Association between mobile phone traffic volume and road crash fatalities: A population-based case-crossover study

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ABSTRACT

Use of mobile phones while driving is known to cause crashes with possible fatalities. Different habits of mobile phone use might be distracting forces and display differential impacts on accident risk; the assessment of the relative importance is relevant to implement prevention, mitigation, and control measures. This study aimed to assess the relationship between the use of mobile phones at population level and road crash fatalities in large urban areas. Data on road crashes with fatalities were collected from seven Italian metropolitan areas and matched in time and space with high resolution mobile phone traffic volume data about calls, texts, Internet connections and upload/download data. A case-crossover study design was applied to estimate the relative risks of road accident for increases in each type of mobile phone traffic volumes in underlying population present in the small areas where accidents occurred. Effect modification was evaluated by weekday/weekend, hour of the day, meteorological conditions, and street densities.

Positive associations between road crashes rates and the number of calls, texts, and Internet connections were found, with incremental risks of 17.2% (95% Confidence Interval [CI] 7.7, 27.6), 8.4% (CI 0.7, 16.8), and 54.6% (CI 34.0, 78.5) per increases (at 15 min intervals) of 5 calls/100 people, 3 text/100 people, and 40 connections/100 people, respectively. Small differences across cities were detected. Working days, nighttime and morning hours were associated with greater phone use and more road accidents.

The relationship between mobile phone use and road fatalities at population level is strong. Strict controls on cellular phone in the vehicle may results in a large health benefit.

1. Introduction

Fatalities caused by road crashes are considered a major problem for both lives lost and social costs. Crashes triggered by distracted driving are a major cause of mortality, with financial and social costs (National Highway Traffic Safety Administration (NHTSA, 2015; World Health Organization (WHO, 2015). Mobile phone use is one of the main contributors to these distracting factors (World Health Organization (WHO, 2011; Oviedo-Trespalacios et al., 2016). In the United States, observational studies revealed that 31.4% of drivers talk on the phone and 16.6% text or dial (Huisingh et al., 2015). Similar studies in Spain and Italy quantified the prevalence of mobile phone usage while driving to 3.8% and 4.5%, respectively (Martínez-Sánchez et al., 2014; Lorini et al., 2012). Assessment of crash risks related to mobile phone use has been carried out by applying different methods and study designs (Oviedo-Trespalacios et al., 2016; Simmons et al., 2016; McCartt et al., 2006; Svenson and Patten, 2005).

“Naturalistic” study (Simmons et al., 2016), based on the involvement of volunteer drivers to capture their behaviours, is one of the most common methods used in the literature. Simulation of specific in-vehicle tasks in a laboratory or simulated driving under controlled conditions (Caird et al., 2014; Garrison and Williams, 2013) and the use of surveys (Yannis et al., 2015) are other methods used by investigators to assess crash risks. Epidemiologic studies based on road crash data (Redelmeier and Tibshirani, 1997; McEvoy et al., 2005) or collected video data from volunteers (Klauer et al., 2006; Fitch et al., 2013) are another approach to estimate risks. Data are examined to determine whether a distracting activity was involved in the crash or might be the cause of it.

Using a different approach, Muehlegger and Shoag (2014) examined the relationship between car accidents and directly observed hourly data on cell phone call volumes at the local level, investigating whether...
there was a nearby vehicle accident that led to a serious injury or fatality. This methodology enables the measurement of real-world crash outcomes based on information on all traffic accidents reported by police departments, and relate them with real-time detailed information on cell phone use provided by mobile phone operators. This novel approach, based on mobile traffic volumes at the exact time of the crash episode, offers the opportunity to investigate the impact on crash risk of alternative ways to use smartphones, such as Internet connections for interacting with social networks (such as Facebook, Twitter and WhatsApp) as well as other activities that need cognitive resources and a substantial amount of attention deflected from driving. Such a large amount of data can be analysed using a case-crossover study design, an epidemiological method perfectly suited when the risk factor/exposure of interest is transient, as in the case of cell phone use. This methodology has been largely used in several epidemiological studies addressing various risk factors (Navidi and Weinhandl, 2002; Bateson and Schwartz, 1999; Stafoggia et al., 2006, 2010).

The present paper aims to investigate the impact of different types of mobile phone use traffic volumes at population level on road crash fatalities in seven Italian urban areas using the case-crossover design. Specifically, the study hypothesis is that increased use of mobile phones (in various forms, calls, texts, internet) in the underlying population (of both drivers and non-drivers) in a given time period can act as a distracting force for that population, increasing the probability of crash fatalities. The distracting forces can be the individual driver using the phone, other individuals using the phone in the same car, use of the phone in another vehicle involved in the same crash, or even distracted pedestrian crossing urban road while using the phone. In addition, the study aims to evaluate specific temporal or meteorological covariates as potential effect modifiers.

2. Materials and methods

2.1. Road crash fatalities

In the present study, data on road crashes that led to an injury or fatality were collected for two months in 2015 (March and April) for seven Italian cities and the corresponding Provinces (Rome, Milan, Turin, Naples, Venice, Palermo and Bari). Data are collected by the National Institute of Statistics (ISTAT), on the basis on data recorded from different authorities, “Carabinieri”, Road Police, and Local Police, to document traffic accidents occurred on the national public roads network. The collected data include information about time and location of the accident, classification of type of road, paving and meteorological conditions, number and types of vehicles involved, general characteristics of the road accident, and data about possible injuries and fatalities. In addition, information was available on the geographic coordinates of the location of accidents. A GIS mapping procedure was then applied to assign each accident to a corresponding mobile phone traffic cell to further link with the mobile traffic volume data. Fig. 1 shows the road crashes (red circles) occurring in Rome during the study period.

These data are gathered by means of questionnaires filled in by the involved Authorities, based on accident reports. The procedure of data collection is standardized among the Authorities, as it follows a unique form delivered by ISTAT. The form contains variables and classifications harmonized at European level, allowing the CARE (Community Road accident database) to be used for data archiving, reporting and dissemination of results. In this way the consistency and integrity of data among Authorities are assured. The ISTAT archive represents the most complete and accurate information about road accidents available at the national level. However, some inaccuracies at territorial level

![Fig. 1. Road crashes (red circles) occurring in Rome during the study period superimposed with mobile phone traffic volume data grid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image-url)
might exist due to personal judgement about some accident data parameters, also reported by literature (Ma et al., 2012; World Health Organization (WHO, 2011). Overall, 7939 crashes were selected. Data were also separated for weekdays and weekends, time periods (night-time (21:00–6:00), morning rush hours (6:00–10:00), midday (10:00–16:00), and evening rush hours (16:00–21:00)), meteorological and paving conditions (fair, unfair, dry, and other) and street densities (defined as low, medium, high, and very high on the basis of the distribution of the length of the street segments within each grid cell). These variables were defined a priori in order to evaluate peculiar accident conditions as potential effect modifiers in the following analyses.

2.2. Mobile phone traffic volume data

In the frame of the Telecom Italia (TIM) Big Data Challenge 2015 (www.telecomitalia.com/bigdatachallenge), seven datasets were made available for the main Italian cities and their Provinces, derived from post-processing of mobile phone traffic collected by the Italian mobile TIM operator for billing purposes. By means of localization procedures based on such data, high temporal and spatial resolution mobile traffic volume data were derived. The methodology is described in Gariazzo et al. (2016) and only summarized herein. Basically, for each serving base transceiver station (BTS) belonging to the network, a coverage area is defined by taking into account its technical characteristics, orography and characteristics of the host building. If a user performs a telecommunication action (e.g., phone call) while connected to a BTS, his presence is distributed over the coverage area associated to such a BTS. All telecommunication actions occurring in a BTS are summed up to obtain the total number of specific communications (calls, text, Internet) given in a certain period. The coverage area of involved BTS was spatially gridded to deliver a spatialised information of the total volume of the specific type of communication at a certain time, as well as an estimation of the total population located in each cell. Table 1 shows the characteristics of data grids by city and the Fig. 1 shows an example of data grid for the city of Rome.

As for personal data, mobile users were associated with grid cells depending on where they performed their last action (e.g., made a call or received a text message). The last position of individuals was kept until the next phone action, thus preventing the loss of those with lower communication frequency or with phones switched off. These datasets do not deal with individual data as only aggregated data were made available. Consequently, the tracking of individuals was not possible and privacy was guaranteed by design. In addition, as already mentioned, the study was not designed to individually link crashes to personal use of cell phone while driving, but aimed to estimate the risk of crash fatalities in the underlying population (of both drivers and non-drivers) in a given time period as a consequence of an increased use of mobile phones in the same time period.

In detail the datasets used included the following variables for each grid cell and time: (1) number of people, (2) number of incoming and outgoing phone calls; (3) total call times; (4) number of incoming and outgoing text messages; (5) number of Internet connections and amount of megabytes uploaded/downloaded. The incoming and outgoing calls and texts were summed up to obtain the two datasets: the total number of calls and the total number of texts. Data were provided on irregular grids at a time resolution of 15 min and spanned from 1st March to 30th April 2015. Data were related to mobile TIM operator subscribers. Based on the market rate position of the TIM company (32% on a national basis (National Authority for Communication, 2016)), data can be considered of statistical relevance and high generalisability to the overall population.

As mobile phone traffic volumes are provided on an irregular grid, it is expected that larger inhabited cells will produce larger mobile traffic volumes than smaller and less populous ones. Therefore, mobile phone traffic volume variables have been normalised by the corresponding number of people. In this way, each variable represents the traffic
2.3. Study design

The case-crossover design was applied for the estimation of the association between mobile phone use at population level and road accidents. Its design is a specific matched case-control study where each subject serves as his/her own control, i.e. the study is self-matched (Maclure, 1991). Specifically, for each subject having a road crash, a ‘case window’ is defined as the short time period just before the accident, and a ‘control window’ is defined as a set of short time periods before or after the case, when the study outcome did not occur. Population exposure (e.g. total call time) during the case window is compared to average population exposures during the control windows, and the relative risk of outcome (e.g. road crash) is estimated with conditional logistic regression. As the subject is self-matched, all individual characteristics not changing (or slowly changing) over time (age, smoking/alcohol habits, chronic conditions, etc.) cannot confound the association between mobile phone use and road accident risk. In addition, if control windows are properly chosen close enough to the case window, confounding from slowly time-varying covariates is resolved as well. Using the conditional logistic regression model, other short-time changing variables can be adjusted for. We estimated the association between the cell phone traffic volumes variables and the risk of car accident by use of the case-crossover design on the pooled dataset of all 7 City-Provinces.

For each road crash occurring in a specific grid cell of one Province, we defined the “risk set” as follows: the “case” was the 15 min time window when the crash occurred, and the corresponding “controls” were the four 15 min time windows occurring ± 30 and 60 min symmetrically before and after the case, in the same grid cell. The case exposures were the mobile phone traffic volumes data (e.g. the total call time) recorded in that grid cell in the case time-window. Similarly, the control exposures were the mean of traffic volumes variables registered during the control time windows.

We selected control time windows shortly before and after the case in order to remove potential confounding from temporal patterns in both the exposures and the outcomes. Furthermore, as each grid cell was matched to itself, confounding induced by spatial patterns (street or population density, for example) was also automatically resolved, as these did not vary between the cases and the controls. Of course, we could not obtain individual-level data such as behaviors (e.g. alcohol, smoking, etc.) of the car drivers before, during or after the road crash but these information are not relevant for the aims of the study. Similarly, we only had data on the prevalent meteorological conditions during individual accidents, so we could not adjust for the potential confounding of individual-level or external factors changing between the case and its controls.

As the case-crossover is a special case of matched case-control design, the analyses were conducted with conditional logistic regression models. Each (lagged) exposure was modelled as a linear term in the main analysis. The estimated ORs were converted into per cent increases of risk (%IR), and corresponding 95% Confidence Intervals (95% CI), and were expressed per fixed increments of each exposure variable.

2.4. Additional analyses

We performed the following additional analyses. First, we evaluated whether accidents might by caused by a delayed (or prolonged) use of the cell phone while driving by considering exposures during the 15 min interval before the case and controls (lag 1) or by averaging exposures during the concurrent and preceding 15 min intervals (lag 0–1). This analysis was also motivated by the possibility of a mismatch between the actual and reported times of crashes. Second, we ran Province-level analyses, as an alternative to the pooled model of the main approach. Province-level results were then averaged with a random-effects meta-analysis (DerSimonian and Laird, 1986). Third, we evaluated a number of factors as potential effect modifiers in the road crash-traffic volumes data associations. These included: day of the week (weekdays/weekends), hours (nighttime/daytime), prevalent meteorological conditions (fair/unfair), road conditions (dry/other), and street density (low to very high). Fourth, we checked whether the association between the main exposures and the study outcome was non-linear by replacing the linear terms with penalised splines (Wood, 2003). Fifth, we selected as alternative control time windows ± 15 min around the crash episodes, to check the robustness of our main results to choice of controls.

All the analyses were conducted using R software, version 3.4.1.

3. Results

3.1. Road crash fatalities data

Table 2 presents summary statistics of the road accidents by Province, hours of the day, and prevalent meteorological conditions. In total, we selected 7939 road accidents with injuries or fatalities, mostly occurring in Rome and Milan, during midday (35%) and evening hours (30%), and under fair meteorological conditions (85%).

3.2. Mobile phone traffic volumes

The mobile phone traffic volumes are characterised by a strong daily pattern, with a relative minimum at nighttime and peak values during the daytime. Fig. 2 shows an example of a typical hourly trend of mobile traffic volumes (number of calls, text messages, and Internet connections) and the corresponding amount of people present within a

<table>
<thead>
<tr>
<th>City</th>
<th>Total crashes 0–24</th>
<th>Nighttime 21–6</th>
<th>Morning rush hours 6–10</th>
<th>Midday hours 10–16</th>
<th>Evening rush hours 16–21</th>
<th>Meteorology</th>
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<td></td>
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<td>Fair</td>
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<td></td>
<td></td>
<td></td>
<td>Un-fair</td>
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<tr>
<td>Rome</td>
<td>2525</td>
<td>345</td>
<td>498</td>
<td>905</td>
<td>777</td>
<td>2134</td>
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<td></td>
<td>360</td>
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<td>Milan</td>
<td>2397</td>
<td>332</td>
<td>484</td>
<td>878</td>
<td>703</td>
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<td>Turin</td>
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<td>136</td>
<td>167</td>
<td>344</td>
<td>272</td>
<td>724</td>
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<td>Naples</td>
<td>796</td>
<td>160</td>
<td>124</td>
<td>285</td>
<td>227</td>
<td>682</td>
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<td>Bari</td>
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<td>87</td>
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<tr>
<td>Palermo</td>
<td>404</td>
<td>150</td>
<td>102</td>
<td>77</td>
<td>75</td>
<td>346</td>
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<td>58</td>
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<tr>
<td>Venice</td>
<td>339</td>
<td>30</td>
<td>77</td>
<td>121</td>
<td>111</td>
<td>300</td>
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<td></td>
<td>36</td>
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<tr>
<td>TOTAL</td>
<td>7939</td>
<td>1215 (15%)</td>
<td>1539 (19%)</td>
<td>2817 (35%)</td>
<td>2368 (30%)</td>
<td>6721 (85%)</td>
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<td>959 (12%)</td>
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grid cell with the maximum spatial resolution located in the city centre. Table 3 presents summary statistics of the mobile phone traffic volume data, while Table 1A in the Supplementary Material shows the matrix of pairwise Pearson correlation coefficients.

### 3.3. Association between crash fatalities and mobile phone traffic volume

Table 4 shows the estimated % IR and 95% CI of road crash fatalities for fixed increments of the phone traffic volume variables. The most relevant associations were found in relation to the total number of calls (% IR = 17.2%, 95% CI = 7.7, 27.6, for 5 calls/100 people increments) and the number of Internet connections (% IR = 54.6%, 95% CI = 34.0, 78.5, for 40 connections/100 people increments). As these two variables were only moderately correlated (r = 0.50, see Table 1A in Supplementary Material), we evaluated whether they displayed independent effects on road crashes by fitting a two-exposure model, where both variables were added simultaneously. Percent increases of risk diminished to 10.4% (95% CI = −0.4, 22.5) and 29.7% (95% CI = 8.5, 55.1) for the total number of calls and number of Internet connections, respectively (data not shown).

Other variables (call times, incoming texts and Internet traffic in upload) were moderately associated with increased risks of road accidents. It is worth noting that the results at lag 1 (15 min before the accident) were weaker, supporting the hypothesis of a plausible causal association between road crashes and concurrent mobile phone traffic volumes (Table 2A of the online Supplement Material).

When we analysed the data separately for each Province, we found little evidence of heterogeneity in Province-specific results (see Supplementary Material Table 3A): the only two Provinces with null results on the total number of calls or Internet connections were the smallest ones, Palermo and Venice, with a high degree of uncertainty in their estimates. The meta-analytical results were almost identical to the pooled associations estimated using the main approach (Fig. 3).

Effect modification was evaluated only for the two exposures mostly associated with the risk of road crashes, the total number of calls and the total number of Internet connections. Positive associations were found with both exposures during working days (IR = of 17.9% and 59.9%, respectively), night-time (21:00–06:00) (IR = 41.3% and 61.0%), and morning hours (06:00–10:00) (IR = 12.1% and 45.8%, respectively). Detailed results of the effect modification analysis are reported in the Supplementary Materials, Table 4A.

Fig. 4 shows the estimated dose-response curves about the relationship between the number of calls, total call times, number of Internet connections, and number of text messages with road crash fatalities, when the linearity assumption was relaxed. Additional dose-response curves (e.g., incoming and outgoing texts) are shown in Fig. 1A of the Supplementary Material. Most of the curves were consistent with a linear association, although some showed a plateau for higher exposure values.

The sensitivity analysis on the choice of the control windows confirmed our main findings (Table 5A of the Supplementary Material): when we choose ± 15 min as control windows (as opposed to ± 30 and 60 min) we still detected statistically significant associations between road crashes and total numbers of calls and Internet connections.

### 4. Discussion

We found strong associations between mobile phone use at population level and road crash fatalities. In particular, the number of calls and the number of Internet connections displayed the strongest...
association, although increased risks were also identified for the number of text messages and Internet traffic in upload. City-specific results showed homogeneous risks among cities. We found the highest effects during the working days, night, and morning hours. Finally, dose-response curves displayed a linear relationship between most of the exposures and road crashes.

The above results confirm the positive association with the use of phone calls and text messages already seen by other authors.
Our results are consistent with those reported by others. Muehlegger and Shoag (2014), by examining the relationship between car accidents and directly observed hourly data on cell phone call volumes, estimated that a 100% increase in call volumes was associated with a 15%–43% increased likelihood of a serious crash. Earlier studies (Redelmeier and Tibshirani, 1997; McEvoy et al., 2005) reported a fourfold increase in the likelihood of crashing, much higher than in the present study. Klauer et al. (2010) reported a risk of 1.3 for talking on a cell phone, rather similar to the value obtained here. However, recent results from the same author (Klauer et al., 2014) estimated lower or no risk of talking on a phone for experienced drivers.

As for text messages, the risk of crash fatalities obtained in this study are much lower than those reported by Simmons et al. (2016) (10.3 [2.38, 44.67]) in a meta-analysis naturalistic study and those found by Klauer et al. (2014) (3.87 [1.62, 9.25]) in the 100-Car Naturalistic Driving Study. Conversely, Fitch et al. (2013) reported much lower risks (1.73 [0.98, 3.08]).

To the best of our knowledge, no specific results are available in the literature for risks associated with Internet connections. Hickman and Hanowski (2012) carried out a naturalistic study on commercial truck and bus drivers, which involved activities such as browsing, email, or accessing the Internet on mobile phones. Klauer et al. (2014) also considered Internet cell phone use in their evaluation of risks. However, both papers reported results as text/browse risks. While Klauer et al. (2014) reported a text/browse risk of 3.87, Hickman and Hanowski (2012) found a large risk for text/browse (163.59 [51.77, 516.73]). The present study estimated the risk for Internet connections to be much lower than those reported above. Differences in study designs (population vs naturalistic) might explain discrepancies. We also found a higher risk of road accidents in relation to uploading Internet traffic than downloading. As Internet-related connections, such as browsing, email, and social networking, require user interaction with the mobile

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**Fig. 4.** Estimated dose–response curves (solid lines) and 95% CIs (dashed lines) for the number of calls, total call times, number of Internet connections, and number of text messages with road crash fatalities.
phone, the associated risk can also be compared with those related to dialling and locating/answering the phone that different authors estimated. All these studies (Simmons et al., 2016; Fitch et al., 2013; Klauer et al., 2014; Hickman and Hanowski, 2012) found much higher risks spanning from 0.99 to 8.32 for dialling and from 1.37 to 7.05 for locating/answering.

The above-mentioned discrepancies in the results might be caused by different factors. First, differences in methodologies and study designs can produce different evaluations of risks. Another factor for possible discrepancy could be that our evaluation of risks was dependent on the amount of population producing the analysed mobile phone traffic volumes. We used a normalised factor of 100 people to estimate the risk of road crash fatalities, but different values can produce different risks. Finally, possible inaccuracy in the evaluation of risks might be induced by inaccuracy in the determination of case and control exposures, as outlined below.

This epidemiologic study has a number of strengths. The case-crossover study design exploited the full potential of comprehensive real-world datasets on road accidents and mobile phone use, while removing most of the potential confounders by design. The availability of data such as the number of text messages and Internet connections are not conventional mobile phone data. The literature normally refers to a user’s involved call logs or call detail records (CDRs), which are often undistinguishable for typology of mobile phone traffic. Conversely, our data allowed the analysis of the specific risks due to specific phone uses. Finally, this study was population-oriented: despite the lack of data allowing a direct link between individual drivers and personal phone use, the study had a wider perspective as its hypothesis was that increased use of mobile phones in the underlying population (of both drivers and non-drivers) in a given time period could act as a distracting force for that population that increased the probability of crash fatalities.

This study has a number of limitations. First, the exact time of a crash may be not known with absolute certainty, as authorities usually round it in their report. An erroneous identification of the crash time could cause a shift in the time slot containing the crash time and consequently a misclassification of the corresponding case and control windows. Second, although most of the accidents were located in the highest resolution downtown cells, the remaining ones occurred in larger cells, where exposure is more spatially diffused with possible misclassifications. Third, not all of the crashes analysed necessarily involved the use of a mobile phone and not all of the involved drivers were connected to the mobile service provider that we used to get the exposure to mobile phone traffic. This could cause a bias in the overall risk estimations that we tried to minimise by collecting data from the provider with the highest market penetration.

5. Conclusions

This case-crossover study was applied to real-world crash fatalities data coupled in time and space with mobile phone traffic volume data, both collected in seven Italian metropolitan areas. Our study indicates an association but not necessarily a causal relation between the use of cellular telephones while driving and a subsequent crash with fatalities. We found the use of phone for calls, texts and Internet to be positively associated with road crash fatalities with incremental risks of 17.2%, 8.4%, and 54.6%, respectively, for an increment of 5 calls, 3 texts, and 40 connections for 100 people, respectively, during an interval of 15 min. Modifications of effects were identified for working days, night-time, morning hours, and areas with low street densities.

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All authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.aap.2018.03.008.

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