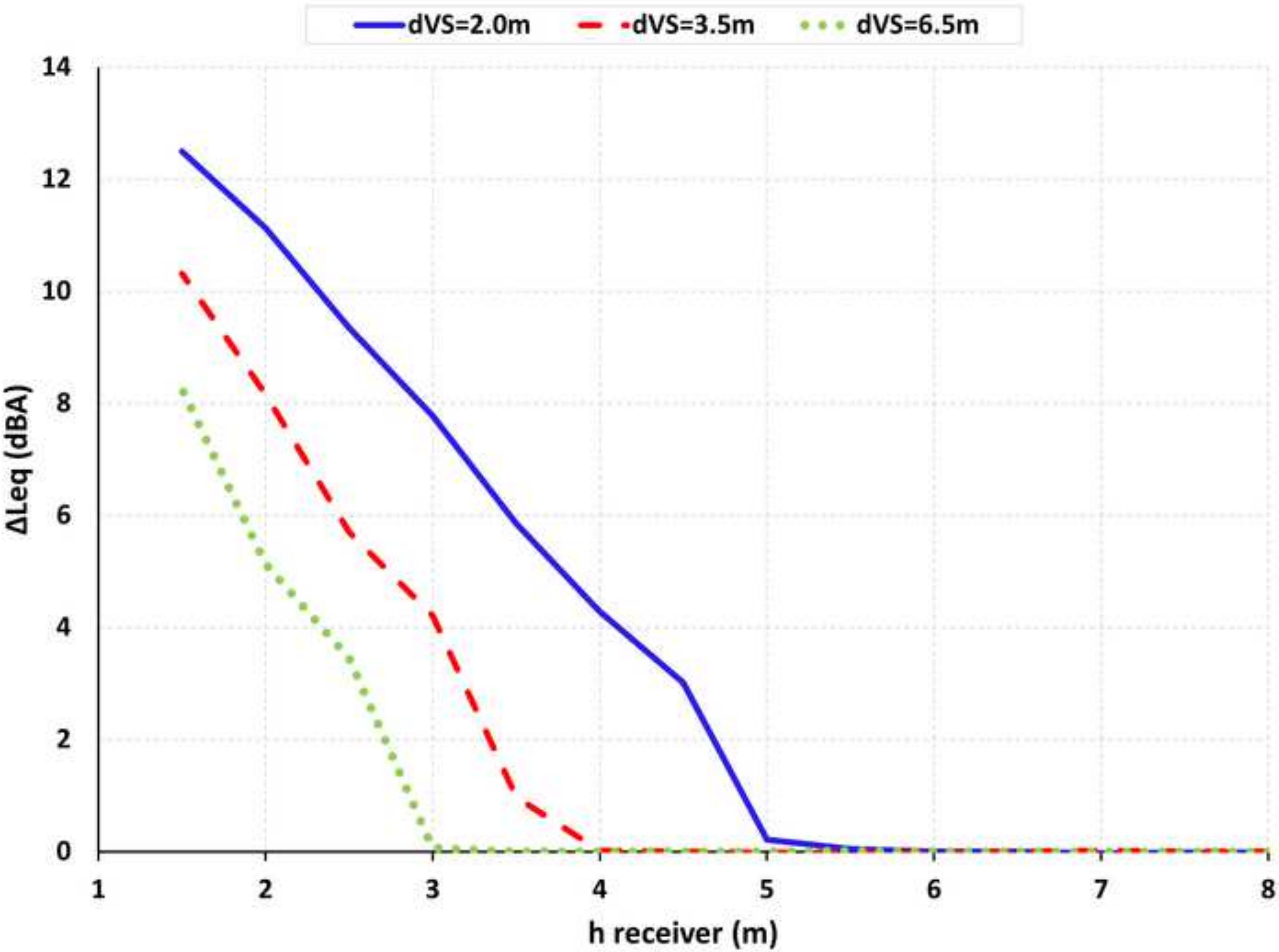

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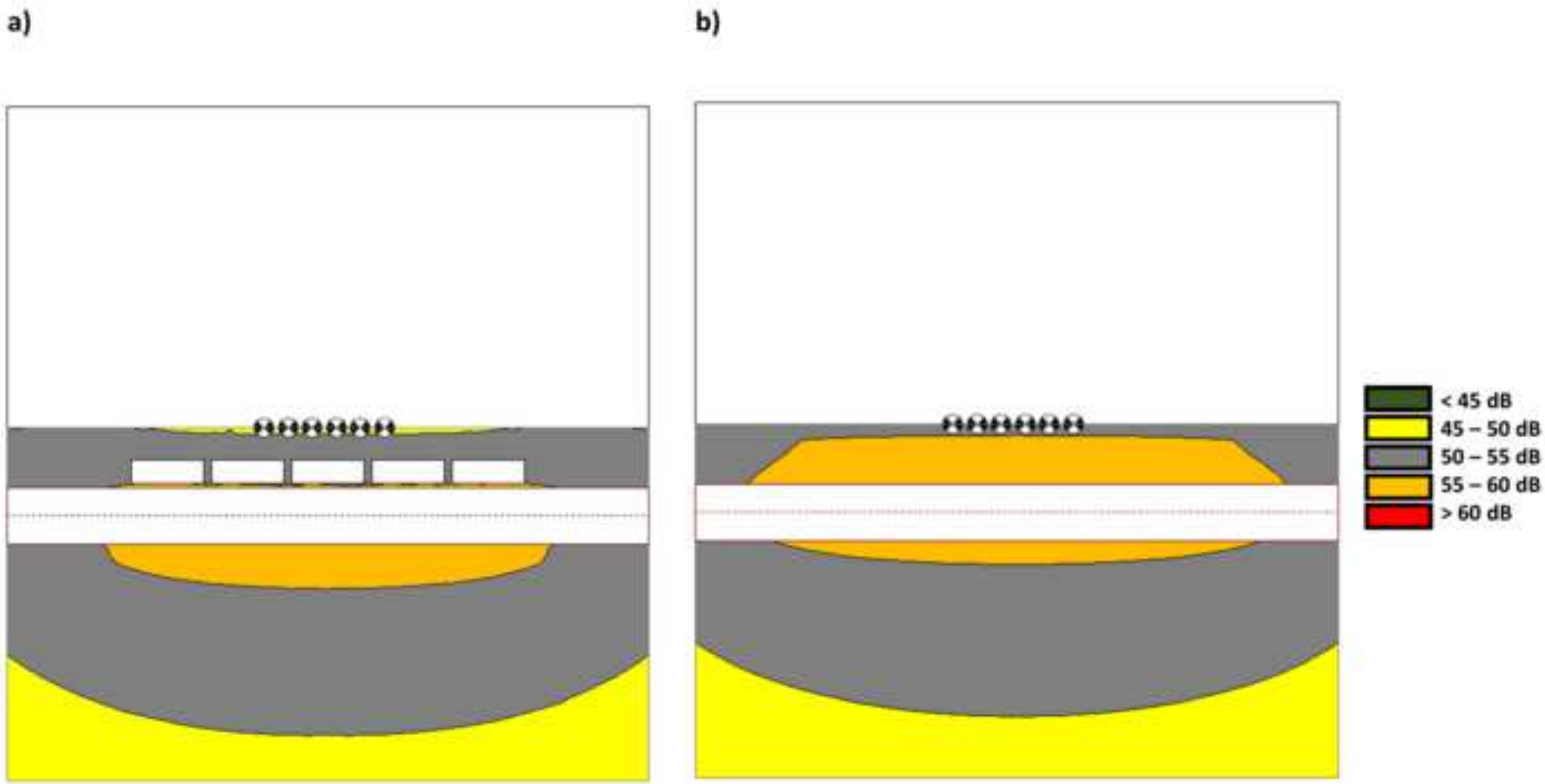

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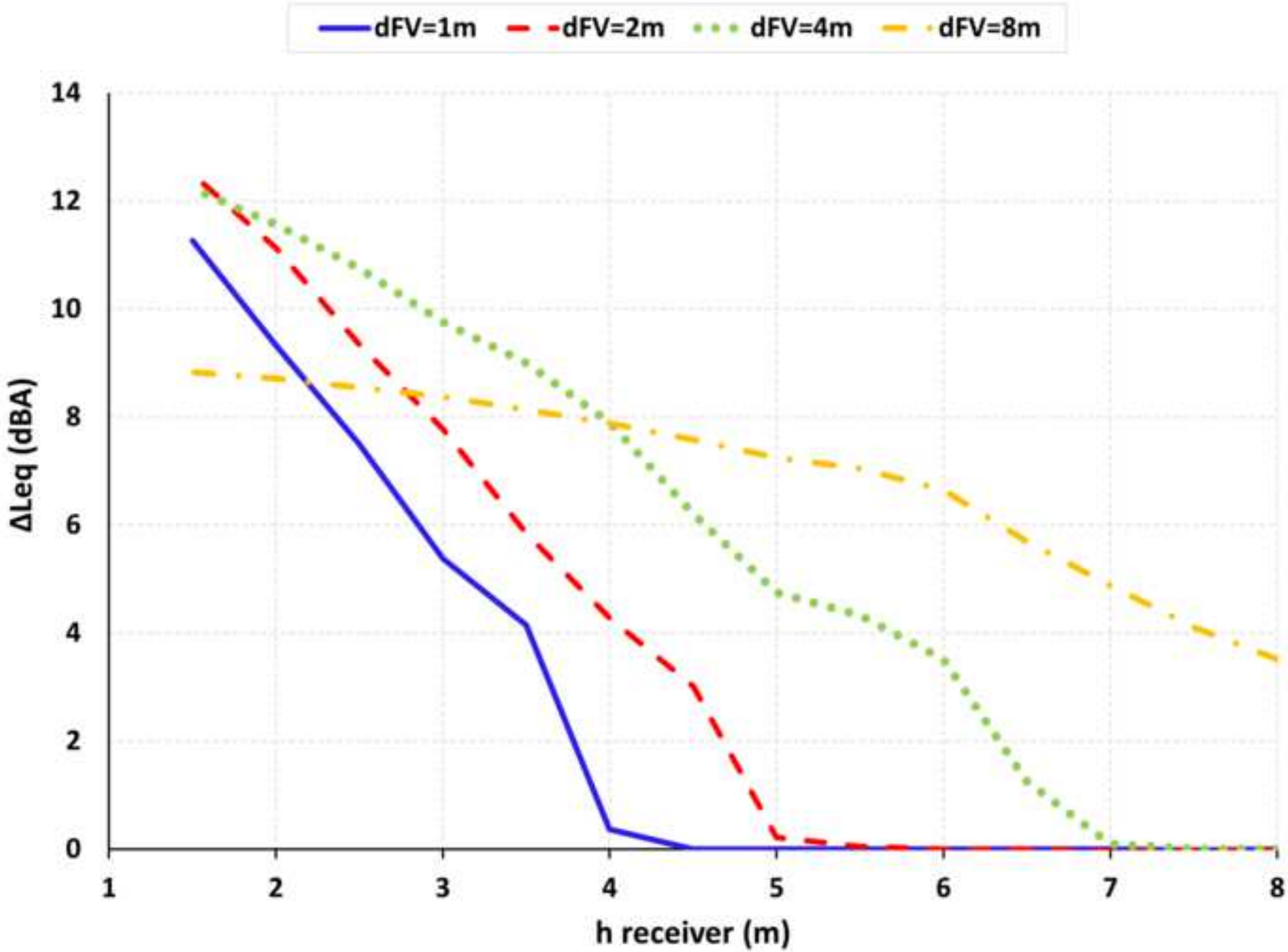

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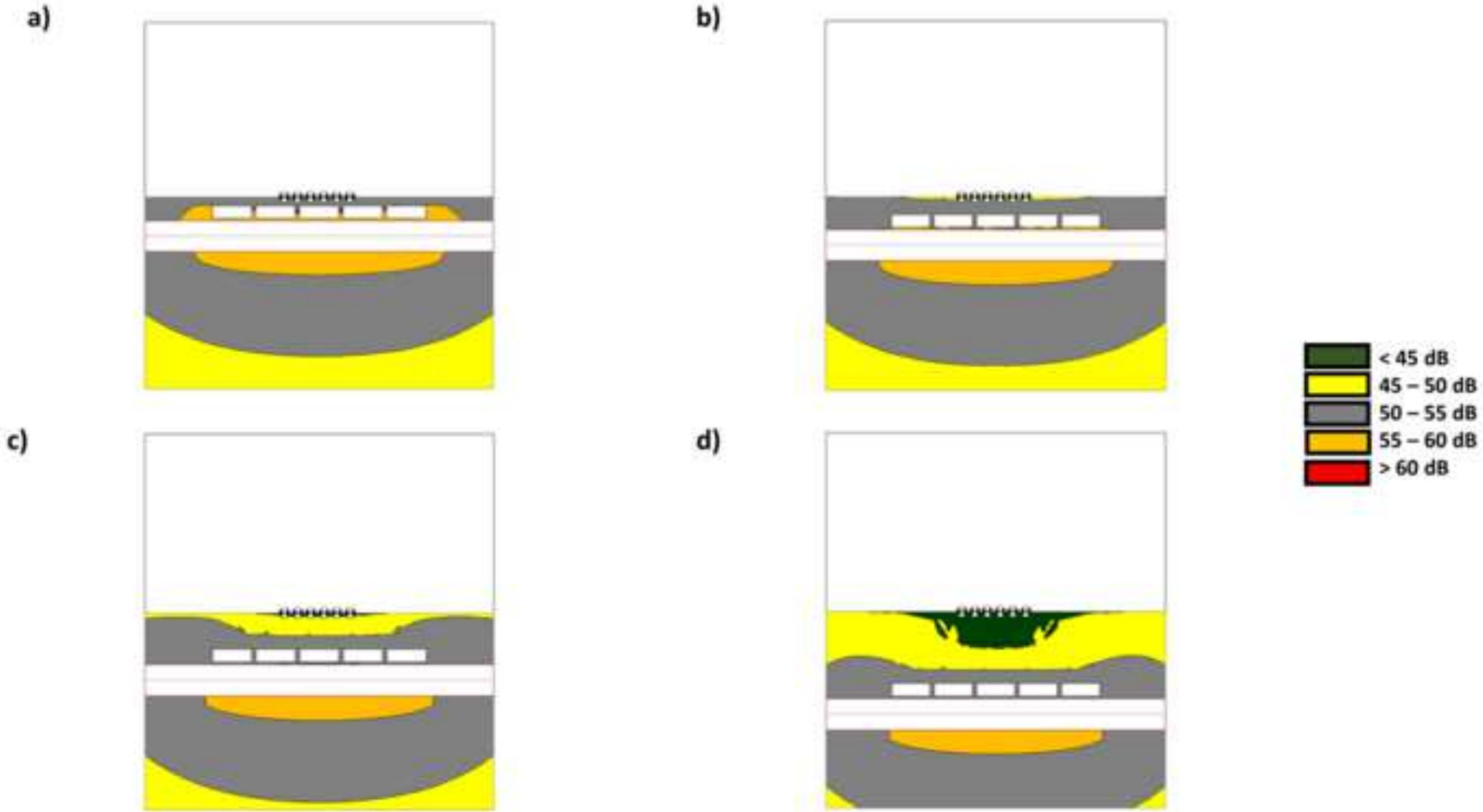

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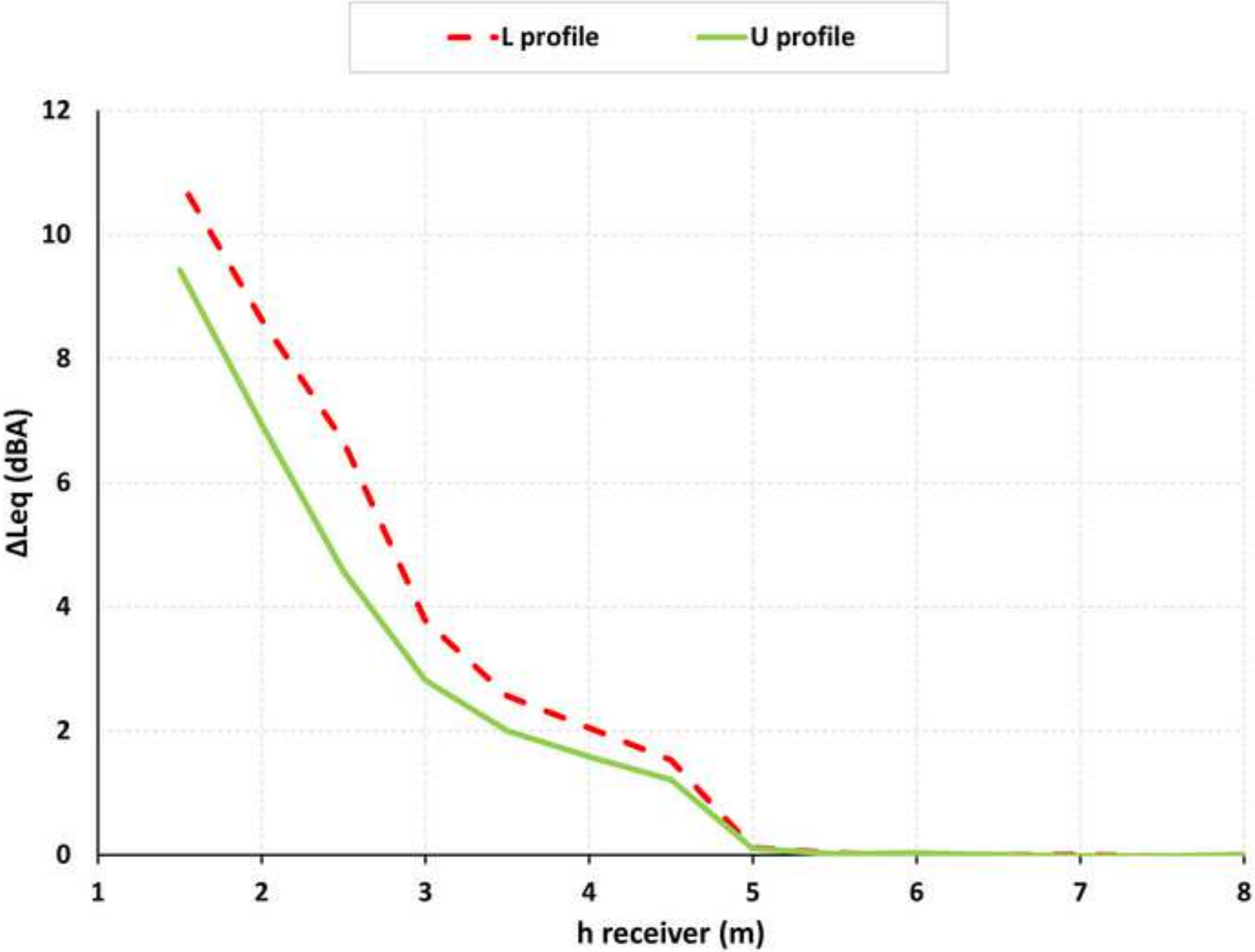

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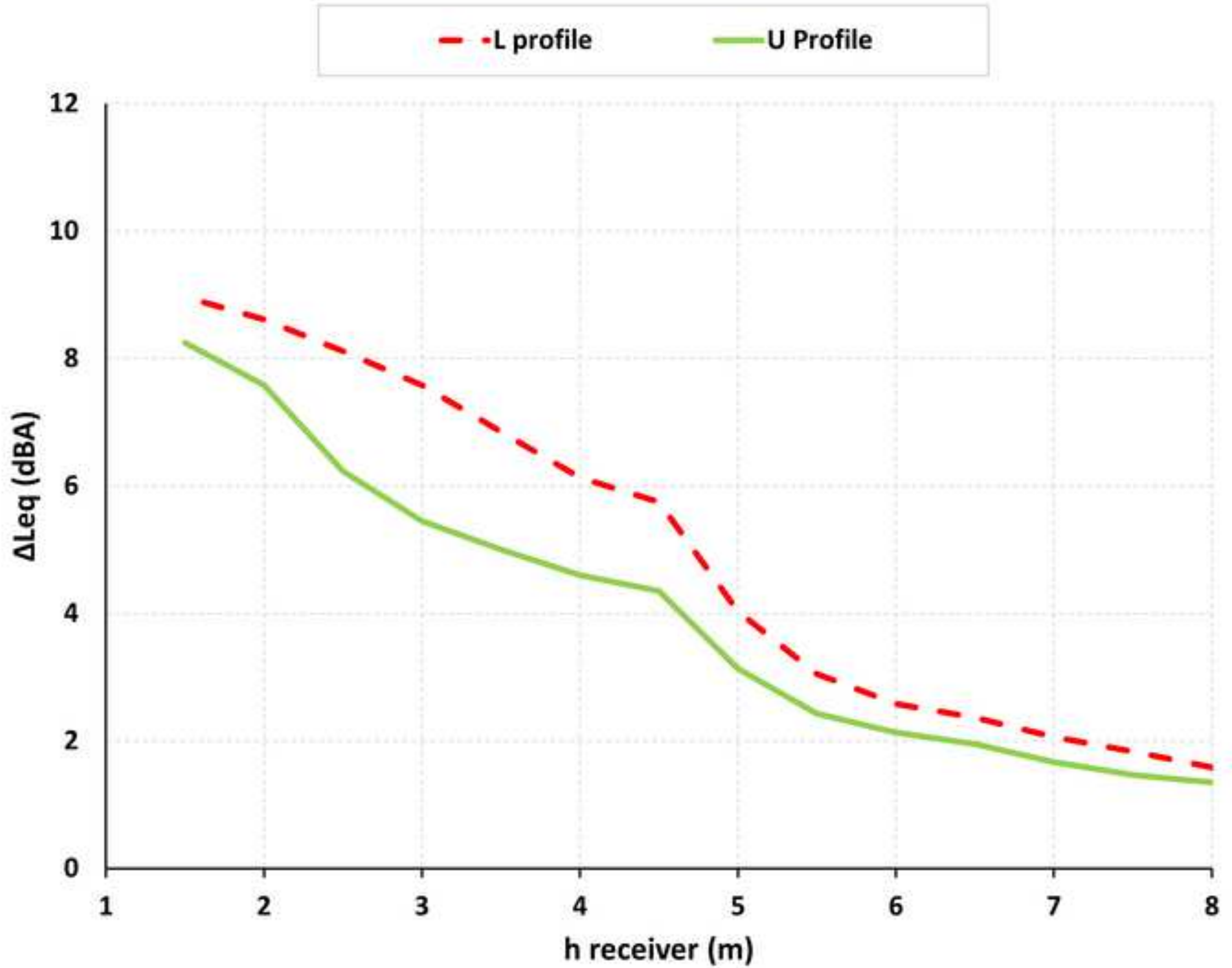

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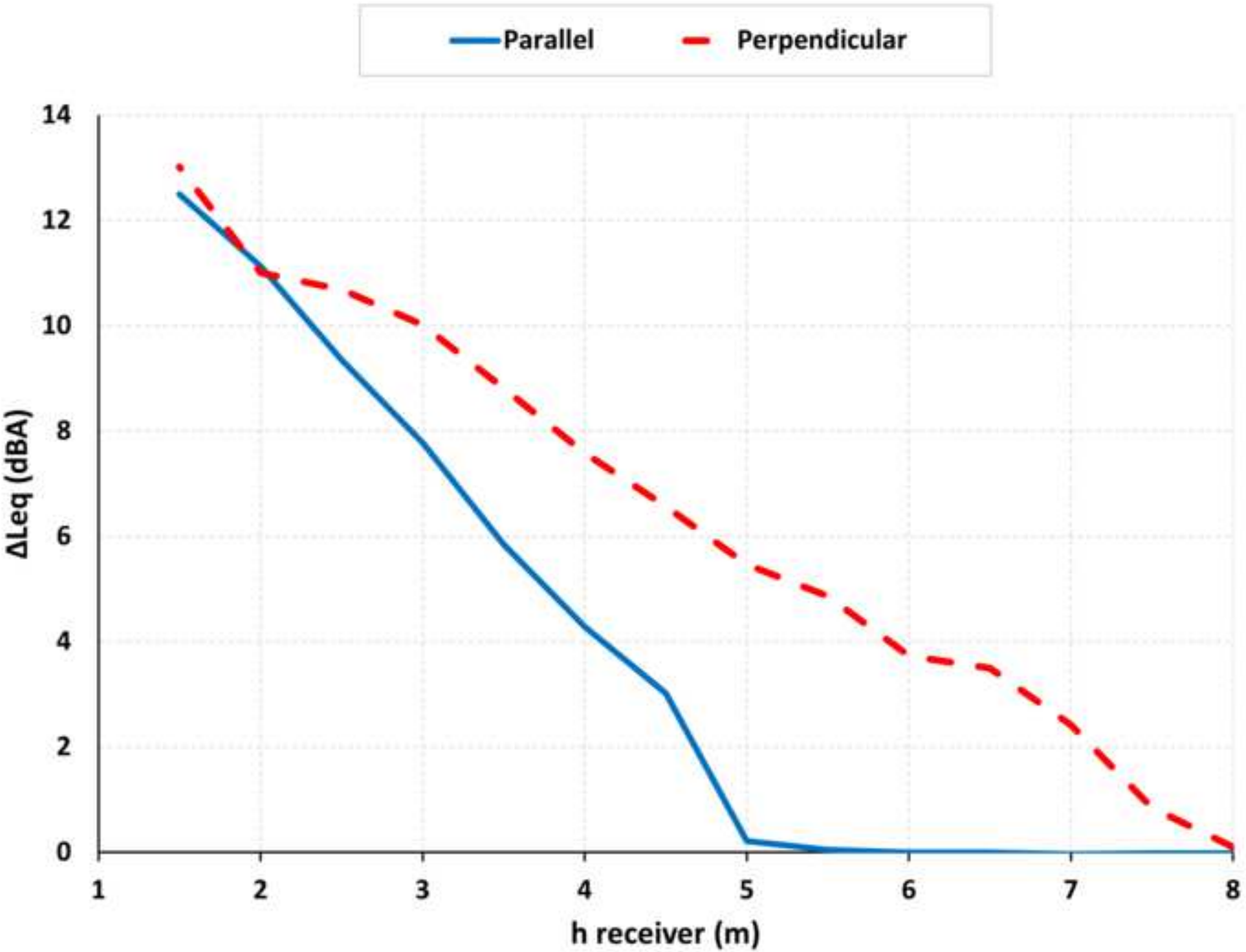

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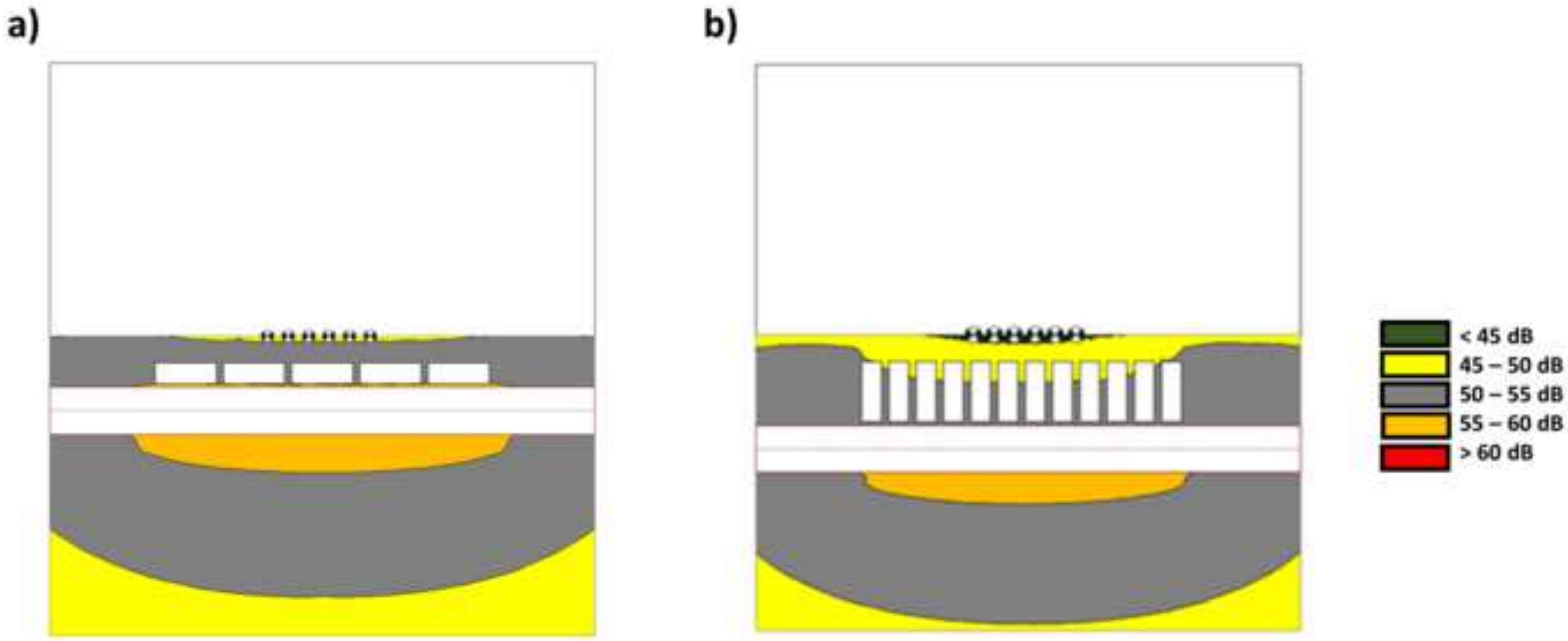

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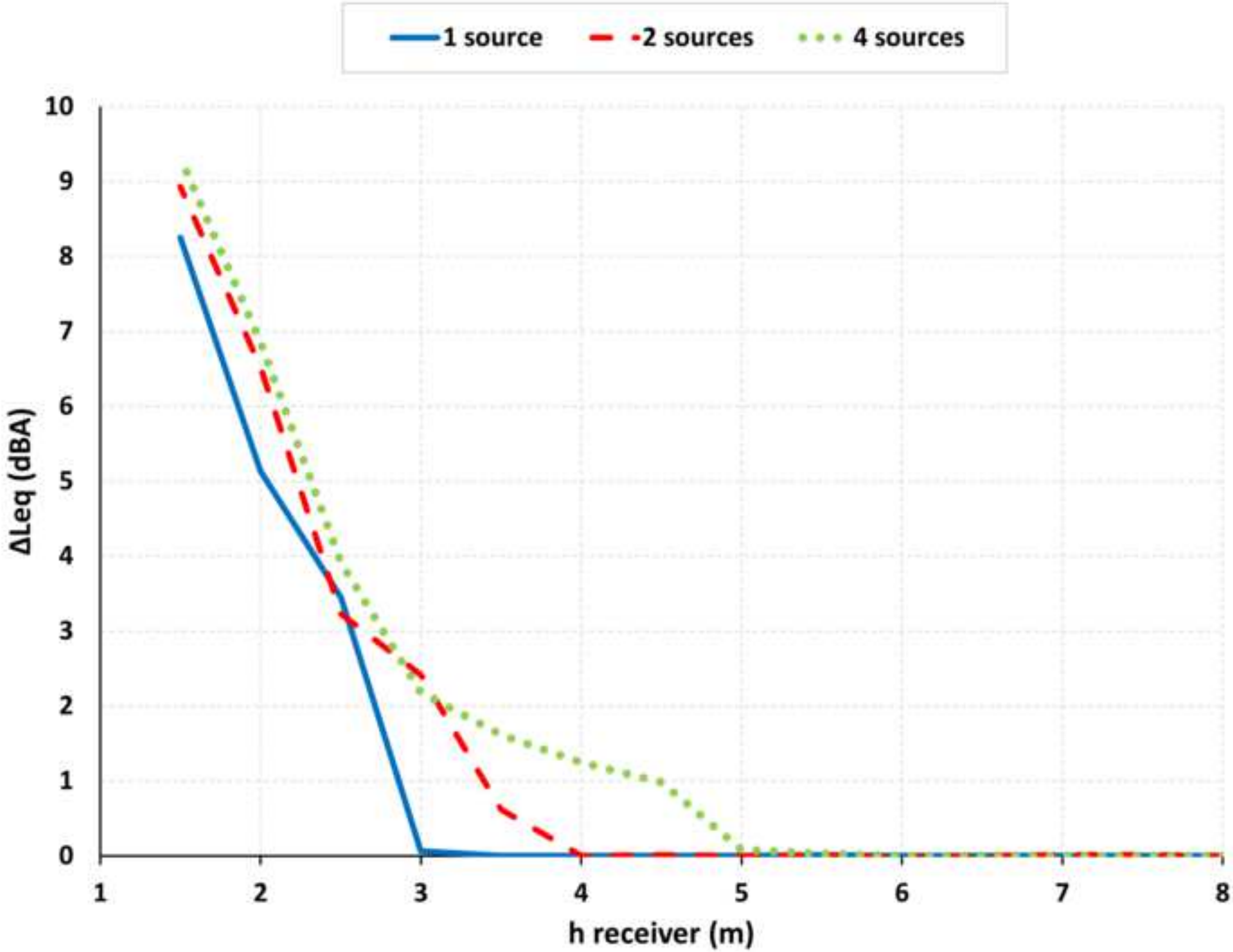

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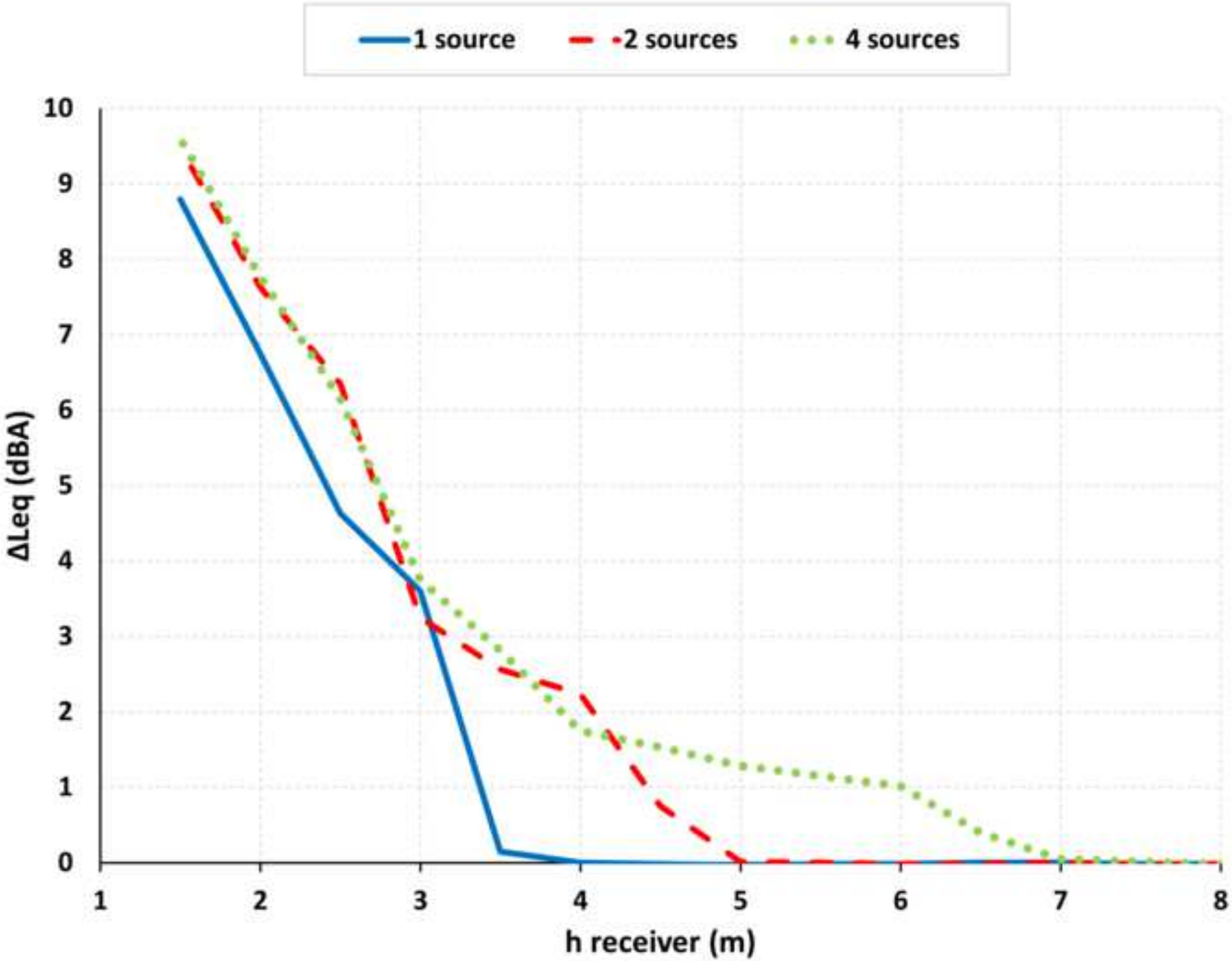
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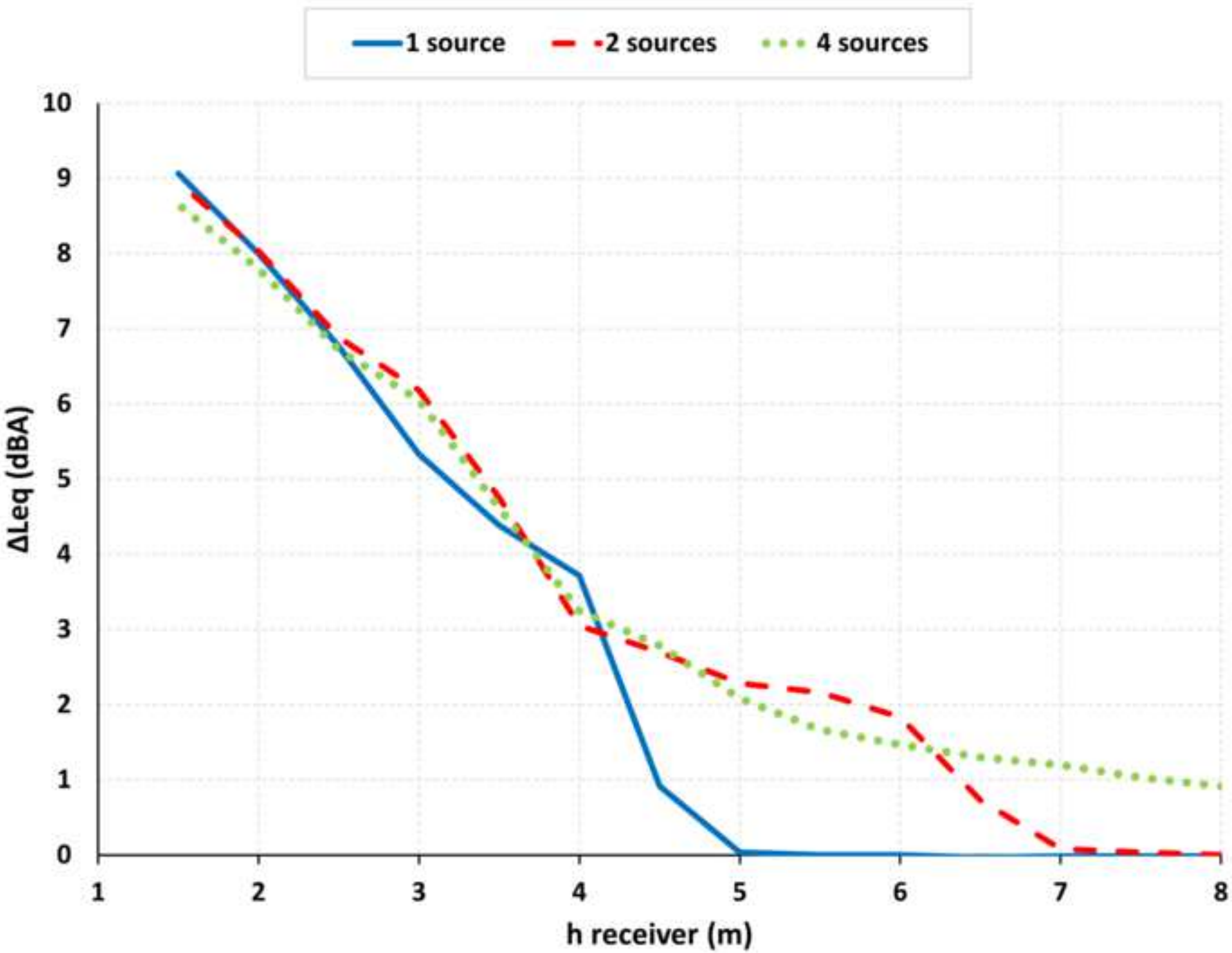
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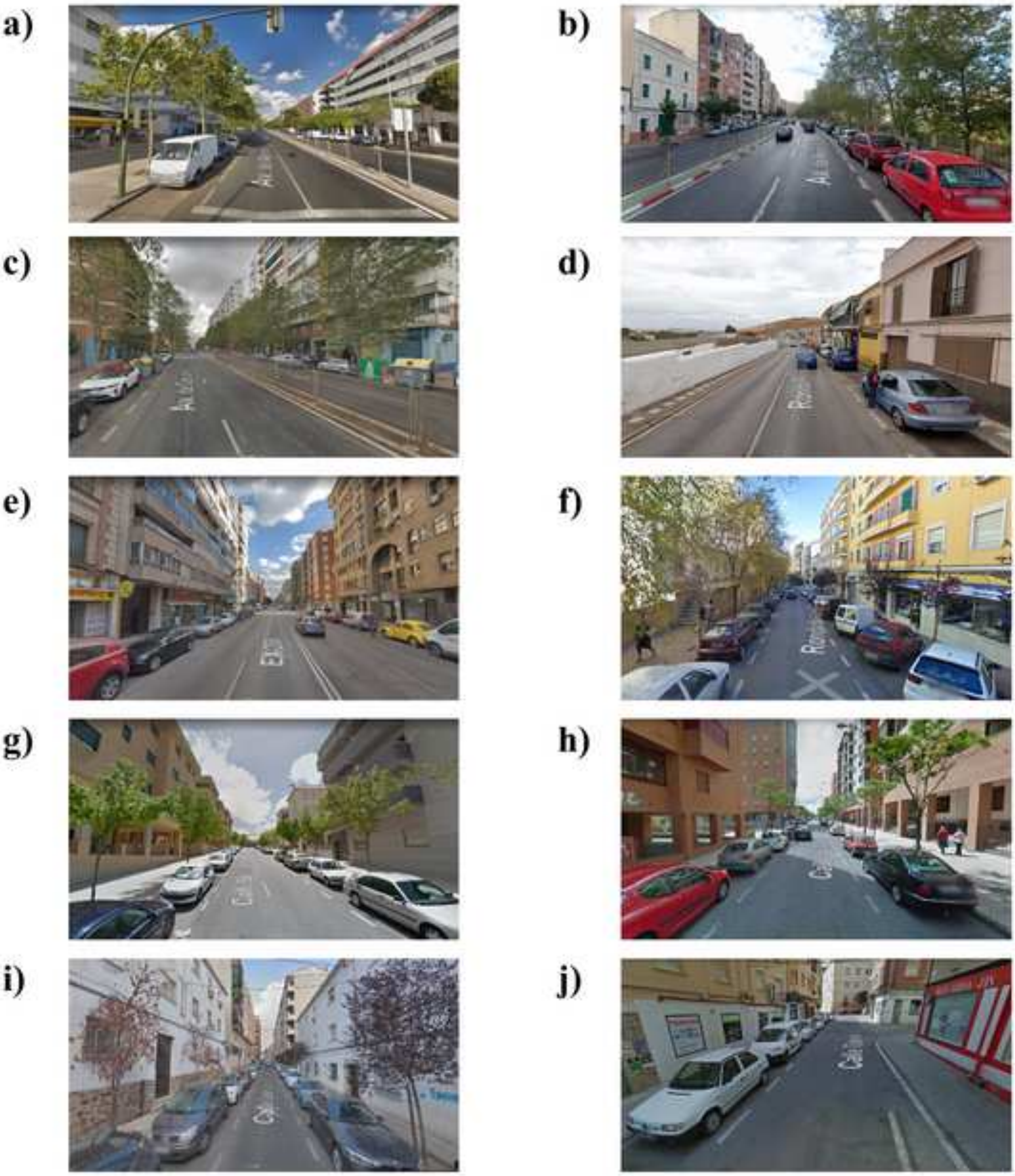

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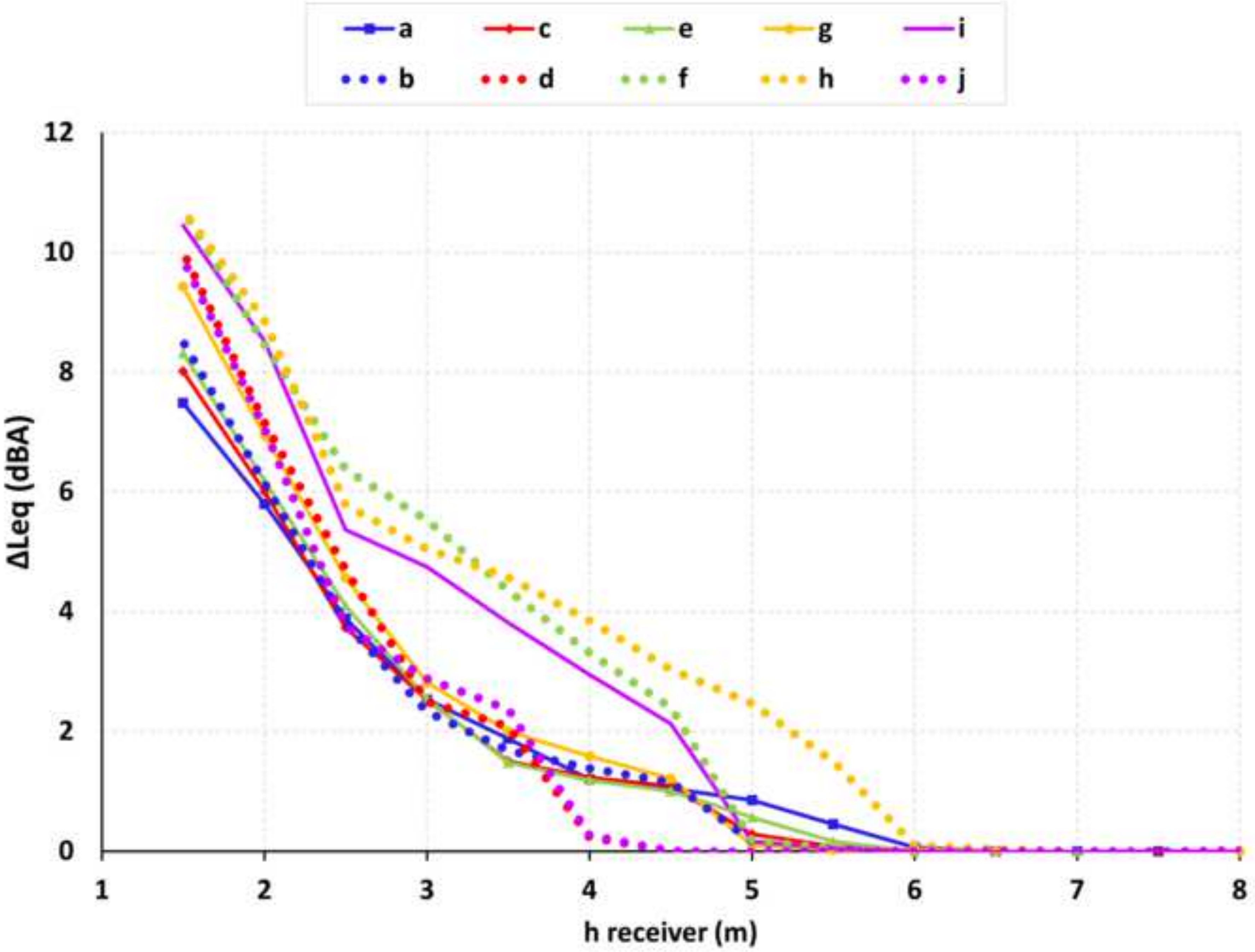

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Credit Author Statement

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David Montes González: Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Funding acquisition. **Juan Miguel Barrigón Morillas**: Conceptualization, Methodology, Validation, Investigation, Resources, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Guillermo Rey Gozalo**: Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision, Funding acquisition. **Luís Godinho:** Investigation, Resources, Writing - Review & Editing, Project administration, Funding acquisition.

***conflict of Interest Statement**

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:
