Noise abatement and traffic safety: The trade-off of quieter engines and pavements on vehicle detection

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Road traffic sounds are a major source of noise pollution in urban areas. But recent developments such as low noise pavements and hybrid/electric engine vehicles cast an optimistic outlook over such an environmental problem. However, it can be argued that engine, tire, and road noise could be relevant sources of information to avoid road traffic conflicts and accidents. In this paper, we analyze the potential trade-offs of traffic-noise abatement approaches in an experimental study, focusing for the first time on the impact and interaction of relevant factors such as pavement type, vehicle type, listener’s age, and background noise, on vehicle detection levels. Results reveal that vehicle and pavement type significantly affect vehicle detection. Age is a significant factor, as both younger and older people exhibit lower detection levels of incoming vehicles. Low noise pavements combined with all-electric and hybrid vehicles might pose a severe threat to the safety of vulnerable road users. All factors interact simultaneously, and vehicle detection is best predicted by the loudness signal-to-noise ratio.

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1. Introduction

Traffic related noise is nowadays the major source of environmental noise in most industrialized nations and developing regions. Its negative impact has been demonstrated at several instances, from health to school efficiency and overall emotional annoyance (e.g., Gorai and Pal, 2006; Passchier-Vermeer and Passchier, 2000; Sanz et al., 1993; Freitas et al., 2012). It is therefore a matter of active concern for traffic-related researchers, public authorities in health and traffic, as well as transportation and road industries, to find quieter alternatives to the major sources of transportation noise. In a near future, we might expect a reduction of road traffic noise both by pavements that are more efficient and because of the growing popularity of hybrid and all-electric vehicles. Therefore, there is an optimistic outlook on health improvement and annoyance reduction due to a quieter road traffic environment, specifically for populations living in urban areas.

However, in urban areas traffic noise could also be a key factor for the awareness of imminent conflicts by vulnerable road users. In other words, road, tire and engine noises might be used as meaningful signals by pedestrians and bicyclists: they can act as attentional triggers, allowing for a better perception of speed and proximity of incoming traffic and for timely reactions to avoid conflicts. Therefore, due to traffic noise abatement, we might face in the near future an increasing trade-off between the improvement of population’s health and the rise of accidents involving vulnerable road users. Such trade-off analysis has never been approached from an experimental perspective.

When compared to internal combustion vehicles, electric/hybrid engine vehicles have higher incidence of crashes involving pedestrians and bicyclists (Garay-Vega et al., 2010; Hanna, 2009). On the one hand road users show substantial interest in driving quiet hybrid or all-electric cars; but on the other hand they are concerned with the reduced conspicuity of such vehicles (Wolgater et al., 2001). Some experimental studies have addressed this issue. Ashmead et al. (2012) analyzed the path identification of electric engine and internal combustion engine vehicles in quiet and noisy environments. They found that in quiet environments there were timely path identifications of the electrical vehicles, but not in noisy ones. They also found that these judgments were based on sound level, the main characteristic that is altered in electric/hybrid cars. Studies with visually impaired populations have also revealed lower vehicle detectability of hybrid and all-electric...
vehicles (Emerson et al., 2010). All these data have contributed to the official recognition by the U.S. National Highway Traffic Safety Administration that electric vehicles in low-speed operation may induce a safety issue for blind pedestrians (Garay-Vega et al., 2010).

Other factors might affect traffic-related noise and hence vehicle conspicuity. In a previous study (Freitas et al., 2012) we have demonstrated that pavement type largely affects the levels of environmental noise and related subjective annoyance. However, the way pavement type affects vehicle detection is still not clear. In addition, age might be regarded as a relevant variable. Young pedestrians are more often involved in accidents than older people are, but while being rare, accidents with older people are the most severe (Martin, 2006). In experimental studies with children, the number of correctly identified vehicle sounds was significantly improved with age (Pfeffer and Barncutt, 1996). Despite the strong evidence of the role of several traffic noise factors on vehicle conspicuity, there has never been a comprehensive study analyzing the main relevant variables (Barton et al., 2012).

In this paper, we present for the first time such an integrated approach to traffic noise variables and related vehicle detection levels. We address the detection of approaching vehicles as a function of pavement, vehicle type, background noise and the age of the listener. Binaural pass-by noise samples were recorded using several combinations of pavement, vehicle and speed. These samples were then edited to create scenarios of approaching vehicles in noisy environments. Under controlled laboratory conditions, participants had to detect the approaching vehicles.

2. Materials and methods

2.1. Participants

Eighty-nine participants were recruited from educational and social institutions (7–86 years old, M = 36.68, SD = 22.12). Split into age groups, 26 participants were juvenile (19 years and below, M = 12.93, SD = 2.31), 27 were early adults (20–39 years old, M = 27.98, SD = 5.33), 19 were middle adults (40–59 years old, M = 50.51, SD = 5.94), and 17 late adults (60 years and above, M = 71.35, SD = 6.96). To exclude prior major hearing deficiency all participants underwent audiometric screening tests at 250, 1000 and 4000 Hz. As major hearing deficiency criterion, late adults all had the 1000 Hz and 4000 Hz thresholds under 40 dB HL. The remaining participants had those thresholds under 30 dB HL. On average, children had as thresholds 14, 10, and 4 dB HL at 250, 1000, and 4000 Hz respectively. At those frequencies, adolescents had 9, 5, and –1 dB HL thresholds; juvenile and early adults had 15, 10, and 9 dB HL; and late adults had 24, 19, and 21 dB HL respectively.

Participants were all volunteers. They were instructed about the general purpose of the study and provided their informed consent about the participation in the tests and the confidential data manipulation. Under-aged participants had the informed consent of their caregivers.

2.2. Stimuli and equipment

The pavement surfaces selected for the tire-noise recordings in this study were: cobble stones, dense asphalt, and open graded asphalt rubber. The vehicles were a small passenger car (petrol, Volkswagen Polo), a hybrid (Toyota Prius), and a pickup truck (diesel, Mitsubishi Strakar). Both the representative sections of the road surfaces and the recording techniques were selected according to the European ISO Standard 11819-1:1997. The controlled pass-by method (CPB) was used, with each single vehicle tire-road noise recorded with speeds of 30, 40 and, 50 km/h.

The tire-road noise was binaurally recorded with a Brüel & Kjær Head and Torso Simulator (HATS) type 4128-C, a Brüel & Kjær Pulse Analyzer type 3560-C and the Pulse CPB Analysis software. The noise samples were recorded with the HATS at 7.5 m from the road centre and at a height of 1.7 m (for methodological details see Freitas et al., 2012).

From each single vehicle recording, sound samples with the duration of 2 s were produced. Sound samples were edited according to a time-to-passage (TTP) criterion. As such, sounds were not presented only by vehicle speed or distance to the listener, but in a combined form that is relevant for the road user. The TTP for all stimuli was fixed to 3.5 s i.e., at the end of the stimulus presentation the vehicle would need 3.5 s to cross the line of sight of the observer. This TTP value is considered the amount of time in which a pedestrian of any age is able to perceive and make an informed decision about crossing a road in safety.

To mask the vehicle signal, five levels of white noise were generated with WavLab 6: −40, −35, −30, −25, and −20 dB, presented through the headphones at 62, 67, 72, 77, and 82 dB (A), respectively. A total of 135 stimuli with signal plus noise were generated with audio software (Ardour): 3 pavements × 3 vehicles × 3 speeds × 5 noise levels.

The stimuli were presented through a computer with a sound card Intel 82801BA-ICH2, a custom built C++ application, and AKG K 271 MKII closed headphones. The C++ application allowed the reproduction of different audio scenes: multiple audio files, stimuli with different number of audio files, configuration of reproduction time, configuration of the visual stimulus that appeared along sound reproduction, setting of the sound pressure for each ear and collecting the participants’ answers. Using the Brüel & Kjær HATS and the Pulse Analyzer referred before, this system was calibrated to achieve sound pressure levels identical to those recorded in the real scenarios. The values of loudness were assessed with the Psysound3 application (Cabrera et al., 2008).

2.3. Procedure

Within each trial, the participant was presented with two consecutive sound samples, with a fixed gap of 1 s, one with the signal plus noise and the other with only noise. Both noise backgrounds of each trial had the same level of white noise. The 135 trials were presented in a pseudo-random order (method of constant stimulus). Participants were requested to detect in which of the intervals, i.e., first or second sample, was the approaching vehicle (two-interval forced choice, 2IFC). To avoid biased answers from participants the left-right orientation of the approaching vehicle and the order of intervals were randomized across the 135 trials. Each trial started only after an answer was given to the previous trial, and no time limits were imposed. Therefore, experiments did not have a fixed duration.

3. Results

3.1. Pavement, vehicle and noise levels

A preliminary analysis of the data, after computing detection thresholds per participant, revealed clear differences as a function of age. The global mean detection was of 80.51% and the standard error (SE) of 1.09. The results across age groups were: for juvenile a mean of 78.27% (SE = 2.07); for early adults 87.93% (SE = 1.34); for middle adults 79.84% (SE = 1.90); and late adults 72.88% (SE = 2.33). These results did differ significantly in a one way ANOVA ($F_2 = 10.95, p < 0.001$). In a post-hoc Sheffé test, it was found that the early and middle adults did not differ significantly ($F = 0.05, n.s.$), and neither did the juvenile differ from the late.
adults ($F = 1.2$, n.s.), but all other age group comparisons remained significantly different. Therefore, average results only represent an overall tendency, and they should be interpreted separately by group age. As such, the following analyses of detection thresholds per pavement, vehicle, and noise are based first on the overall data and then on age group aggregated values.

The analyses of vehicle detection as a function of the main variables (pavement, vehicle type, and background noise) revealed clear trends as depicted in Fig. 1. Detection percentages increase from the open asphalt rubber pavement ($M = 71.87$ SE = 1.25) to the dense asphalt ($M = 76.79$, SE = 1.25) and cobble stones ($M = 92.99$, SE = 1.16). Differences in vehicle detection per pavement type were significant across all age groups in a two-way ANOVA for repeated measures ($F_{2,3} = 99.84$, $p < 0.001$).

Values as a function of vehicle type show a smoother but still consistent trend from the hybrid ($M = 78.72$, SE = 1.18) to the small passenger car ($M = 80.22$, SE = 1.17) and pickup truck ($M = 82.56$, SE = 1.17). We found a significant interaction between vehicle type and detection across age groups ($F_{3,2} = 14.74$, $p < 0.001$), and an overall significant difference in detection level across vehicles ($F_2 = 3.37$, $p < 0.05$), but post-hoc mean testing revealed that only the hybrid and pickup truck reached a significant difference ($F = 2.32$, $p < 0.05$).

For background noise, detection percentages were above a threshold of 75% for the lowest three levels of 62, 67 and 72 $L_{Aeq}$ (dB A), with mean values of 91.48 (SE = 1.24), 88.01 (SE = 1.38) and 83.09 (SE = 1.42), respectively. Mean detection was close to the threshold for the noise level of 77 ($M = 74.44$, SE = 1.34) and below it for higher noise level of 82 ($M = 65.72$, SE = 1.04).

Detection as a function of age showed similar trends as the global ones described above but with clear differences across groups (see Figs. 2–4). An inverted U pattern of results is evident, with participants from 20 to 39 years old reaching detection percentages above 75% for all but the noisiest background ($M = 72.04$,

**Fig. 1.** Mean detection percentages and SE for pavement, vehicle and noise ($n = 89$).

**Fig. 2.** Mean detection percentages and SE for pavements and age groups.
Participants of 60 years old and above did not reach a mean 75% threshold in several conditions, and in some cases, they performed close to random. For the pavements of open asphalt rubber and dense asphalt, the mean values were of 62.41 (SE = 2.65) and 67.94 (SE = 2.20), respectively. Detection means were of 69.65 (SE = 2.57) for the hybrid and of 73.18 (SE = 2.68) for the small car. Impairment of late adults was also clear for the highest background noise levels of 72, 77 and 82 dB(A), with mean detection values of 74.47 (SE = 2.95), 67.29 (3.11) and 57.53 (2.22), respectively.

Younger participants (7–19 years old) performed slightly better than the oldest listeners, but clearly worse than early adults. In addition, the detection ratios of juvenile participants were similar or lower than those of middle-aged adults (40–59 years old). For the pavements of open asphalt rubber and dense asphalt, the juvenile mean values were of 69.85 (SE = 1.98) and 75.23 (SE = 2.20), respectively. Detection was barely above the threshold for the hybrid vehicle (M = 76.38, SE = 1.86). For the highest noise levels of 77 and 82 dB(A), detection was below threshold with mean values of 72.77 (SE = 2.14) and 63.65 (SE = 1.77), respectively.

As a complementary analysis, we selected some case scenarios. We compared a foreseeable combination of low noise pavements with hybrid cars against traditional pavements with conventional passenger cars. In the first case, the impairment of vehicle detection is even clearer (Fig. 5). The overall mean detection in the sample is of 69.60 (SE = 1.64) for the hybrid/open asphalt rubber condition with only the age group of 20–39 years old being able to reach a suprathreshold of 79.48 (SE = 2.36). Older participants reached the lowest mean detection percentage of 58.41 (SE = 3.17) in that condition and they were still below threshold for the ordinary vehicles – dense asphalt scenario with a percentage of only 70.76 (SE = 2.55) of correct detections.

The combination of pavement and vehicle types seems to have an interactive effect on detection performance, which is consistent across age groups. Considering the overall data from the sample, the detection decreases 4.95% and 21.15% from dense asphalt and cobble stones to the open asphalt rubber pavement, respectively. The mean decrease is of 2.67% from the internal combustion engine vehicles to the hybrid. In the extreme scenarios, the detection of the approaching vehicles decreases 8.55% from ordinary vehicles/dense asphalt to ordinary vehicles/cobble stones. The highest difference is found when comparing hybrid vehicles/open asphalt rubber with ordinary vehicles/cobble stones, with a 23.5% of decrease in detection.

Older adults of 60 years old and above are the most impaired in these extreme scenarios with detection differences of 12.35% and 29.88%. These results point to a somehow additive effect where noisier vehicles add up to noisier pavements and interact with the listeners’ auditory accuracy.

To analyze this interactive effect, we addressed the detection of incoming traffic in light of a signal-to-noise perspective. We focused on the ratio between the actual traffic signal and the background noise, aiming to find the relation between this ratio and vehicle detection.
A systematic preliminary analysis compared several equations to compute the signal-to-noise ratio (SNR), namely: SNR = S/N, SNR = S – N, SNR = fS/N, and SNR = fS – N, where S stands for signal, fS stands for final signal (last 250 ms of the stimulus), and N stands for noise. All these analyses were performed both for the median and for the maximum values of the sound samples. From all acoustic measures, the best detection prediction was obtained by SNR = fS/N. Both median and maximum values yielded similar results.

Comparing all acoustic indicators, we found that the best measure was loudness, when compared to $L_{Aeq}$ and $L_{Amax}$. There were no interactions with Sharpness or with Roughness indicators. The scatter plot of all loudness SNRs against detection accuracy levels is presented in Fig. 6.

Several data fitting methods were tested to predict how both the SNR and the detection levels interact, namely linear, polynomial and logistic fits. The best correlation was obtained with a logistic fit ($r^2 = 0.77, p < 0.001$), despite significant correlations with the polynomial and linear fits ($r^2 = 0.34$ and $r^2 = 0.67$, respectively).

Fig. 5. Overall and age groups mean detection percentages and SE for selected scenarios.

Fig. 6. The signal-to-noise ratio [dB (A)] against detection levels and logistic fit.

Fig. 7. The signal-to-noise ratio against detection levels, separating the vehicle variable.

Fig. 8. The signal-to-noise ratio against detection levels, separating the pavement variable.
$L_{eq}$ SNR did not reach statistically significant fits, while $L_{eq,max}$ SNR only correlated marginally with detection (linear fit: $r^2 = 0.32$; polynomial fit: $r^2 = 0.37$; logistic fit: $r^2 = 0.38$).

To analyze how pavement and vehicle type affected the SNR detection values, we plotted each variable separately (see Figs. 7 and 8). As observed in Fig. 7, vehicle type is well distributed across the plot. There is, however, a clear distinguished pavement pattern, as seen in Fig. 8.

Curve fitting for each separate pavement variable was performed. We found a significant linear correlation between the open asphalt rubber pavement ($r^2 = 0.79, p < 0.001$) and the dense asphalt ($r^2 = 0.75, p < 0.001$), but not for the cobble stones ($r^2 = 0.22$, n.s.). It was the logistic fit that provided the best result prediction for each variable, as seen in Fig. 8, open asphalt rubber obtaining a correlation of $r^2 = 0.86$ ($p < 0.001$) and dense asphalt of $r^2 = 0.83$ ($p < 0.001$). Again, there was no significant interaction between the cobble stones pavement and the detection levels with the logistic fitting procedure. This result highlights the specific properties each pavement type and suggests that each variable should be analyzed separately.

4. Discussion

Our results clearly show a negative impact of traffic noise abatement on the detection of approaching vehicles. Detection is significantly lowered by low noise pavements and quieter vehicles. Interestingly, pavement type had a stronger effect than vehicle type on the detection levels. This might reveal that tire-road noise is a more relevant cue for vehicle detection than engine noise, namely at lower traffic velocities such as those used in this study. The analysis of this finding may become very complex since tire-road noise at low speeds is influenced not only by the type of road surface but also by tire characteristics such as pattern and wear. In this study, the tires of the hybrid vehicle were nearly new, therefore less noisy, while the tires of the other vehicles were worn. In this way the effect of the vehicle type was clearly differentiated.

This finding should be taken into consideration in future studies on traffic noise abatement. Indeed, there is barely any research related to pavement type and specifically low noise pavements, when compared to the high data volume on vehicle engines. Our data strongly suggest that different asphalt mixtures will contribute differently to traffic conspicuity and vulnerable road users’ safety. Furthermore, a novel approach to tire effect on detection should be carried out.

Also, age is a critical factor. Younger and particularly older participants are the most impaired. The worse detectability levels in older listeners most likely reflect the typical hearing loss associated with age. On the other hand, the decreased detectability in younger groups is congruent with data pointing out that as they grow older, children increase their accuracy in vehicle identification (Pfeffer and Barnewalt, 1996).

Not only the variables revealed direct and separate effects on the vehicle detectability, but they also showed interactive effects. This fact points out to the need for comprehensive approaches that account for subject’s age (or listening abilities), vehicle and pavement type, as well as background noise. These interactions might be regarded as a result of loudness additivity. Noisier cars and pavements should be more accurately identified by better listening groups. Loudness signal-to-noise ratio did indeed reveal some predictability, but it did not account for all variables. Cobble stones traffic sounds remain highly detected despite varying loudness levels, probably due to their spectral or rhythmical patterns. Nevertheless, the finding that loudness is the best acoustic measure to predict vehicle detection, against $L_{eq}$ and $L_{eq,max}$, is consistent with our previous results, pointing to loudness as the best predictor of traffic-noise annoyance (Freitas et al., 2012), and brings further support to the claim that environmental noise assessment should have this measure as a standard.

One major concern standing out from this study relies on some age groups (younger and older participants) performing below a threshold of 75%, or even close to random, in several traffic scenarios.

In the real world, the detection performance is likely to be even worse. On the one hand, we used a standard white noise background, while in everyday situations road traffic contributes heavily to the noise environment, thus reducing the conspicuity of the sound envelope of each vehicle. On the other hand, in our experiments, participants only had to detect one approaching vehicle at a time instead of simultaneously facing several targets, which would be the case in common urban scenarios.

Moreover, transition periods between vehicle or pavement type are potentially very difficult and risky. Vulnerable road users will inevitably have to cope with a growing mix of vehicles and pavements, with varying degrees of conspicuity. In such a transition scenario, hybrid and all-electric vehicles, circulating on low noise pavements, might prove quite difficult to detect. Therefore, a trade-off between a more pleasant and healthy urban road environment and an increase of traffic conflicts and accidents involving pedestrians and bicyclists should be a matter of concern. In the next section we approach this matter from the decision-maker point of view.

5. Trade-off analysis

From the data here presented a new debate should start on noise, urban design and traffic policy to account for the benefits and dangers of traffic sounds. Here we present an analysis of this trade-off accounting for the vehicle detection levels above discussed and overall traffic annoyance levels found in another paper (Freitas et al., 2012).

The critical factors to consider in the decision making process are: pedestrians’ age, vehicle type, pavement type, environmental noise and traffic speed.

i. Pedestrians’ age: Age is a critical factor in vehicle auditory detection, but not in traffic sound annoyance ratings. Therefore, vulnerable road users, such as children and older adults, detect less efficiently vehicles in noisy environments, but they are still as affected by noise as other age groups. On the other hand, using age as a criterion for traffic noise management would be difficult in practice. Planning urban design by finding the most frequent target users would require surveys or population studies, which would not be feasible in most cases. The simple solution of introducing elements that create loud sounds (such as cobble stone pavements) at obvious sites such as around schools is also to be avoided, as traffic noise significantly affects children learning (Sanz et al., 1993). From this data, it stands out that specifically addressing these road users by introducing loud elements is not the best approach, as the annoyance trade-off would emerge.

ii. Vehicle type: Vehicle type affects both detection levels and annoyance ratings in a symmetrical way. Louder engines are more detected and more annoying, while quieter engines are less detected and less annoying. Therefore, from the trade-off point of view, there is no optimal solution regarding vehicle type. Some solutions have been pointed out, such as introducing sound in quieter vehicles, but such solutions would reintroduce some environmental noise, with unpredictable psychological reactions. While these solutions are still under debate, and are therefore of difficult application and analysis, other approaches should be sought.

iii. Pavement type: Interestingly, this factor is more crucial than vehicle type in lower speed traffic environments, such as those
where pedestrians might be involved. Cobble stone pavements are significantly more annoying than other pavement types. They also provide the best detectability levels, being always above 85% on average. Dense asphalt yields greater detectability than asphalt rubber, while not being significantly more annoying. As such, cobble stone pavements are an efficient measure to ensure that even in worst traffic/environment combinations road users will detect incoming vehicles. On the other hand, when no specific traffic safety concern exists, dense asphalt pavements should be preferred due to their higher detectability with no annoyance trade-off.

iv. Environmental noise: This critical factor influences both annoyance and vehicle detection and it is affected by pavement, speed, and vehicle type. Average detectability results reveal that with environmental noise at 77 dB (A) detections are close to 75% threshold. Louder environments will be below threshold, and therefore more dangerous. More silent environments will be safer in general. As such, environmental noise should be taken as a decision criterion. Louder environments should have cobble stone pavements; and silent environments (under 77 dB A) should have asphalt pavements. As such, in silent environments, annoyance would be prevented while preserving safety. In loud environments, safety would come first.

v. Traffic speed: This factor was not considered in this study, as it interacts with the other elements, such as vehicle distance. Faster vehicles will generate more noise, and therefore better identified, but they will become more dangerous. The opposite is observed with slower vehicles. But velocity strongly affects annoyance ratings. Both dense asphalt and asphalt rubber become more annoying with higher traffic speed, but even at 70 km/h they will not be as annoying as a cobble stone pavement at only 30 km/h. Cobble stone pavements also become more annoying with higher speed, achieving 80% of annoyance at 50 km/h. Taking such data into account, lower traffic speeds should always be promoted, namely in residential and work areas. Also, lower traffic speeds should be enforced in all cobble stone pavement areas.

In conclusion, from our trade-off analysis, we propose a simple decision model for urban designers. Environmental noise should always be assessed at the planning phase. If under 77 dB A, asphalt pavements are preferred. If higher, cobble stone pavements will better promote traffic safety, but additional measures to control traffic speed should be envisaged. Naturally, most environmental noise is indeed influenced by traffic noise namely in urban areas. Therefore, this decision model should be carefully considered, accounting for the predicted environmental noise after urban and traffic changes. Additional studies should test and validate our assumptions, and other potentially relevant parameters should be addressed.

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