Directionalization and Classification of Motorized Vehicles using a Smartphone

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***Abstract*—The dramatic increase of smartphones over the past decade causes a rise of people using their smartphones in traffic. People distracted by their smartphone could cause dangerous situations. Besides distraction, smartphones could also be an advantage in traffic. We propose a method to determine the direction and type of surrounding motorized vehicles by using the two microphones present in most modern smartphones. This enables the smartphone user, a pedestrian or user of a non-motorized vehicle, to be warned of surrounding motorized vehicles. Studies on algorithms to localize the sound of speech and motorized traffic have been done. However, these studies focus on static systems using non-moving microphones. Using a smartphone to determine the direction and type of motorized vehicle by its sound may improve the safety of the smartphone user in traffic. In this study, four experiments were conducted in a controlled environment where a smartphone recorded the sound of passing motorized vehicles. These recordings were analyzed with an algorithm to determine direction and vehicle type. Using cross-correlations of two microphone signals, the time delay and thus the angle to the sound source can be found. Classification of the type of motorized vehicle was performed by cross-correlating the recordings with pre-recorded samples. Marks were placed on the road to provide ground proof. Video analysis validated the results of the algorithm with ground proof. Results showed a directionalization deviation of the average angle from the ground proof angle between 1.20 and 13.94 degrees for a stationary smartphone. Classification accuracy ranged from 88.08 to 100 percent with the exception of the scooter at 50 km/h, where the accuracy dropped to 8.6 percent. Finally, a smartphone application containing this algorithm showed a directionalization deviation of the average angle from the ground proof angle between 0.89 and 17.11 degrees, when used while riding a bicycle. Classification accuracy ranged from 73.27 to 95.10 percent.**

***Index Terms*—Directionalization, Classification, Microphone, Smartphone, Road Safety.**

I. Introduction

Road safety is an important topic. The number of fatal traffic accidents in the Netherlands has decreased over the past decade [1]. On the other hand, in this same decade the amount of smartphones has dramatically increased [2]. In the Netherlands, 81 percent of people between the age of 18 and 80 years old own a smartphone [2]. Study [3] showed that 89 percent of motorists use their smartphone while driving. The exact number of accidents due to the use of smartphones is unknown, since it is difficult to determine whether the smartphone was the direct cause of the accident [4]. However, smartphones are a major cause of distraction in traffic [4]. Distraction contributes to 23 percent of accidents involving passenger cars [5]. This study focuses on turning the smartphone into a benefit rather than a risk in traffic. Specifically, research was conducted on how the two microphones in a smartphone could be used to determine the direction and classify the type of motorized vehicle. The directionalization and classification of vehicles by means of their sound could be useful for future safety systems for cyclists and pedestrians.

Silverman and Kirtman suggested a method to localize a talking human in a conference room using an eight microphone array [6]. Most modern smartphones contain two microphones. Three or more microphones are needed to determine the location of a sound source. Therefore, we are bound to determine the direction instead of the location of the sound source. In [7] a method is proposed for determining the direction of multiple speakers using only two microphones. The use of two microphones in traffic safety systems was researched to detect vehicle speed on Indian highways [8]. In this study, the two microphones were spread 25 meters apart. The microphones of a smartphone are used in the application 'Awareness! The Headphone App' which detects background noise and lowers the volume of earphones in case of a peak in background noise, possibly caused by an approaching vehicle [9]. However, all studies mentioned above do not fully cover directionalization and classification of traffic participants using a smartphone. In comparison to the setups in the previous studies, our study will involve moving microphones and sources. Furthermore, the microphones are spaced closely together compared to the study of Sen et al. [8] which makes their algorithms inapplicable for our study.

Motorized vehicles typically form a source of sound because of tire and engine noise. It has been shown that the tire noise has a peak in the frequency range 700-1300 Hz [10]. Engine noise typically has peaks in lower frequency ranges at approximately 100 Hz [11] for cars and trucks at highway speeds, 80 km/h to 110 km/h. This peak for engine noise may be absent or located at a different frequency in case of electric vehicles. These peaks are expected to occur in our case but may be different in frequency or intensity compared to the research done in [11]. Instead of highway speeds our tests are performed at urban area speeds of 30 km/h and 50 km/h. Detection of unmotorized traffic participants such as pedestrians or cyclists based on their sound is outside the scope of this research, since they do not cause consistent sound signals [12].

The aim of this study is to determine the direction and classify the type of motorized vehicles based on their sound in an urban area by using the two microphones in a smartphone, which is carried by a moving cyclist. Thus, our system differs from studies mentioned, because both microphones are fixed close together in a single smartphone, record real vehicle sound and are moving while recording in order to determine the direction and classify the type of vehicle.

II. Method

A. Directionalization

Two microphones in most modern smartphones [13] are able to determine the direction of the source by calculating the angle of the smartphone relative to the source. For this calculation sound waves are assumed to propagate as plane waves instead of spherical waves, because the distance x in Figure 1 is considered small with respect to the distance to the sound source. With this assumption, angle θ can be determined from Equation 1 [14].

$$\theta = \arcsin\left(\frac{\Delta t \cdot c}{x}\right) \tag{1}$$

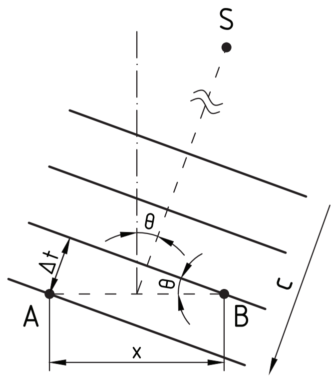

Fig. 1: Sound source localization with two microphones. Plane waves propagate from sound source (S) with speed c to microphones A and B spaced at distance x [15].

The algorithm to determine the direction of vehicles is based on inter-aural time difference (ITD). ITD is the difference in the time of arrival of the same wave at different microphones [16]. The signal samples of both microphones are filtered with a high-pass filter [17]. This filter is used to reduce environmental noise and improve the quality of the signal. Cross-correlation is then applied to the signals to determine the delay between them. Peaks in cross-correlation indicate maximum similarity between the two signals. Then by applying peak detection the delay can be determined [18]. Using this delay, the distance travelled by the sound wave y can be calculated. From there the direction can be calculated from Equation 2.

$$y = \frac{x}{\tan(\theta)} \tag{2}$$

B. *Classification*

Three normalized samples from pre-recorded audio of the scooter at 30 km/h and three of the car at 30 km/h at the 0 m, 5 m and 10 m mark, shown in Figure 3, were used to determine similarity with the recorded sample by doing six cross-correlations. The first cross-correlation determines the similarity of the first pre-recorded scooter sample and the recorded sample. The second cross-correlation determines the similarity of the second pre-recorded scooter sample and the recorded sample, etc. The vehicle type is determined by the largest value of the maxima of these cross-correlations. The maximum value of the cross-correlation must be higher than a threshold of 1 or else no decision is made for the type of vehicle.

C. *Experimental Setup*

For the first experiment the 'Xiaomi Redmi 2 Pro' smartphone was mounted on a tripod with the vertical axis of the smartphone parallel to the road. Since the smartphone has one microphone at the top and one at the bottom, the two microphones have a relative distance between them for sound waves travelling along the road. This forms the delay required for the algorithm. In order to verify the audio data, a 'GoPro Hero 4 Silver' camera was mounted parallel to the road to see oncoming traffic. In addition to the high-pass filter built into the algorithm, a microphone cover was put on the smartphone to filter wind noise in a practical way. The smartphone including the windscreen cover, camera and wind meter were mounted on a cubic frame placed on a tripod shown in Figure 2. Test marks were placed on the road at predetermined distances in order to verify the results of the algorithm with the actual angles as shown in Figure 3. The actual angle will from now on be referred to as the ground proof angle.

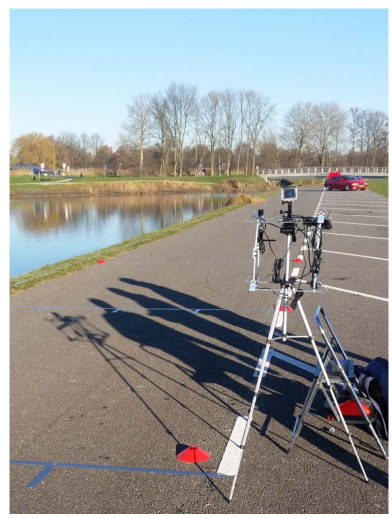

Fig. 2: Test setup experiment 1.

A Garmin GPS tracker was mounted on the test vehicles. The test vehicles were a 1996 BMW 328i car, a Vespa LX50 scooter, a racing bicycle and a conventional bicycle. Both car and scooter are petrol vehicles. The test location was the 'Willem Alexander Baan' rowing course. After testing, video footage of the camera and audio of the smartphone were synchronized using 'Adobe Premiere Pro' software. GPS data and video footage were synchronized using 'Dashware' software.

D. *Experiments*

1) Experiment 1: The first experiment consisted of the car and scooter driving past the microphone setup at different speeds. The car drove past the microphone setup at both 30 km/h and 50 km/h in the middle of the road, i.e. the car's center line is located at a two meters distance from the microphone setup. These are the speed limits for motorized vehicles in urban areas in the Netherlands. The scooter was driven past the microphone setup at the same speeds at three marked distances. We measured at one, two and three meters distance from the microphone setup, because we expected the noise level, which declines when moving the source further away, to influence the filter that is to be implemented in the algorithm. All measurements were performed three times. In Figure 3 a layout of experiment 1 can be seen.

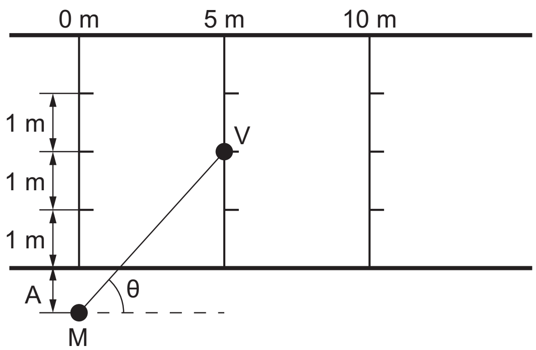

Fig. 3: Sketch of the test setup. A represents the distance between the microphone setup and the road, V represents the vehicle and M represents the microphone setup. θ is the angle between the vehicle and the microphone. Markings are applied every 5 m along the road and every 1 m across the road.

The sound recorded by the smartphone could now be analysed by MATLAB and by applying the equations mentioned in the method section, the direction and the type of vehicle could be calculated. The interface can be seen in Figure 4.

2) Experiment 2: The second experiment was performed to test our algorithm for a moving microphone carrier. This is closer to a real life scenario in which a cyclist uses our system to become aware of approaching vehicles. We drove the car past the cyclist from both directions at different speeds. The cyclist moved at speeds of 15 km/h, 20 km/h and 25 km/h which are common cycling speeds [19]. For these three situations the car passed the cyclist at 30 km/h and 50 km/h in both directions. The camera, smartphone and GPS tracker were mounted on the bicycle at a height of approximately one meter, as can be seen in Figure 5. The smartphone was mounted with its vertical axis oriented parallel to the road.

3) Experiment 3: The third experiment was executed in a similar way as experiment 2. However, instead of mounting the smartphone on the bicycle, the smartphone was kept loosely in the back pocket of the cyclist's jacket. This is closer to a real life scenario where a cyclist could easily put the smartphone in the back pocket of his/her jacket.

4) Experiment 4: The forth experiment served to test our algorithm when built into a smartphone application. Based on the output of the smartphone microphones the application classified the type of vehicle and displayed the direction of the vehicle in a real time polar plot similar to the polar plot in Figure 4. The application includes a manually adjustable threshold value and high-pass filter. This allows the user to adjust the minimal value of the cross-correlation between the microphone signals and high-pass filter for environmental noise respectively. The microphones of the smartphone were covered by the wind screen. The camera was mounted on the right side of the bicycle handlebar. The smartphone was

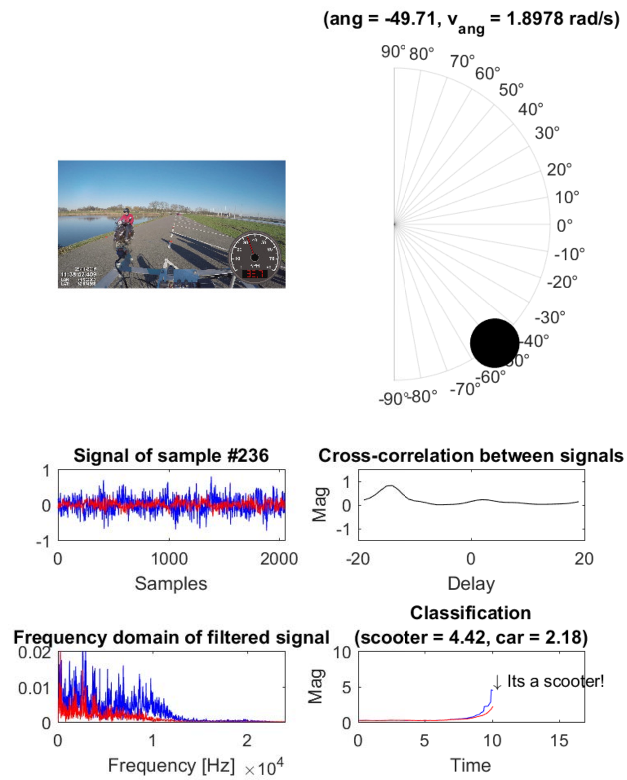

Fig. 4: Output from MATLAB of the scooter passing the smartphone at 30 km/h during experiment 1. Video footage displayed top left, the angle of the sound source to the smartphone plotted in the top right, plots of the signal and its frequency domain bottom left and the cross-correlation and classification bottom right.

Fig. 5: Setup of experiment 2. The smartphone with windscreen cover and GoPro camera mounted above the rear wheel of the bicycle.

mounted on the left side of the bicycle handlebar such that it was oriented parallel to the road. The handlebar has a height of approximately 1.20 meters. The complete configuration is displayed in Figure 6.

The output of the application can be seen in Figure 7. It shows the calculated angle of the sound source and the classification of the sound. The smartphone screen was recorded and the camera recorded the passing vehicles. The cyclist rode at 20 km/h while the car and scooter drove past the cyclist at 30 km/h and 50 km/h. The resulting interface allows for verification of the accuracy of the application.

Fig. 6: Setup of experiment 4. The smartphone with windscreen mounted on the left side of the handlebar. The vertical axis of the smartphone parallel to the road. The camera mounted on the right side of the handlebar, to capture passing vehicles on film.

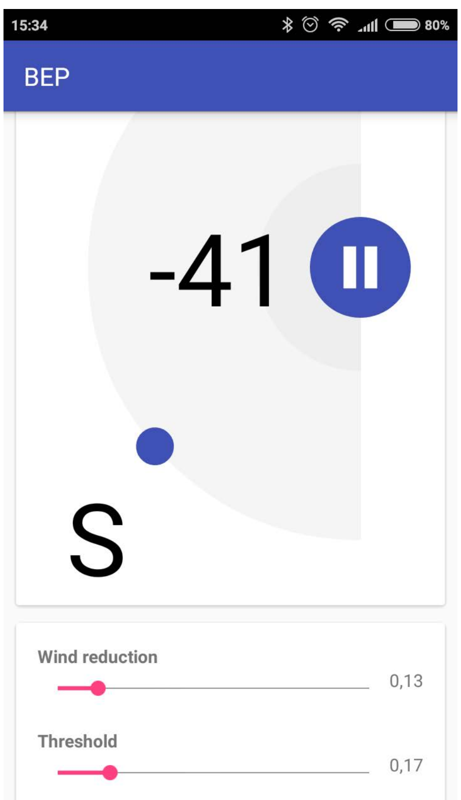

Fig. 7: Screenshot of smartphone application indicating an approaching scooter (S) at -41 degrees.

III. Results

A. *Experiment 1*

Tables I, II and III display the results of experiment 1. As can be seen in Tables I and II the deviation of the average measured angle of the scooter and the ground proof angle could be considered small. This deviation ranges from 1.20 degrees to 13.94 degrees for both 30 km/h and 50 km/h. However, the standard deviation can be considered large. It can also be seen that most values of the angle of the scooter driving towards the microphone setup are closer to the ground proof angle than the values of the angle of the scooter driving away from the microphone setup. Considering the car, there seems to be less of a division compared to the scooter between accurate and inaccurate estimation of the angle for a vehicle passing the measurement setup. As can be seen in Table III, the car has both a large standard deviation and a large deviation of the average angle. Our algorithm often assigns a 90 degrees angle to the scooter. This is in all cases far off the ground proof angle. However, for the car the algorithm did not assign an angle of 90 degrees.

Overall, a minimum standard deviation of 8 degrees and a maximum of 17 degrees can be seen. This could be caused by the sample rate of the audio signal and the distance between the microphones. The sample rate of the smartphone is 48 kHz and the distance between the microphones is 13 cm. Combining this with the speed of sound of 340 m/s, one can determine that only 18 samples can be recognized between the first and the second microphone. This results in discrete steps when calculating the angle, causing the angle step size to increase when the angle increases. The precision is thus limited by the dimensions of the smartphone, microphone position and sample rate.

The results from the classification are shown in Table IV. The accuracy is the percentage of samples with correct classification. At 30 km/h the scooter is classified correctly in approximately 88 percent of the cases. In approximately 99 percent or more of the cases the algorithm is able to correctly classify the car. On the other hand, the algorithm has issues with classifying the scooter at 50 km/h.

TABLE I: Scooter at 30 km/h, passing the smartphone 4 times in experiment 1. (T) stands for driving towards the test setup. (A) stands for driving away from setup. The value for the ground proof is the true angle measured by marks on the road. The values for each pass represent the angles as calculated by the algorithm. The Distance to the vehicle represents the distance from the side of the road to the vehicle across the width of the road. The indications front and rear in the left column stand for the front or rear wheel of the scooter.

Distance to the vehicle	1 meter	2 meters	3 meters
Ground Proof (deg)	78.69	68.20	59.04
(A) Pass 1 front (deg)	90	67.86	60.67
(A) Pass 1 rear (deg)	90	78.75	67.86
(T) Pass 2 front (deg)	78.75	67.86	54.82
(T) Pass 2 rear (deg)	67.68	54.82	45.10
(A) Pass 3 front (deg)	90	67.86	60.67
(A) Pass 3 rear (deg)	90	78.75	67.86
(T) Pass 4 front (deg)	78.75	67.86	54.82
(T) Pass 4 Rear (deg)	60.67	52.27	45.10
Average (deg)	80.73	67.00	57.11
Standard deviation (deg)	10.75	8.98	8.33
Deviaton of Average (deg)	-2.04	1.20	1.93

TABLE II: Scooter at 50 km/h, passing the smartphone 4 times in experiment 1. (T) stands for driving towards the smartphone. (A) stands for driving away from smartphone. The value for the ground proof is the true angle measured by marks on the road. The values for each pass represent the angles as calculated by the algorithm. The indications front and rear in the left column stand for the front or rear wheels of the car.

Distance to the vehicle	1 meter	2 meters	3 meters
Ground Proof (deg)	78.69	68.20	59.04
(A) Pass 1 front (deg)	90	78.75	67.86
(A) Pass 1 rear (deg)	90	90	67.86
(T) Pass 2 front (deg)	67.86	64.27	47.40
(T) Pass 2 rear (deg)	54.82	45.10	36.90
(A) Pass 3 front (deg)	67.86	78.75	67.86
(A) Pass 3 rear (deg)	90	90	78.75
(T) Pass 4 front (deg)	67.86	67.86	59.67
(T) Pass 4 rear (deg)	49.71	45.10	33.02
Average (deg)	72.26	69.98	57.41
Standard deviation (deg)	15.06	16.69	15.43
Deviation of Average (deg)	6.43	-1.78	13.94

TABLE III: Car at 30 km/h and 50 km/h, passing the smartphone 3 times in experiment 1. (T) stands for driving towards the smartphone. (A) stands for driving away from the smartphone. The value for the ground proof is the true angle measured by marks on the road. The values for each pass represent the angles as calculated by the algorithm. The distance to the vehicle represents the distance from the side of the road to the vehicle across the width of the road. The indications front and rear in the left column stand for the front or rear wheel of the car.

Car Speed (km/h)	30	50
Ground Proof (deg)	68.20	68.20
(T) Pass 1 front (deg)	67.86	67.86
(T) Pass 1 rear (deg)	36.82	40.83
(A) Pass 2 front (deg)	54.82	45.10
(A) Pass 2 rear (deg)	78.75	67.86
(T) Pass 3 front (deg)	67.86	-
(T) Pass 3 rear (deg)	40.83	-
Average (deg)	57.82	55.41
Standard deviation (deg)	15.16	12.96
Deviation of Average (deg)	10.38	12.79

TABLE IV: Classification of car and scooter at 30 km/h and 50 km/h for experiment 1. The table lists the number of audio samples in which classification was performed when a vehicle passed the smartphone. The accuracy is the percentage of samples with correct classification.

Case	Samples classified	Classification Scooter	Classification Car	Accuracy (%)
Scooter 30 km/h	889	783	106	88.08
Scooter 50 km/h	907	78	829	8.60
Car 30 km/h	187	1	186	99.47
Car 50 km/h	127	0	127	100.00

B. Experiment 2

Results of experiment 2 showed a big variety in angle calculation. Two random examples are documented in tables V and VI to demonstrate the incoherence of the results. The examples demonstrate large fluctuations of the calculated angle. This did not improve using a filter. The six samples have a total duration of 0.213 seconds. Also, the normalized classification cross-correlation did not reach the threshold value of 1.

TABLE V: Bicycle at 15 km/h and car at 50 km/h, pass 1, experiment 2. Each sample belongs to a certain instant of the car passing the cyclist. The bottom row describes the angle corresponding to the sample number above as calculated by the algorithm

Sample No.	198	199	200	201	202	203
Angle (deg)	-40,83	67,86	9,41	67,86	6,26	-3,12

TABLE VI: Bicycle at 20 km/h and car at 30 km/h, pass 2, experiment 2. Each sample belongs to a certain instant of the car passing the cyclist. The bottom row describes the angle corresponding to the sample number above as calculated by the algorithm

Sample No.	365	366	367	368	369	370
Angle (deg)	12.59	-22.42	36.82	12.59	-60.67	-49.71

C. Experiment 3

Placing the smartphone in the back pocket of the cyclist did not improve the directionalization and classification. Tables VII and VIII document two examples demonstrating that results were ambiguous. Wind or bicycle rattles seem to distract the algorithm from the correct source. Again, the cross-correlation threshold was not reached.

TABLE VII: Smartphone in pocket, bicycle at 15 km/h and car at 50 km/h, pass 1, experiment 3. Each sample belongs to a certain instant of the car passing the cyclist. The bottom row describes the angle corresponding to the sample number above as calculated by the algorithm.

Sample No.	197	198	199	200	201	202
Angle (deg)	-49.71	-40.83	67.86	9.41	67.86	6.26

TABLE VIII: Smartphone in pocket, bicycle at 20 km/h and car at 30 km/h, pass 2, experiment 3. Each sample belongs to a certain instant of the car passing the cyclist. The bottom row describes the angle corresponding to the sample number above as calculated by the algorithm

Sample No.	289	290	291	292	293	294
Angle (deg)	90	22.42	9.41	29.37	54.82	-60.67

D. Experiment 4

Measured angles from experiment 4 show a standard deviation ranging from approximately 1.7 degrees to approximately 8 degrees. Table IX shows that for an angle of 0 degrees and 45 degrees at all speeds for all vehicles the average measured angle lags behind the ground proof angle. At a ground proof angle of -45 degrees only the average angle of the scooter at 50 km/h lags behind the ground proof angle. For the scooter the rear wheel was taken as point of reference, since the engine and exhaust are located next to it. For the car the tire located closest to the smartphone was taken as point of reference. The classification performs well as shown in Table X. The lowest accuracy is 73.27 percent, mainly caused by an outlier of 21.63 percent, which we consider a decent performance. The classification in Table X is taken from video footage where classification was performed while a vehicle passed the smartphone.

TABLE IX: Calculated angles from experiment 4 compared to ground proof angles of -45, 0, and +45 degrees. 8 tests were done at 30 km/h, 9 tests were done at 50 km/h. The point of reference for the scooter was the rear wheel. The point of reference for the car was the wheel located closest to the smartphone. Each value indicates the average angle including the corresponding standard deviation as calculated from all the angles given by the algorithm

Case	At -45 deg	At 0 deg	At +45 deg
Scooter 30 km/h	-43.63 ±3.25	-5.63 ±2.97	32.63 ±5.13
Scooter 50 km/h	-50.56 ±1.67	-11.89 ±4.65	30.22 ±3.96
Car 30 km/h	-36.00 ±4.14	-5.75 ±5.75	40.75 ±7.57
Car 50 km/h	-44.11 ±6.79	-17.11 ±5.46	31.67 ±7.91

TABLE X: Classification of car and scooter at 30 km/h and 50 km/h for experiment 4. The table lists the number of video frames in which classification was performed when a vehicle passed the smartphone. The accuracy is the percentage of frames with correct identification.

Case	Frames classified	Classification Scooter	Classification Car	Accuracy (%)
Scooter 30 km/h	2491	2245	246	92.59
Scooter 50 km/h	2097	1500	568	73.27
Car 30 km/h	2091	127	1905	91.45
Car 50 km/h	2093	91	2002	95.10

When comparing the values of the accuracy of experiment 1 and experiment 4, the drop in accuracy for the scooter at 50 km/h passing a non-moving smartphone stands out. In all other cases for both a moving and non-moving smartphone the accuracy is at least 73.27 percent. This implies a relationship between the difference in speed of the smartphone and the vehicle. As it appears from Table IV, the scooter is classified correctly unless the difference in speed between the scooter and smartphone is more than 30 km/h.

IV. Discussion

In this paper we proposed a method for directionalization and classification of motorized vehicles using a smartphone. This could be useful for future safety systems for cyclists and pedestrians since, in the Netherlands, 81 percent of people between the age of 18 and 80 years old own a smartphone [2]. Cross-correlating the audio signals of two microphones in a smartphone shows the similarity of the signals. The peak value indicates the delay between the signals, thus the angle with respect to the source. When cross-correlating the audio signals with pre-recorded samples from a car and scooter, the maximum value of the cross-correlations indicates the type of vehicle. Having a stationary smartphone, results showed a directionalization deviation of the average angle from the ground proof angle between 1.20 and 13.94 degrees. Classification accuracy ranged from 88.08 to 100 percent with the exception of the scooter at 50 km/h, where the accuracy dropped to 8.6 percent. Having a moving smartphone and recording with the smartphone application, results showed a directionalization deviation of the average angle from the ground proof angle between 0.89 and 17.11 degrees. Classification accuracy ranged from 73.27 to 95.10 percent.

With regard to the results of experiment 4, we feel the accuracy drop for the scooter at 50 km/h may be caused by the sound of the tires becoming the dominant sound source over the engine noise. Also, the engine noise of the scooter may contain characteristic frequencies at lower speeds which make for more accurate classification as demonstrated by the accuracies in Table IV and X.

In this study, we simplified the sound source as a single point. A vehicle produces sounds at different positions caused mainly by the tires and the engine. Therefore, the sound of a motorized vehicle does not come from one specific point. In experiment 1 it can be seen that the accuracy of the angle as calculated by our algorithm differs when the vehicle is driving towards or away from the setup. This is caused by the unknown position of the centroid of sound. The centroid of the sound is not exactly at the front or rear wheel. For both vehicles the engine lies in between the front and rear wheels, making it likely that the centroid of sound lies at least between the front and rear wheels. Therefore we feel that the angles calculated by the algorithms give the minima and maxima for the range of angles in which the actual angle lies. One could assume this plays an important role especially for the car since the tires are not at the center line making the centroid of sound even more difficult to find than the centroid of sound of a scooter. It should be noted, that it is expected that the centroid of sound will also change when differentiating the speed of the vehicle. Tire noise will increase with increasing speed and engine noise is determined by the rotations per minute of the engine and therefore not entirely speed dependent. Thus, the ratio of tire and engine noise will change causing the centroid of sound to move. The results for the classification of vehicles could be made more accurate with a different baseline or multiple baselines. Our current baseline is based on one recording of the car and one recording of the scooter. Both baseline recordings were done at 30 km/h at 2 meters distance from the smartphone. Currently this baseline is used for classification of measurements performed at both 30 km/h and 50 km/h. Including baselines at 50 km/h for both vehicles could improve the classification accuracy, also increasing the amount of baselines at both speeds may be beneficial to the classification accuracy.

The aim of this study was to determine the direction and classify the type of motorized vehicles based on their sound in an urban area by using two microphones in a smartphone, which was carried by a moving cyclist. The smartphone application fills the gap left by previous studies. For a moving smartphone, i.e. while riding a bicycle, the application showed results of a directionalization deviation of the average angle from the ground proof angle between 0.89 and 17.11 degrees. Classification accuracy ranged from 73.27 to 95.10 percent.

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