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Terrorist acts and pedestrians' behaviours: First insights on European contexts for evacuation modelling

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Highlights.

- Videotapes of real-world terrorist acts **in Europe** are analyzed.
- Qualitative assessment in the evacuation process **identifies more and less frequent** behaviors.
- Evacuation speeds in free-flowing conditions are analyzed.
- Fundamental diagrams of pedestrians' dynamics in emergency condition are provided.
- Results are compared **with** other evacuation types.

Abstract.

Europe has been subject to a significant increase in terrorist acts and their impact in recent years. In this context, real-world events **pointed out** how the pedestrians' **safety is** significantly affected by the attacks and their consequences on the **Built Environment**. **As already** done for other Sudden-onset disasters, **evacuation behaviours** should be investigated to properly define risk-mitigation strategies, thus considering the impacts of main factors such as attack type, crowd level, pedestrians' typologies, built environment conditions. This work tries to fill these literature gaps by innovatively proposing a **behavioural** database for terrorist acts according to consolidated methods. Firstly, videotapes of recent terrorist acts all over Europe are collected. Qualitative analyses reveal which **behaviours** are common with other kinds of emergencies and which seem to be more frequent, while quantitative analyses provide first structured data to simulate the pedestrians' evacuation, such as speeds and fundamental diagrams of pedestrians' dynamics. Comparisons with existing databases concerning other disasters are provided. Results highlight differences between **behavioural** outputs of qualitative and quantitative variables considering terrorist acts and other evacuation types. **Thus**, provided data could be used as input for developing and testing evacuation models in the contexts of terrorist acts.

Keywords. Human behaviors in emergencies; built environment; terrorist acts; emergency management; behavioral design; pedestrians' evacuation

Terrorist acts and pedestrians' behaviours: first insights on European contexts for evacuation modelling

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Terrorist acts and pedestrians' behaviours: first insights on European contexts for evacuation modelling

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1. Introduction

Terrorist acts in the Built Environment (BE) are characterized by a complex system of interactions between the attackers, the exposed **pedestrians and** the BE itself (Bruyelle et al., 2014; Golshani et al., 2019; Haghani, 2020; Institute for Economics & Peace, 2019; Ludvigsen and Millward, 2020). The effects of a no-notice emergency event **on pedestrians are** more relevant in case of crowded indoor and outdoor areas **where they** can gather. Hence, as for other kinds of emergencies, **pedestrians' behaviours** in case of terrorist acts should be

understood to improve the safety of **the BE itself**. The analysis of real evacuation events by videotapes **allows researchers to have a potentially unbiased** data source to this aim (Bernardini et al., 2019, 2016; Haghani and Sarvi, 2018; Yang et al., 2011). This process will ensure to move towards the development and use of emergency and evacuation simulation tools for risk assessment and risk-reduction solutions definition (Lin et al., 2020; Liu et al., 2019; Zhu et al., 2020).

The 9/11 terrorist act (Averill et al., 2005; Gin et al., 2014) defined a milestone in such issues for Authorities, designers and citizens, and oriented researchers towards the development of **behavioural** models and simulation tools. Nevertheless, efforts to provide a quantitative and qualitative characterization on pedestrians' **behaviours** in terrorist acts were limitedly performed, as well as efforts to develop experimental-based simulators (Averill et al., 2005; Bruyelle et al., 2014; Li et al., 2017; Liu, 2020, 2018; Ludvigsen and Millward, 2020). In particular, this simulation tools development cannot be correctly accomplished if experimental data are missed. **These actions are** urgently needed especially if comparing the state of the art on **other sudden onset** disasters in the BE like earthquakes and fires (Haghani, 2020; Lin et al., 2020; Liu et al., 2020; Zhu et al., 2020). In this context, only a few studies involved the analysis of pedestrians' **behaviours** in real-world videotapes of terrorist acts.

To move toward filling this gap, the present work performs quantitative and qualitative analyses on real-World events to provide **one of the first and wide databases** of pedestrians' **behaviours** in terrorist acts, focusing on different characteristics of the BE (e.g. indoor and outdoor; obstacles presence; safety management) and of the terrorist acts (e.g. type of attack; proximity between the pedestrians and the trigger). Due to the recent trends of terrorist acts all over the World, the European context is selected for such analyses. **Europe has** been subject to "the biggest improvement in the impact of terrorism" in **recent years, considering the whole World scenario**, especially in terms of victims (**70% between 2017 and 2018**) (Institute for Economics & Peace, 2019). **Nevertheless, the overall trend in terms of the number of terrorist acts has been significantly increased, for instance, +52% if comparing years 2014-2018 and 2009-2013** (National Consortium for the Study of Terrorism and Responses to Terrorism (START), n.d.). In this context, most of the terrorist acts were performed in few

Countries, i.e. France, Spain, United Kingdom, Belgium, Sweden, Italy, Germany (88% for acts during the years 2014-2018).

In view of the above, this work is organized in the following parts. The literature review compares and contrasts this work to the main existing researches, by also tracing the main capabilities of the proposed **behavioural approach** (Section 2). Then, methodologies to create the database, organizing it and analyzing the **evacuation behaviours** from qualitative and quantitative standpoints are provided (Section 3). Results are offered by distinguishing qualitative (i.e. *common* and *peculiar* emergency **behaviours**) and quantitative (i.e. fundamental diagrams) aspects (Section 4), so as to discuss the main key findings and comparing results with previous outcomes of other kinds of emergency and of terrorist-related emergencies (Section 5).

2. Literature review

The “behavioural design” perspective for risk-reduction strategies considers that the BE and its emergency management should be adapted depending on the behaviours of exposed pedestrians, to supply “information to damaged individuals about how to correctly behave, as, for instance, the ones connected to the evacuation path and safe area choice” (Bernardini et al., 2019). Simulators can be used by safety planners, local Authorities and first responders to this end. An experimental-based approach should be adopted to develop and validate reliable simulation models, by analyzing behaviours in real emergencies, and considering interactions between pedestrians, first responders, the surrounding BE and its modifications due to the event (Haghani and Sarvi, 2018; Liu et al., 2019; van der Wal et al., 2021; Yang et al., 2011; Zhu et al., 2020).

In this general **context**, efforts to provide databases reporting qualitative and quantitative **data** have been performed (Haghani and Sarvi, 2018; Templeton et al., 2020). Research works organize the *noticed behaviours* in relation to the 3 main common evacuation phases (Bañgate et al., 2017; Bernardini et al., 2019; Kobes et al., 2010; Lin et al., 2020):

- the pre-movement phase, which essentially deals with the identification of the emergency conditions (including warnings) and with preliminary actions towards the evacuation motion;
- the motion phase, that constitutes the evacuation itself;

- the immediate post-evacuation phase, in which people are “in safe conditions” and try (if possible) to overcome the disaster event.

The methodologies provided by previous works (Bernardini et al., 2019; Helbing et al., 2002; Yang et al., 2011) arranged **behavioural** results into more and less frequent **behaviours** according to their (statistical) frequency in relation to the analyzed sample. They distinguished *common behaviours*, that is, belonging to different disasters, from *peculiar behaviours*, that is, only belonging to a single disaster. They also evaluated discrepancies between real-world conditions and evacuation drills. Qualitative and quantitative differences among evacuation kinds exist and could affect the final process (Bernardini et al., 2019; Lin et al., 2020; Zhu et al., 2020). Hence, since the analysis on how people behave in emergency conditions due to terrorist acts is still limited, efforts to provide reliable (qualitative and quantitative) databases on such issue is urgently needed especially if based on real-world events (Haghani, 2020; Liu et al., 2020).

In fact, previous studies investigated **behavioural** issues concerning the terrorists/attackers, their organizations and related issues dealing with security aspects in large scale events, such as work safety, security and intelligence actions (Freytag et al., 2011; Fu et al., 2020; Marchment and Gill, 2019; Ruiz Estrada and Koutronas, 2016; Tutun et al., 2017; US department of Homeland Security, 2018). Meanwhile, general countermeasures to terrorist acts were developed and organized into national regulations, by additionally considering the relation with the different types of attacks that could be performed (Federal Emergency Management Agency, 2009; Institute for Economics & Peace, 2019; National Consortium for the Study of Terrorism and Responses to Terrorism (START), n.d.). As a result, literature works and guidelines investigated how to implement the related risk-mitigation solutions into the BE, thus encompassing layout-oriented and a building components-oriented perspective (Coaffee et al., 2009; Cuesta et al., 2019; Federal Emergency Management Agency, 2007). Besides, studies on risk perception and preparedness were also performed by involving wide population samples, by including data on, for instance, gender, nationality, education level, age, ethnicity, income (Bourque et al., 2013; Gin et al., 2014).

On the contrary, a limited number of studies **dealt with** the assessment **of pedestrian behaviours in** terrorist acts-related emergencies (Averill et al., 2005; Bernardini et al., 2017b; Bruyelle et al., 2014; Haghani, 2020; Li

et al., 2017; Liu, 2020; Ludvigsen and Millward, 2020). They mainly pointed out qualitative issues in motion, generally basing outcome data on interviews with survivors and, in a more limited way, videotapes of real-world events. Such studies were mainly related to indoor scenarios, that is to terrorist acts in buildings. They focused on (Bourque et al., 2013; Li et al., 2017; Liu, 2020): the possibility of receiving or detecting warnings related to the attack; the related analysis of risk-perception issues, also in view of the trigger proximity, that is the distance between the pedestrians and the source of the attack; the resulting activation of protective action responses and evacuation procedures, including the path selection. They also tried to include the analysis of security staff members' actions during the emergency (Liu, 2020; Ludvigsen and Millward, 2020). The main results provided evidence that, after a pre-movement phase, pedestrians start running towards a safe area. Group effects common to other evacuation kinds were noticed (Templeton et al., 2020; von Sivers et al., 2016). They can influence the path selection, the speed of the overall group and the group's delay timing, thus underlining pro-social issues in "panic" conditions. The lack of information in the first evacuation phases was remarked as one of the main drivers for the possibility to adopt not appropriate choices and to delay the evacuation starting (Bruyelle et al., 2014). A limited number of works provided first insights on individuals' motion quantities, such as evacuation speeds and their fluctuations (range from about 0.2m/s to 1.6m/s) (Wang et al., 2019). In this context, no structured data on fundamental diagrams of pedestrians' dynamic are provided at today. Finally, only few works tried to provide insights on solutions to increase people safety against terrorist acts based on real-world data (Bernardini et al., 2017b; Bruyelle et al., 2014).

Besides such poor behavioural analyses, simulation models for representing terrorist acts were developed, by also trying to represent attack effects and damages on the BE and the hosted pedestrians (Albores and Shaw, 2008; Chen et al., 2018; Manley et al., 2016; Wang and Wang, 2017). Most of them included general-purpose behaviours, such as those related to fire egress (which can be considered in respect to specific effects due to the attack, e.g. smokes in bombs explosions), while only a few of them were based on effective evacuation behaviours (Li et al., 2017; Liu, 2020). Microscopic approaches to the simulation seem to be widely adopted, due to the possibility to represent the interactions among attackers, attack actions and pedestrians over time

and space. For instance, relevant studies tried to pursue a social-force based (Liu, 2020, 2018) or a cellular automata (Chen et al., 2018) approach, also integrating Agent-based models (Şahin et al., 2019).

3. Phases and methods

The videotapes selection and analysis followed the workflow in Figure 1 and were based on consolidated behavioural analysis criteria of different kinds of emergency (Bernardini et al., 2019, 2016; Haghani and Sarvi, 2018; Johansson et al., 2008; Lu et al., 2019; van der Wal et al., 2021; Wang and Shen, 2019; Zhou et al., 2018). Firstly, videotapes of real-world emergencies due to terrorist acts were collected in a database and each of them was divided into specific “scenes” (Section 3.1). Then, qualitative analyses were performed to detect emergency behaviours and assess their activation frequency as well as the BE conditions that could induce their activation (Section 3.2). Finally, quantitative analyses on motion speeds were carried out to assess the pedestrians’ instantaneous evacuation speeds and the fundamental diagrams (Section 3.3).

3.1. Videotapes database and “scenes” creation

Videotapes, freely available from the Internet, were collected in the database if:

1. they came from reliable sources, such as Law Enforcement Agencies, Civil protection bodies, mass-media channels, and/or confirmed by them;
2. they concerned the European context, considering different European Countries at major risk (Institute for Economics & Peace, 2019);
3. the related terrorist acts involved pedestrians, and also provoked a relevant number of injured people and victims, thus demonstrating the impact of emergency conditions on the safety of the pedestrians;

Then, as shown by Figure 1, each selected videotape was divided into one or more “scenes” (Bernardini et al., 2019, 2016; Yang et al., 2011; Zhou et al., 2018). Each “scene” concerned one of the emergency phases (pre-movement, evacuation and immediate post-evacuation) and was characterized by the same *scenes characteristics*, that were:

1. *The type of attack according to codified threat types*, such as vehicles running into the target, bombing attacks and so on (Federal Emergency Management Agency, 2009; National Consortium for the Study of Terrorism and Responses to Terrorism (START), n.d.);
2. *BE in which the event occurs*, by subdividing them into (Lin et al., 2020; O'Neill et al., 2012): a) indoor, as for means of transportation and buildings; and b) outdoor, that is confined open spaces in the BE as urban streets, as well as unconfined ones as squares, parks and wide avenues;
3. *Presence of Safety/Security personnel*, to consider the visible influence of emergency authorities on the evacuation process, according to leader-follower interactions (Bernardini et al., 2019; Fang et al., 2016; Gayathri et al., 2017);
4. *Presence of "low" obstacles*, including fixed and movable ones. People can interact with them while moving along the paths and towards the targets, for instance by climbing them or knocking over them (Bernardini et al., 2019; Helbing et al., 2002). They refer to barriers, railings, street furniture and so on (Coaffee et al., 2009);
5. *Scenario modifications*, that are strictly related to the type of attack (i.e. bombing attacks). In this sense, the BE damages and modifications could constitute an impediment to pedestrians' motion, by varying the boundary conditions to the evacuation process (Averill et al., 2005; Kobes et al., 2010; Li et al., 2017);
6. *Trigger proximity*, since the pedestrians can perform different behaviours depending on their position with respect to the sources of the act (Li et al., 2017; Liu, 2020). According to the previous point 4, the videotapes were distinguished between those related to fixed cameras, such as surveillance cameras, or mobile cameras, including smartphones and by including the trigger proximity;
7. *the Level of Service (LOS), to trace* the density of pedestrians depending on the general limits classification (Transportation Research Board (TRB), 2000): A- up to 0.17pp/m², B- up to 0.27pp/m², C- up to 0.45pp/m², D- up to 0.72pp/m², E- up to 1.33pp/m², F over 1.33pp/m². LOS classification was also combined by jointly considering A+B, C+D, E+F (Klүpfel and Meyer-König, 2014) to define wider density ranges increasing the sample dimension. As for previous works (Bernardini et al., 2016; Chen et al., 2012; Shi et al., 2018), the open-source image analysis software Tracker (Version 5.1.5, <https://physlets.org/tracker/> - last access:

02/07/2020) (Brown and Christian, 2011) was used to manually determine the density of people within a specific area defined by the coder, thanks to filters for the framing perspective correction, the calibration of videotapes BE “scenes” dimensions and to the introduction of mass points for each pedestrian in the area. More details on the calibration and tracing process are given in Section 3.3. In case of poor “scenes” framing quality, LOS evaluations were reasonably performed according to LOS general qualitative definitions: A+B-people moving in quasi free-flowing conditions; C+D-movement in crowding conditions with limited physical contacts; E+F-movement with many physical contacts, up to compact crowd conditions.

All the “scenes” were classified according to these *scenes characteristics*.

“Scenes” with deleted frames, inadequate illuminance or excessive camera movements were removed from the database. “Scenes” from fixed cameras were preferred for quantitative analysis, because they permitted to focus on fixed boundary conditions of the BE, while pedestrians’ actions during the procedures were detected as long as possible in the camera field-of-view.

In view of the above, 39 videotapes were included in the database as reported in Appendix A. The final database contained 93 “scenes” and is available at: <https://drive.google.com/drive/folders/1H7SmChfkgQU1kEoMEZVQbAdK323gp1t7?usp=sharing> (last access: 14/07/2020). When the framing quality of these scenes allowed to continuously track individuals’ motion over time, manual tracking methods for quantitative analysis were applied (see Section 3.3). 23 “scenes” were investigated for these quantitative analysis purposes (Appendix A, Table A.1).

3.2. “Scenes” analysis: methods for qualitative analysis

Each scene was manually analysed to notice the presence of emergency behaviours defined in previous literature works and common to other kinds of disasters (called “common behaviours”), or the presence of peculiar or new behaviours, relating only to such terrorist acts (called “peculiar behaviours”) (Bernardini et al., 2019; van der Wal et al., 2021).

Then, each noticed behaviour was assigned to: (1) the specific evacuation phase filmed by the scene, to detect behavioural outcomes over the emergency timing; and (2) the scenes characteristics, to detect the most

frequently *noticed behaviours* for given boundary conditions. Specific subsamples of “scenes” were hence identified in terms of homogeneous conditions to organize the related results.

Finally, the statistical frequency of each *noticed behaviour* was calculated by considering the overall “scenes” sample and in each subsample depending on the related *scenes characteristics*. Each behaviour was also characterized by an Identification Code-ID, and a short description linking the possible literature references.

3.3. “Scenes” analysis: methods for quantitative analysis

The manual method for tracking pedestrians’ motion in evacuation conditions was chosen because of the videotape’s characteristics such as the not uniform *backgrounds* or the resolution of the images (Bernardini et al., 2016; Yang et al., 2011). The “scenes” involved unidirectional motion scenarios by considering physical limits to pedestrians’ motion. For indoor “scenes”, walls were identified as limits for pedestrians’ motion. For outdoor scenarios, the principal physical limits to the movement were building walls, street furniture and trees.

Firstly, the Tracker “perspective” filter was applied to the original videotape frame. In this way, the floor shape in the input frames was represented as a straight-on plane shape in the output frames, *where each* pedestrian was associated with a point mass, pointed at about hip level (Bernardini et al., 2016). Secondly, the geometric dimensions of the involved BE were calibrated by using real-world dimensions through plan data (e.g. for outdoor spaces, the width of the street, basing on Google Maps and Street View, <https://www.google.it/maps>; last access on 09/06/2020) and/or objects having known dimensions (e.g.: chairs, doors, cars). A general approximation of about 10cm was used in length measures for both calibration and individuals’ *tracking*. A constant time step equal to 0.067s (1 or 2 frames according to the videotapes framing features) was chosen to *track the instantaneous pedestrians’ position and then evaluate pedestrians’ instantaneous and average evacuation speeds* (Section 3.3.1) and *fundamental diagrams of pedestrians’ dynamic* (Section 3.3.2). All the tests and the statistical analysis were performed using MATLAB R2016b tools (<https://www.mathworks.com/help/doc-archives.html>, last access: 30/03/2021).

3.3.1. Pedestrians' evacuation speed

59 pedestrians were randomly selected between those that could be tracked for a significant time in the "scene", i.e. some seconds or more. 2057 instantaneous evacuation speeds v_i [m/s] were hence collected and organized into specific subsamples considering the related *scenes characteristics* (i.e. LOS, type of attack, indoor/outdoor BE, the city where the attack occurred).

According to previous works (Bernardini et al., 2016; Bosina and Weidmann, 2017; Kady, 2012; Zhou et al., 2018), basic statistics, boxplot representations and distribution analyses of v_i were provided. For each pedestrian, v_i outliers were identified according to the Interquartile Range IQR method (fence: $1.5 \cdot \text{IQR}$) (Rousseeuw and Hubert, 2011). This analysis allowed semi-quantitatively tracing the variation of speeds in such different conditions relating to the considered *scenes characteristics*.

Instantaneous evacuation speeds in LOS A were collected to evaluate (quasi) free-flow motion speeds, by involving the "scenes" of the terrorist acts of Stockholm, Brussels airport, Nice and Turin. The Anderson-Darling test (Anderson and Darling, 1952) was performed to assess the type of main distribution of v_i data, according to previous approaches (Bernardini et al., 2016; Kady, 2012). This test was selected since it allows evaluating v_i distribution shape in reference to Normal, Lognormal, and Weibull distributions, which refer to classical distribution shapes of instantaneous speeds (Bernardini et al., 2016; Bosina and Weidmann, 2017; Kady, 2012), and allows calculating critical values (thus ensuring more sensitive tests) (Evans et al., 1989)¹. Histograms and cumulative frequency diagrams were also provided. Comparisons to previous works outcomes about other kinds of evacuation and general purposes databases (Bernardini et al., 2016; Bosina and Weidmann, 2017; Shi et al., 2009) were then carried out.

Finally, basics statistics were also provided on the average speeds of the traced individuals over the analysis time, so as to mitigate the effects of instantaneous values over time. Boxplots were provided as for the v_i values.

¹ <https://www.itl.nist.gov/div898/handbook/eda/section3/eda35e.htm> (last access: 02/12/2020)

3.3.2. Fundamental diagrams

The instantaneous pedestrians' position tracking was also used to provide fundamental diagrams, by applying the so-called "Method A", as introduced by (Zhang et al., 2011) and already used by previous reference works (Bernardini et al., 2016). In fact, this method relies on the instantaneous detection of pedestrians' movement crossing a given cross-section of a certain width, and then "calculates mean value of flow and density over time" (Zhang et al., 2011).

478 pedestrians were tracked by obtaining 31 density-speed and density-flows pairs. These pairs were discussed by providing their classification for the overall "scenes" sample, and for indoor and outdoor BE subsamples. In particular, the flow values were normalized through the cross-section width to have comparable results in different "scenes". The Kladek formula described in Equation 1 (Bruno and Venuti, 2008; Seyfried et al., 2010) was used to define, for the first time, fundamental diagrams of pedestrians' dynamics in emergency conditions due to a terrorist act. This formula can be implemented in simulation models.

$$v_{F,hi}(\rho) = (v_{F,hf} - v_{min}) \left\{ 1 - \exp \left[-k \left(\frac{1}{\rho} - \frac{1}{\rho_{max}} \right) \right] \right\} + v_{min} \quad \text{if } 0 \leq \rho \leq \rho_{max} \quad (1)$$

This empirical relation allowed linking the pedestrian speed at a given density $v_{F,hi}(\rho)$ [m/s] to four parameters: the preferred speed $v_{F,hf}$ [m/s], related to free-flowing conditions (minimum experimental density); the maximum experimental density ρ_{max} [pp/m²]; the minimum experimental velocity v_{min} [m/s], that is the one measured at ρ_{max} ; and a constant factor k that influences the curve shape. The Kladek formula was provided by considering density-speed pairs composing:

- the whole sample. In this case, the regression model according to the Kladek formula was also shown with respect to the related prediction boundaries at 95% of confidence;
- only the outdoor scenarios sample;
- only the indoor scenarios sample.

The fittings accuracy was analyzed through the R^2 value and the Root Mean Square Error (RMSE) to evaluate the standard deviation of a typical observed value from the Kladek formula-related prediction.

Finally, such experimental results were compared to the main previous works outcomes from:

- the studies of (Hankin and Wright, 1958) and (Mori and Tsukaguchi, 1987) for both density-speed and density-flow pairs, so as to trace differences with available general-purpose correlations;
- experimental-based curves following the Kladek formula proposed by: (1) (Bosina and Weidmann, 2017), to trace differences with general-purpose databases; and (2) (Bernardini et al., 2016), to trace differences with other kinds of emergencies involving a potential high excitement of the evacuating pedestrians while running far from the event triggers (i.e. earthquake).

4. Results

Figure 2 reports the frequency related to the Country from where the “scenes” are identified (also compare to Appendix A). 65% of the “scenes” refers to videotapes from mobile cameras. In particular, pedestrians were placed near to the trigger and directly participated in the emergency process in 38% of the overall “scenes”. 70% of the “scenes” involved open spaces in the BE, such as streets, squares and building courtyards, while 30% refers to indoor spaces, such as public transportation hubs, means of transportation, concert halls. “Scenes” are quasi-homogeneously characterized in terms of the type of attack, that is 31% for armed assault, 33% for vehicle running into the crowd and 36% for explosion. Safety/security personnel was present and visible in 29% of “scenes”. Obstacles' presence was registered in 50% of the “scenes” and, in 59% of them, the environment was altered by the attack influencing the choices of pedestrians during their motion (Kobes et al., 2010; Lin et al., 2020; Zhu et al., 2020). Such attack effects are present for bombs explosion, that can provoke smokes in the BE. Moreover, 70% of “scenes” were filmed near the attack source, thus strongly influencing the individual perception of imminent threats (Li et al., 2017; Liu, 2020). Finally, 89 “scenes” allowed the LOS calculation. Related LOS classifications outline how 40% of “scenes” refer to LOS A+B, 19% of “scenes” refer to LOS C+D and 41% of “scenes” refer to LOS E+F.

4.1. Qualitative analysis: results on noticed behaviours

Table 1 offers an overview of noticed behaviours. For each of these behaviours (x-axis) and considering the whole “scenes” sample, Figure 3 graphically shows the related percentage frequency (left y-axis) and sample dimension (right y-axis). Then, Figure 4, Figure 5 and Figure 6 point out the percentage frequency of the same behaviour depending on the scenes characteristics defined in Section 3.1. The noticed behaviours are shown

in these figures according to Table 1 ID. Differences in the sample dimensions of each *noticed behaviour* in Figure 3, Figure 4, Figure 5 and Figure 6 exist because of the specific *scenes characteristics and reference elements of interaction for the pedestrians*.

In the following sections, the *noticed behaviours* are discussed in reference to the order of the evacuation phases in which they are performed, as shown by Table 1. *Some examples* are proposed by means of significant videotapes frames, shown in curly brackets², according to the identification codes of *Appendix A, Table A.1*.

4.1.1. Pre-movement phase

Since effects on the BE depend on the *type of attack*, the event could be perceived by the crowd in different ways depending on the possibility to have or not widespread and evident scenario modifications, as well as specific perceived cues. *In general terms, this* phenomenon is *common to* other emergency events in the BE, that are fires (i.e. smokes, fires and alarm), floods (i.e. the level of floodwater) and earthquakes (i.e. earthquake-affected damage or relevant ground shaking) (Lovreglio et al., 2016; Zhu et al., 2020). *Anyway, although similar* trends in pre-movement *behaviours* exist, differences between the type of attack are noticed in Figure 4. *“Pro-social” behaviours* seem to be generally performed to evaluate the effective emergency scenario, *in common* with other emergencies. *They* lead the pedestrians to evaluate the possibility to start the evacuation process. *According to Figure 3, these behaviours* generally *seem* to be less frequent than the others relating to the pre-movement phase. Nevertheless, a higher incidence seems to be correlated to specific *scenes characteristics that could increase interactions among the pedestrians*, such as: (1) *LOS E and F* scenarios, where the density of *pedestrians* could improve communication exchange and group *behaviours* {M2, S8}; (2) when no *safety/security personnel* is present, thus promoting self-organization *behaviours* into the crowd {N2, Ma5} (Bañgate et al., 2017; Haghani and Sarvi, 2018); (3) in case of *trigger proximity*, thanks to the possibility to effectively look for direct information on the event {Ma8, T10} (Bourque et al., 2013; Li et al., 2017; Liu, 2020).

² *in the related figures, we included* video timing when needed in the form minutes:seconds

Meanwhile, the perception of the event through sensible cues generally provokes the activation of *response to sensible events behaviours, in common with other emergencies, such as fires* (Li et al., 2017; Liu, 2020). This *behaviour* seems to be more frequent when surrounding conditions allow the pedestrians to have a more free view of the scenario, such as in case of: (1) *trigger proximity* {Br4,T2}; (2) *indoor BE* {Ma2,P1}; and (3) *for lower LOS values* {N1, N2, S7}. These conditions can be additionally combined together, as in the example of *Figure 7* {Ma5}, where the distance with the event trigger in an indoor BE affects the response time of different building sectors. Concerning the *type of attack*, this *behaviour* is less frequent in *the* case of vehicles running into the crowd, essentially because of the surrounding conditions in which the attack happens and the duration of the attack itself (e.g. {N1, N2, B1}). Similar issues *were noticed* in the outdoor BE with low *LOS* values, such as in the Nice and Berlin events, where the attackers drove a truck against the crowd. As shown by *Figure 7* for the Nice event {N1}, people started to run away after they *saw* the approaching truck. On the contrary, people placed in front of the truck did not immediately react to the imminent risk, because it was placed behind them. Furthermore, in such a scenario, people started running in the same truck direction.

Different reactions can also be reconducted to the action performed by other people, because of indirect “pro-social” *behaviours* including “imitative *behaviour*” and herding in pre-movement responses (Haghani and Sarvi, 2018). For instance, the Turin event was characterized by an armed assault using spray, according to further police investigations. Nevertheless, *this* videotape analysis *highlights* that no direct action by the supposed terrorists was noticed by the crowd. In fact, the crowd simultaneously started to evacuate after having seen the motion of a restricted group of pedestrians, without perceiving any other sign about the real presence of a risk. The event consequences in terms of injured people and deaths demonstrated that collective response in absence of clear information about the threat could be more dangerous than direct ones. In this sense, suggestions from previous works on “phantom panic” and waves in the crowd seem to be confirmed (Helbing et al., 2002; Helbing and Johansson, 2010; Johansson et al., 2008).

In five “*scenes*” related to two videotapes {P1,Br2}, the *response to a sensible event* also *included* the adoption of pre-movement safety *behaviours*, such as drop-hold on strategies, by means of additional “*pro-social*” *behaviours, in common with other emergencies such as earthquakes* (Bañgate et al., 2017; Haghani and Sarvi,

2018). Considering the *scenes characteristics*, this phenomenon is mainly pointed out in case of: (1) type of attack provoking sensible cues, such as during an armed assault with fire guns {P1}; (2) immediate *scenario modifications* to the surrounding BE, such as those due to smokes or debris {Br2}; and (3) trigger proximity, since pedestrians could directly perceive it/its consequences {Br2}. For instance, in the Brussels airport attack {Br2}, pedestrians protected themselves remaining in groups and laying on the ground immediately after the explosion, as shown by Figure 9. They started the evacuation towards the exits in a second moment, that is after about 2 minutes from the activation of the drop-hold on strategies. Nevertheless, such behaviours appear to be marginally frequent with respect to the general response behaviours. In this sense, this result could be also affected by the sample dimension, as well as by different risk perception and risk awareness levels of the involved pedestrians (Lovreglio et al., 2016).

The *curiosity effects* can be considered as the most frequent pre-movement behaviour, in common with other kinds of evacuation, such as floods (Bernardini et al., 2019, 2017a; Kaigo, 2012). Main drivers to this behavioural response seem to be identified in the trigger proximity, as shown by Figure 4-C. People placed far from the trigger are allowed to remain in safer conditions for a longer time, thus ignoring the evacuation procedure while shooting the scene {N4, Ma5}. Nevertheless, pedestrians involved in the evacuation process could also use their mobile devices to shoot the disaster. In fact, this behaviour is confirmed by 38% of “scenes” that are directly associated with mobile devices videotapes shooting near the trigger and into the moving crowd. Outdoor conditions seem to provide the highest activation frequency {B2, Ma7; T15}. According to Figure 4-A, this behaviour seems to be less frequent in case of armed assault {T15}, while it is more frequent in explosion-related “scenes” {Ma4, Ma5, Ma7}. This outcome could be due to the different rapidity in the evolution of the scene after the trigger appears, that is immediate in case of the explosion, while longer for armed assault. Nevertheless, such results could be also affected by the sample dimensions, too.

Finally, previous works underlined that attachment to belongings behaviours during the pre-movement time should be common to both terrorist acts and other kinds of emergency (Averill et al., 2005; Bañgate et al., 2017; Lin et al., 2020). However, these behaviours were not shown in the assessed sample at this stage. This

result could be due to the fact that “scenes” refer to pedestrians who still owned or were moving with belongings.

4.1.2. Evacuation phase

Regardless of the specific conditions of the surrounding BE scenario, the *attraction towards safe areas* and the related evacuation path choice seem to be the most frequently noticed *behaviour*. This behaviour is common to all the different emergencies in the BE (Bernardini et al., 2019; Haghani and Sarvi, 2016; Helbing et al., 2002; Liu, 2018). Considering the *scenes characteristics*, this behaviour is more frequent in *indoor* scenarios, as shown by Figure 4-B, and when *no safety/security personnel* is present, as shown by Figure 4-C. Furthermore, according to Figure 5-C, it seems to be more frequent in respect to people far from the event trigger, as a supposed consequence of the possibility to perform evacuation issues due to the distance from the attack source. In this sense, this result confirms the pre-movement related behaviours described in Section 4.1.1.

As a peculiar issue in *attraction towards safe areas* behaviours, the choice of *running far from the event trigger* can be mainly aimed at leaving the initial position in a short time and without a precise awareness about “where to go”. People could hence select the first available direction, including dead-end paths. Although this behaviour seems to be common with earthquake and fire evacuation as well as remarked by studies on terroristic acts (Bernardini et al., 2019; van der Wal et al., 2021), its frequency varies depending on the *type of attack* (Figure 4-A) and the *BE in which the event occurs* (Figure 4-C). Moreover, when pedestrians are placed near the trigger source, the activation of *running far from the event trigger* behaviour seems to be more frequent, as shown by Figure 5-C. As shown by the examples in Figure 10, this phenomenon can be seen in mono-directional spaces, such as corridors, including those of means of transportation {M2}, passageways and narrow streets {N4}, as well as in confined outdoor spaces such as squares {T16}. Considering the LOS A+B sample in Figure 6, it is worth noticing that the presence of such behaviour can be linked to lower density in pedestrians’ crowd. A possible reason for this outcome is the lower influence of “pro-social” behaviours in the evacuation process, which can point out the collective motion effects rather than the individual’s choices. According to previous works (Haghani and Sarvi, 2018; Koo et al., 2014; Li et al., 2017; Zhu et al., 2020), the BE layout can affect the evacuation path selection as a paramount element with respect to the necessity to

perform response actions under pressure conditions, and in case of limited familiarity with the surrounding spaces. In this sense, the first pedestrians' choice seems to be the first available path/evacuation target perceived as safe. This behaviour could also provoke people to adopt risky behaviours, e.g. getting out of windows to be repaired from the terrorist act, such as in the Bataclan event shown by Figure 11 {P2}.

As stated before, "pro-social" behaviours highly affect the whole movement towards the evacuation target, in common with other kinds of evacuation. In particular, the attraction for group ties and the possibility of supporting more vulnerable pedestrians while moving is more frequent for lower LOS values, thanks to the possibility to better identify groups sharing motion purposes in the scene. Furthermore, it could be also noticed that:

- the absence of safety/security personnel seems to increase both the effects, because of the need in the self-organization of groups during the motion process (Johansson et al., 2008);
- the attraction for group ties seems to be more frequent for people placed far from the event trigger, since here people can move more freely (Haghani and Sarvi, 2018; Koo et al., 2014). On the contrary, the formation of evacuation groups in view of herding behaviours (and, marginally, the presence of stop-and-go waves) is more frequent in presence of modifications to the BE induced by the attack source, and, mainly, in higher density conditions, as expected, in common with other evacuation conditions (Johansson et al., 2008). Figure 6 graphically shows this trend.

In common with other crowd conditions (Fang et al., 2016; Templeton et al., 2020), such kind of attractive phenomena points out how the counterflow in evacuation motion has a significant impact in statistical frequency terms for the overall sample {S8, Ma2}. As for the avoidance of evacuation performing, Figure 4-C shows how the absence of safety/security personnel seems to increase the frequency of this behaviour, while low obstacles could amplify it by creating boundary conditions for counterflow creation, according to data in Figure 5-A.

Apart from attractive phenomena in motion, the pedestrians' trajectory seems to be limitedly affected by repulsive mechanisms to avoid physical contact. It is worthy of notice that such modifications to the individual's motion towards the target can be significantly altered by the necessity of preventing people who

avoid performing evacuation procedures. An example in this sense is also shown in Figure 12 {T5}. This phenomenon can additionally lead to possible pressures and collision between pedestrians, being common to other evacuation kinds, such as flood, earthquakes, and general purposes evacuation in high density conditions (Bernardini et al., 2017a; Helbing and Johansson, 2010; Wang et al., 2019). The avoidance to performing evacuation procedures could be amplified by the activation of social behaviours (including milling related issues) and curiosity-related effects, thus confirming common outcomes of other kinds of evacuations characterized by a slow increase of risk conditions for the pedestrians, such as flood emergencies. As expected, this behaviour seems to be more frequent considering people placed far from the event trigger, in outdoor scenarios (thus increasing the possible distances between the event source) and for LOS A conditions (due to the lower influence of crowd movement on the individuals) {Ma5, P2, T5, T10}. Finally, this behaviour seems to be partially affected by the absence of safety/security personnel visible in the “scene” (lacking information about the emergency conditions and instruction to be followed), being common to general evacuation issues concerning guidance behaviours and self-organization of the crowd (Bańgate et al., 2017; Haghani and Sarvi, 2018).

Such repulsion phenomena seem to be limitedly activated in relation to indoor obstacles like walls, railings and chairs, as well as to outdoor typical BE elements like fences, trees, street furniture and other movable elements such as metal barriers. This finding is common to other kinds of evacuation, such as during earthquakes, in view of the possibility to allow physical contacts or look for them to get support, especially in outdoor scenarios (Bernardini et al., 2019). In some case, pedestrians move from not keeping a “safety distance” from “low obstacles” to climbing over low obstacles/knock over mobile obstacles while moving, to minimize variations in the evacuation direction {M8, T2, T5}. Such climbing and pushing behaviours are also common to previous researches between the pedestrians placed in crowded/confined spaces (Cornes et al., 2017; Helbing et al., 2002; Johansson et al., 2008; Schadschneider et al., 2009). According to the results of this work, this behaviour occurs only in LOS E+F “scenes”, as shown by Figure 6. In these cases, mobile barriers and also fixed railings (compare to Figure 13-A) can easily knock over because of the pressure of the crowd in “stampede” conditions (compare to Figure 14). As a result, low and movable obstacles can become hazardous

items for the evacuation motion. In particular, people can tread on them in crowding conditions by potentially falling down, thus being stepped on by other pedestrians, such as in the Turin event.

Moreover, **pedestrians** can decide to climb low obstacles such as platforms to be safe from the stampede scene, as shown in **Figure 13-B**. **Figure 5-C** also shows how such **behaviour** seems to be more frequent when **pedestrians** are placed near to the event trigger, by confirming the aforementioned general trends in the reaction due to proximity issues. Although barriers seem to essentially knock over because of the pressure phenomena inside the crowd, results additionally **point out** how “*Selfish*” and *competitive behaviours* seem to be relevant in the analyzed sample, **in common with previous works** (Drury and Cocking, 2007; Haghani and Sarvi, 2018). In particular, as shown by **Figure 5-A** and **Figure 5-C**, these **behaviours** seem to be more frequent when low obstacles are present and for people placed near to the event trigger, thus relating the pushing phenomena with the overall crowd excitement {N1, N2, Br4, T2, T10}.

The *guide effect for presence of rescuers* **is common to the other kinds of evacuation** (Averill et al., 2005; Fang et al., 2016). **Nevertheless, this behaviour seems** to be less frequent **than** the other interactions among the pedestrians, and mainly related to **indoor scenarios** (see **Figure 4-B**) and **in the case of trigger proximity** (see **Figure 5-B**). The reasons could be related to: **(1) the crowd** excitement in the immediate emergency response; **(2) the** necessity by first responders, such as police officers, to respond to counterterrorism actions. Nevertheless, examples of rescuers’ support to the exposed **pedestrians** are shown, by means of {Br2, M5, T5}: **(1)** direct physical guidance and assistance (as in **Figure 14**) and support by instruction via Emergency Public Address Announcement and Alert Sound Systems, if considering the evacuation process; **(2)** support to injured people in the immediate aftermath (as in **Figure 15-A**), by also cooperating with evacuating pedestrians.

4.1.3. Safe area reaching

In view of the *attraction towards safe areas*, once **pedestrians** arrive in outdoor scenarios, trends in *Safe area definition* seem to be mainly related to specific BE and attack conditions, **being peculiar of the terrorist act emergencies**. This is the most frequent **behaviour** in the safe area reaching phase, but it seems to be less frequent than the *avoidance of evacuation procedure performing*. However, we can assess that **pedestrians**

tend to gather as far as possible from the event trigger/of the attack-damaged BE, as also remarked by Figure 5-C {Ma7, Br3a}. In this sense, this behaviour confirms the fear of the event as pointed out by evacuation behaviours described in Section 4.1.2.

In some cases, the *influence of not immediate danger feelings or helplessness conditions* implies the *evacuation end* (or interruption), in the first available safe area. In this sense, this behaviour is mainly common to earthquake evacuation scenarios (Bernardini et al., 2019) {M1, S5, Ma1, T10}. As for the safe area definition, this result is affected by the *avoidance of evacuation procedure performing, which seems to be a peculiar behaviour, too. For instance*, raised platforms are considered safe positions in case of crowd stampede, as in Figure 13-B. This phenomenon seems to be more frequent at greater pedestrians' densities, as shown by Figure 6, mainly as a consequence of group behaviours.

The BE in which the event occurs, and thus its layout, as well as the type of attack, can influence the peculiar definition of the safe area as well as the evacuation end, especially in crowded spaces (NaCTSO - National Counter Terrorism Security Office, 2017), as well as in view of possible wayfinding strategies. In this sense, this phenomenon is combined with *running far from the event trigger*, as discussed in Section 4.1.2. In case of a fixed trigger, such as an explosion, pedestrians can tend to interpose the greatest distance as possible between them and the bombing site, especially in outdoor conditions. Attacks with fire guns at the Bataclan {P1, P2} show similar reactions to those of the bombing attack at the Brussels airport {Br3a}. In both cases, people covered their heads and remained on the ground, while others tried to reach a safe area, maybe having a low level of familiarity with the BE layout. Consequently, they could be involved in serious threats, as shown by Figure 11, and they can end their evacuation in the toilettes or blind alleys. Similarly, a movable trigger in outdoor conditions, such as a vehicle running to the crowd, could provoke damages in a wider area of the BE. In this sense, during the Nice attack, the truck driven by the attacker travelled over the street and the sidewalk, and no obstacles to cover people were present. For this reason, some exposed pedestrian decided to escape on the beach {N1, N2, N3}. On the contrary, during the Stockholm assault in the historic centre {S5, S7}, the

vehicle running into the target led pedestrians to try to refuge behind obstacles or inside shops (such as in “invacuation”³ or sheltering in place procedures (FEMA-426/BIPS-06, 2011)).

In safe areas, pedestrians can gather by performing additional “pro-social” behaviours in post-evacuation conditions, including those related to support injured people, as shown by Figure 15. Then, they can wait there for the rescuers’ arrival. This behaviour is common to other emergencies (Averill et al., 2005; Bernardini et al., 2019; Rao et al., 2011). Such “pro-social” behaviours are also activated: (1) in collaboration to safety/security personnel, as shown by Figure 16-A, thus according to increased guide effect for presence of rescuers; or (2) spontaneously performed as a consequence of social shared identity in the crowd, as shown by Figure 16-B, in view of the aforementioned “pro-social” behaviours in the evacuation phase.

Finally, according to the attachment to things effect in the immediate aftermath, people located in a close position in respect to the initial one could be led to collect personal belongings in the event site, in common to other emergencies in outdoor BE, such as earthquakes or hurricanes (Rao et al., 2011; Riad and Norris, 1996). As an example, Figure 17 {T2} shows a girl moving towards the hypothetical attacker to retrieve her bag, in correlation to evacuation end behaviours.

4.2. Quantitative analysis: results

The quantitative analysis is traced with respect to pedestrians’ evacuation speed (Section 4.2.1), and the fundamental diagrams of pedestrians’ dynamics (Section 4.2.2).

4.2.1. Pedestrians’ evacuation speeds: results

Figure 18 shows the histograms (density) and cumulative probability curves of v_i for the LOS A conditions. According to the collected “scenes” sample, we collected such data only for outdoor conditions. Figure 18 offers the Normal, Log-normal and Weibull distributions. v_i ranges from 0.17m/s to 8.4m/s (at 99th percentile⁴), with a median value of 3.16m/s and an arithmetic mean of 3.32m/s. The Anderson-Darling test at 99% rejects the Normal and Log-Normal distributions, while the Weibull distribution does not seem to be rejected. The

³ Compare to PD 25111:2010 – “Guidance on Human Aspects of Business Continuity”: “the movement of people to pre-identified areas inside the building/site in order to protect them from external dangers during an incident”, without leaving the disaster-affected BE. In many terrorist acts, it concerns remaining (or moving) inside of the building, thus waiting for security officers (e.g. in case of armed assault).

⁴ a maximum value of 10.26m/s is shown by data, but it seems to not be an outlier.

outcoming Weibull distribution is characterized by the following values: mean=3.31m/s, variance=3.76m/s; parameters estimate: A (scale)=3.72 with standard error=0.08, B (shape)=1.77 with standard error=0.06; A-B estimated covariance of parameters estimates always lower than 0.007.

Considering the whole sample (both indoor and outdoor conditions), Figure 19 shows how the v_i values seem to slightly decrease when the density conditions increases, as expected. The position of x values in Figure 19 is qualitatively provided. This outcome is more clearly shown by the Q1 values, although differences seem to be generally smaller. For instance, LOS D and E seem to have similar trends. Anyway, the results of some subsamples could be affected by their dimension.

The same effects are remarked by the average speed boxplot provided in Figure 20-A, which mitigates the possible instantaneous variations of speeds over the analysis time (some seconds). In view of such results, Table 2 summarizes the related basics statistics, by distinguishing values for indoor and outdoor samples and confirming the general aforementioned trend.

In addition, Figure 20-B shows the range of average speeds depending on the *type of attack*, while Figure 21 shows the classification between *indoor/outdoor* conditions and the city-related scenarios. In both these figures, the boxplot values range depends on the sample dimension of the considered grouped LOS.

Finally, Table 3 summarizes the results on average speeds by offering the sample dimensions, while Figure 22 shows these average speed values combining LOS conditions, *indoor/outdoor* BE and *type of attacks*. This classification highlights how differences among types of attacks seem to exist, by suggesting how:

- the lowest speeds can be retrieved in case of an explosion, even if lower pedestrians' densities occur in the scene. It is worth noticing that the explosion-related scenarios mainly refer to LOS B in Brussels attacks;
- the spray attack registers the highest speeds (i.e. Turin event), maybe because of the high excitement level of the pedestrians also due to the trigger proximity.

4.2.2. Fundamental diagrams

Density-speed and density-flow pairs are respectively shown by Figure 23 and Figure 24, by comparing them with previous consolidated data (Hankin and Wright, 1958; Mori and Tsukaguchi, 1987).

In general terms, the noticed speed trend over density confirms previous works outcomes, mainly for indoor sample data (e.g. compare pairs in [Figure 23](#) for flows data). **Anyway, contrarily** to the reference works (Hankin and Wright, 1958; Mori and Tsukaguchi, 1987), experimental density-flow pairs **do not seem to point out** the density values which can maximize the flow. Concerning density-speed data, values of the present work are generally higher than the literature ones, especially by considering low-density cases. **Such an outcome** can be explained by the influence of the high grade of threatening of the selected scenarios, which can increase the **pedestrian's** excitement in quasi free-motion conditions. A similar effect is also discussed in reference to the attraction towards evacuation **behaviours** in Section 4.1.2.

[Figure 25](#) shows the overall sample distribution concerning such density-speed pairs, by tracing the Kladek-based regression (see Equation 2), while [Figure 26](#) shows the regression for outdoor (see Equation 3) and indoor (see Equation 4) separated samples:

$$v_{F,hi}(\rho) = (2.50 \text{ m/s} - 0.72 \text{ m/s}) \left\{ 1 - \exp \left[-0.14 \left(\frac{1}{\rho} - \frac{1}{2.67 \text{ pp/m}^2} \right) \right] \right\} + 0.72 \text{ m/s} \quad (2)$$

$$v_{F,hi}(\rho) = (2.50 \text{ m/s} - 0.31 \text{ m/s}) \left\{ 1 - \exp \left[-0.19 \left(\frac{1}{\rho} - \frac{1}{2.15 \text{ pp/m}^2} \right) \right] \right\} + 0.31 \text{ m/s} \quad (3)$$

$$v_{F,hi}(\rho) = (1.04 \text{ m/s} - 0.72 \text{ m/s}) \left\{ 1 - \exp \left[-0.14 \left(\frac{1}{\rho} - \frac{1}{2.67 \text{ pp/m}^2} \right) \right] \right\} + 0.72 \text{ m/s} \quad (4)$$

The proposed Kladek formula-based regression models effectively suggest a vertical translation with respect to previous **ones** (Bosina and Weidmann, 2017; Mori and Tsukaguchi, 1987). $v_{F,hi}(\rho_{max}) = v_{min} > 0 \text{ m/s}$, thus confirming results from previous experimental data about other kinds of emergencies, such as earthquakes (Bernardini et al., 2016), and modelling approaches (e.g. the Q-model by (Lämmel et al., 2008)). Anyway, no maximum density leading towards null speed is noticed in the experimental sample, although the existence field for density values is lower than the common ones (general limits for pedestrians' movement blockage at about 5.0 to 5.5pp/m² (Bosina and Weidmann, 2017; Hankin and Wright, 1958)). [Figure 27](#) graphically summarizes the differences between this study regression model and references curves for: earthquake (Bernardini et al., 2016); general-purpose (Bosina and Weidmann, 2017). **When** pedestrians'

density **increases**, a significant reduction in motion **speed is noticed**. In particular, the speed measured at the minimum experimental density is 88% greater than the one at the maximum density. On the contrary, the density-induced reduction of speed is **less evident for the indoor sample rather than for the outdoor one**. Nevertheless, the *indoor* density values are more dispersed than the *outdoor* ones, thus affecting the final regression model estimate.

As a result, the combination of *indoor* and *outdoor* pairs in the regression model **affects** the outcoming Kladek formula. On the one hand, the *indoor* subsample mainly affects the density existence field. In fact, the existence field for Equation 2 (both *indoor* and *outdoor* conditions) and Equation 4 (*indoor* conditions only) refers to $0 \leq \rho \leq 2.67 \text{ pp/m}^2$, while for Equation 3 (*outdoor* conditions only), it refers to $0 \leq \rho \leq 2.15 \text{ pp/m}^2$. On the other hand, the *indoor* subsample mainly affects the regression shaping. In fact, k values at 5% and 95% of confidence for the regression model of Equation 2 are respectively equal to 0.09 and 0.19. If relating to the 95% of confidence, Equation 2 moves towards the speed-reduction trend shaping of outdoor sample conditions in Equation 3.

Finally, the Kladek-based regression is characterized by $R^2=0.57$ and $\text{RMSE}=0.43$, while *outdoor* and *indoor*-related models show similar R^2 (about 0.44) and RMSE are respectively equal to 0.54 and 0.16. Although the prediction error **based on RMSE** seems to be lower in *indoor*-related conditions, **such results** can be affected by the sample dimension, as well as by the scattered input values, especially for *outdoor* sample conditions (i.e. the majority of data refers to density values over 0.5 pp/m^2).

5. Discussion

The research outcomes in pedestrians' qualitative and quantitative **behaviours** in case of terrorist acts in the BE provide interesting first insights for comparisons with other kinds of evacuation and for modelling purposes.

Qualitative results for the whole analyzed sample **underline** how the most frequent **behaviours** are essentially those **common** to other kinds of emergencies, thus suggesting **that possible modelling issues and risk-reduction strategies could be borrowed from those** (Bernardini et al., 2019; Haghani, 2020; Helbing et al., 2002; Kobes et al., 2010; Lin et al., 2020; Zhu et al., 2020).

The *curiosity effects* in the pre-movement phase **are performed** in view of the necessity to “see what is happening” and then decide how to behave. **Thus, this behaviour underlines** that a pre-movement time exists. Further works should move towards the quantification of this time span, by also taking into account risk-perception issues for the **pedestrians** and their use of mobile devices, as for fire and earthquake evacuation (Bernardini et al., 2019; Kaigo, 2012). **Communication strategies** between the first responders and the pedestrians could take advantage of the use of such mobile devices. They can inform pedestrians before the event on how to behave in case of an emergency, as well as pedestrians placed farther from the trigger during the emergency itself, also for wayfinding purposes (Aliperti and Cruz, 2020; Ryu, 2015). **Such** interaction strategies **could be combined with** the deployment of safety staff members and **first responders to** the BE, for instance, according to a homogeneous distribution in less attack-sensible **areas, too. More and more pedestrians could be supported and led to correctly behave and evacuate, according to the aforementioned “behavioural design” perspective. This strategy could have three main impacts. First, the risk-increasing avoidance of evacuation procedure performing, which is a peculiar behaviour noticed after the trigger is gone, could be hence reduced.** From a modelling perspective, its influence and probability of activation increase with the increase of distance from the trigger, **thus suggesting a widespread deployment of safety staff members in the whole BE. Second,** the support by first responders could **also** limit the negative effects on the pedestrians’ dynamics of the crowd, thus limiting crushing and stepping **on** (Alnabulsi et al., 2018; Helbing and Johansson, 2010). **Third, effective communication with the exposed pedestrians could be reached, thus also reducing running during the evacuation (van der Wal et al., 2021).**

During the evacuation phase, the *attraction towards safe areas* is the most frequent **behaviour**, but the dynamics of path choice and speed are affected **by: (1) common behaviours, that are “pro-social” behaviours and “selfish” and competitive behaviours; (2) peculiar behaviours linked to the specific safe area definition criteria in a terrorist act.** In this sense, as for fire evacuation, the main driver for the path selection is the immediate **leaving of the** trigger-affected area, but the specific evacuation modelling should consider **the type of attack and** its rapidity to modify the BE over the time, as well as the level of knowledge of the BE layout by the pedestrians (Haghani and Sarvi, 2018; Li et al., 2017; Zhu et al., 2020). At the same time, *not keeping a*

“safety distance” from “low obstacles” is a **behaviour** common to indoor **fire** (Nelson and Mowrer, 2002) and outdoor earthquake (Bernardini et al., 2019) **evacuation**. It can be jointly considered with the aforementioned issues on the motion process towards the safe areas to propose risk-reduction solutions. In fact, obstacles, walls and barriers **could** be attractors for **pedestrians’** motion, also near to the event trigger, since **pedestrians** can be protected by them from weapon attacks (including bombs effects). **In this sense, such obstacles could also reduce** their possible damage level, such as **in the case of a vehicle** running into the crowd. **According to the “behavioural design” standpoint, “low obstacles” could be hence** positioned in the BE to represent a sort of architectural “widespread” countermeasure systems in the space layout. **They could also limit** the visual impact of risk-mitigation solutions **because they can ensure the** architectural integration in the BE itself (Coaffee et al., 2009).

About quantitative results, speed values and their trends **with respect to the** pedestrians’ density seem to be greater than the ones of the majority of evacuation kinds, while similarities **with the** earthquake evacuation process are retrieved.

Results for the LOS A sample can provide interesting preliminary insights on free-flowing motion, that represents the isolated individual’s motion adopted in microscopic models (Helbing and Johansson, 2010).

Results provided by **Figure 18-B remark** that the average instantaneous evacuation speed in terrorist act evacuation seems to be:

- greater than general-purpose evacuation speeds (mainly, fire evacuation) in indoor conditions. For instance, we can consider a speed value of 1.4m/s as relevant for the evacuation process in these circumstances. This value falls in *common* exit speed ranges (Shi et al., 2009). It is also considered for typical walking conditions in non-evacuation motion (Bosina and Weidmann, 2017) and is commonly used also in evacuation simulators (Lakoba et al., 2005). In particular, the average speed in this work is about + 120% greater than this value. Additional differences due to *indoor/outdoor* spaces could exist from this point of view;
- similar to earthquake evacuation-related speeds in outdoors from previous works. The average speed is about +13% with respect to average speeds of 2.95m/s given by (Bernardini et al., 2016).

Furthermore, according to [Figure 18-B](#) and [Figure 19](#), the overall limits for the pedestrian's speed have maximum values over *common* thresholds (e.g. about 6 to 7m/s for earthquake evacuation (Bernardini et al., 2016)). Anyway, it is worthy of notice that such values refer to instantaneous speeds, and the sample framing could affect it. The adoption of a Weibull distribution underlines how the right tail in speed data could be connected to subtleties in evacuation [behaviours](#) (Shiwakoti et al., 2008).

[Either qualitative and quantitative results also suggest that the frequency of the behaviours depends on the specific surrounding conditions in terms of BE and type of attack. From a modelling purpose in the “behavioural design” perspective, such outcomes point out the possibility to represent the evacuation dynamics by mainly using agent-based models and microscopic approaches, thanks to their capabilities to include different interaction levels and BE/pedestrians features, also basing on each element in the scenario \(Liu, 2020, 2018; Şahin et al., 2019\). Quantitative results additionally remark how researchers and safety designers should be discouraged from using general-purpose databases. Thus, previous related models can be modified to include such typical motion quantities, by additionally introducing characterizations of pedestrians' speed in indoor/outdoor BE and type of attacks, as suggested by the results of Table 3.](#)

As shown by previous works on terrorist acts simulation (Liu, 2018), the Social Force Model (Helbing and Johansson, 2010) could effectively include such aspects since the isolated pedestrians' motion is here altered by the additional interactions with the surrounding BE and the other pedestrians. Anyway, the model should modify the typically adopted preferred speed (about 1.5m/s) to those of free-flowing conditions depending on [indoor/outdoor BE and the type of attack](#). Then, further efforts should analyze real-world conditions to quantify the impact on the individual's speed due to additional pedestrian's feature such as gender and age. In addition, investigations should move towards a larger sample [by pointing out](#) differences over time of the evacuation speeds, to trace fatigue-related [behaviour](#)s in maintaining the high evacuation speeds seen in [Figure 19](#).

Results on the macroscopic characterization of the pedestrians' evacuation depending on the crowd density show similar insights in respect to the LOS A conditions. Density-speed trends are different from those of general-purpose databases, as shown [by Figure 27](#) (Bosina and Weidmann, 2017; Hankin and Wright, 1958;

Mori and Tsukaguchi, 1987). On the contrary, **Figure 27 shows** similar results in comparison with other studies on earthquakes (Bernardini et al., 2016). **Reasons for these outcomes could be essentially due to** the limited sample dimension and the differences in pedestrians' excitement in non-controlled evacuation conditions. In this sense, **the** main differences among data could be referred to different factors related to ethnicities and cultural background of involved agents, different environmental conditions, and finally to the specific moment in which data are collected (e.g. emergency or ordinary conditions) (Shiwakoti et al., 2008). **As pointed out by the "behavioural design" perspective, the** importance of collecting data on terrorist acts to define related emergency **behavioural** rules **is hence confirmed**.

In view of the above, modelling approaches based on the fundamental diagrams can be implemented to provide simplified models or introduce mesoscale effects of density in microscopic simulation models. In this sense, the definition of fundamental diagrams could be easily and directly applied to test simplified design procedures of BE configuration. Additional effects due to group motion and social shared identity should be assessed to **underline** the variations in preferred speed because of interactions among the individuals, thus integrating the density-based approach to evacuation speed assessment. According to the aforementioned discussion on *avoidance of evacuation procedure performing behaviour*, particular attention should be also posed to the crowd interactions leading to crushing, stepping on and physical contacts in view of the estimation of casualties due to such phenomena in the compact crowd (Alnabulsi et al., 2018).

6. Conclusions

Understanding the main **behavioural** responses against a sudden onset disaster emergency is a basic element **in the risk assessment** of the Built Environment (BE). **According to a "behavioural design" perspective**, it also allows analyzing which risk-reduction strategies should be applied in the BE to improve the exposed pedestrians' safety in case of quick arising danger conditions for the hosted community. Despite the large number of studies about emergency **behaviours**, terrorist acts are not yet widely investigated from this point of view. This work is aimed at **filling this lack, for the first time, by** collecting and analyzing data from videotapes of real events. **This approach allows taking** advantages of the potentially unbiased sources for **behavioural**

analysis. The work focuses on the European scenario because of its increasing significance in terms of disaster effects, mainly of victims, during recent years.

Starting from literature outcomes analysis, a first terrorist acts database on pedestrians' motion concerning both qualitative and quantitative aspects is here provided by including statistical insights. Collected data are organized in relation to the evacuation phases and to the main drivers (i.e. the BE, the other pedestrians, the attack sources) and then compared to previous works results. Behaviours are distinguished between those common to other evacuations and peculiar of the terrorist act emergency, and their frequency is assessed in respect to the related scenario conditions.

The work demonstrates the capabilities of the adopted consolidated methodology concerning both qualitative and quantities behavioural assessment in pedestrians' evacuation conditions. The results of this study could be also employed to validate evacuation simulators in relatively simple scenarios here analyzed.

The organized database can be easily extended in the future because of the main limitations of this work concerning the limited sample dimension. In fact, considering the application scale and the scalability/replicability of the results, it is worthy of notice that this work constitutes one of the first efforts to develop a database for terrorist acts analysis.

Results could be mainly applicable to the European context, and, principally, to a limited number of types of attack (i.e. vehicle, fire guns, spray and explosion). Nevertheless, the provided sample dimension is consistent in respect to other works on emergency and evacuation analysis on real worlds events (Bernardini et al., 2016; Zhou et al., 2018) and, at the authors' knowledge, greater than previous works on terrorist acts-related analyses, generally involving a single case study (Wang et al., 2019).

In this sense, further studies will have to extend the sample dimension in terms of: number of considered terrorist acts and assessed pedestrians; geographical localization of the terrorist acts; specific individuals' features (e.g. age, gender, disabilities); other types of attack. Furthermore, the effective influences of geographical, social and cultural background (including preparedness and risk-awareness issues) on emergency behaviours should be assessed, as for other emergencies. Data from videotapes can be combined with other kinds of investigation methodologies (e.g. surveys, virtual reality tests). In this process, the results

from this study will surely provide significant comparison inputs to evaluate differences between real-world behaviours and laboratory experiments, including drills and exercises.

The encouraging results of this work can really represent the first needed step to improve evacuation simulation software for terrorist acts analysis, according to the pursued “behavioural design” standpoint. Such simulation tools will be used by local Authorities, first responders (including Law Enforcement Agencies) and safety designers to assess the safety conditions of emergency management procedures (including evacuation plans) under different types of attack, and the effectiveness of risk-mitigation strategies to be deployed in the BE. Simulations results will allow pointing out the possible interactions between the effects of the attack (and the attackers, too), the BE and its modifications, the crowd and the first responders. Pedestrians’ flows and paths characterization will be combined to analyses concerning evacuation time and casualties’ number, so as to outline: (1) the effects of such interactions; and (2) the possibility to reduce risk by structural and management-related actions. These actions will move towards the assessment of the community’s resilience aspects in the BE under such threats. Finally, results will also suggest observations for risk-awareness campaign and training of the population, to improve the community resilience from a bottom-up perspective.

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Appendix A

Table A.1. The online available videos of the adopted sample are reported below with the related link (last access 17/06/2020). Column "source": "into" refers to mobile cameras near to the trigger, while "far" refers to mobile camera far from it; "tv" refers to mobile cameras of massmedia channels and CCTV refers to fixed cameras, e.g. from surveillance systems.

Date City, Country	Video ID	Link	Number of scenes (assessed for quantitative purposes)	Space type	Type of attack	Source
14 th July 2016 Nice, France	N1	https://www.youtube.com/watch?v=BzJ4CJ9IYYA	5 (-)	outdoor	Vehicle (running into the crowd)	into
	N2	http://media.youreporter.it.edgesuite.net/sd/181350.mp4	4 (-)	outdoor		far
	N3	https://www.youtube.com/watch?v=08wiOtJ5QTc	6 (-)	outdoor		far
	N4	http://media.youreporter.it.edgesuite.net/sd/181340.mp4	3 (3)	outdoor		far
19 th December 2016 Berlin, Germany	B1	https://www.youtube.com/watch?v=r1_3AyxsKrk	2 (-)	outdoor	Vehicle (running into the crowd)	CCTV
	B2	https://d1vvp9ihshjy3m.cloudfront.net/video/WFg-CuSwlixljBg4_4.mp4 ; https://youmedia.fanpage.it/video/aa/WFg-CuSwlixljBg4	2 (-)	outdoor		into
11 th March 2004	M1	https://www.youtube.com/watch?v=izZXTwsTbLU	4 (-)	indoor	Explosion	CCTV
	M2	https://www.youtube.com/watch?v=SHHGF-JRfHA	3 (3)	indoor		CCTV

Madrid, Spain						
7 th April 2017	S5	https://www.youtube.com/watch?v=RUBlzEkl5es	2 (1)	outdoor	Vehicle (running into the crowd)	far
Stockhol m, Sweden	S6	https://www.youtube.com/watch?v=QgeHTn-8hms	1 (-)	outdoor		far
	S7	https://www.youtube.com/watch?v=tCJKdc74RQA	1 (-)	outdoor		CCTV
	S8	https://www.youtube.com/watch?v=JJqoeHrLnds	5 (1)	outdoor		into
13 th Novembe r 2015	P1	https://www.youtube.com/watch?v=E-DzmUVmnzM	2 (-)	indoor	Armed Assault (with fire guns)	far
Paris, France	P2	https://www.youtube.com/watch?v=qrC9QAFkNcM&t=116s	2 (1)	outdoor		far
22 nd March 2016	Br1	https://www.youtube.com/watch?v=W3wJvoVKL4g	1 (1)	outdoor	Explosion	far
Brussels, Belgium (airport and metro)	Br2	https://www.youtube.com/watch?v=FOeRMQuSRNY	7 (2)	indoor		into
	Br3a	https://www.youtube.com/watch?v=CLsotlobd2Q	1 (-)	outdoor		into
	Br4	https://www.youtube.com/watch?v=Os5KkmsaErY	3 (3)	indoor		CCTV
	Br3b	https://www.youtube.com/watch?v=CLsotlobd2Q	1 (-)	indoor		far
22 nd May 2017	Ma1	https://www.youtube.com/watch?v=usaiTBELdCw	1 (-)	outdoor	Explosion	into
Manchest er, United Kingdom	Ma2	https://www.youtube.com/watch?v=6vZoG4KbbW4	1 (1)	indoor		into
	Ma4	https://www.youtube.com/watch?v=gqvVXJJwHXo	1 (-)	indoor		into
	Ma5	https://twitter.com/news_xclusive	3 (3)	indoor		into
	Ma6	https://www.youtube.com/watch?v=ehkPwpbvDis	1 (-)	indoor		into
	Ma7	https://www.youtube.com/watch?v=9HvNvH14BGA	5 (-)	outdoor		into
	Ma8	https://www.youtube.com/watch?v=Z6spRNOIFgo	2 (-)	indoor		into
3 rd June 2017 Turin, Italy	T1	http://video.corriere.it/torino-momento-cui-transenna-crolla-sotto-calca/b2ab0280-48b1-11e7-beec-6fc3ec1d3e39	2 (-)	outdoor	Armed Assault by using stinging spray to rob ⁵	tv
	T2	http://www.corriere.it/video-articoli/2017/06/03/juventus-real-madrid-panico-improvviso-piazza-san-carlo-si-svuota-un-attimo/f9c1f72e-489c-11e7-beec-6fc3ec1d3e39.shtml	1 (-)	outdoor		tv
	T3	http://video.corriere.it/torino-testimone-ho-sentito-urlare-bomba-ed-stato-panico-rischiata-un-altra-heysel/ebdb6cde-48b1-11e7-beec-6fc3ec1d3e39	2 (-)	outdoor		tv
	T5	http://video.corriere.it/panico-torino-la-finale-champions/134bbd54-48f4-11e7-bdef-f5dfe5374ed	4 (-)	outdoor		tv

⁵ <https://www.lastampa.it/torino/2018/04/13/news/il-disastro-di-piazza-san-carlo-per-una-rapina-con-lo-spray-urticante-1.34004675> (last access: 06/06/2020)

T6	http://www.lastampa.it/2017/06/03/multimedia/cronaca/la-fuga-da-piazza-san-carlo-a-torino-vista-dallalto-pQFQp0bYyTx8QgfiAfEuVO/pagina.html	1 (1)	outdoor	far
T9	http://www.lastampa.it/2017/06/06/multimedia/cronaca/caos-in-piazza-san-carlo-una-negoziante-ecco-cosa-accaduto-QcbtGjEEI7PGPNm4eczal/pagina.html	1 (-)	outdoor	tv
T10	http://www.lastampa.it/2017/06/04/multimedia/cronaca/il-momento-in-cui-si-scatenato-il-panico-a-torino-tidGC19IXWplWLuJr0QSsM/pagina.html	5 (-)	outdoor	tv
T11	https://www.youtube.com/watch?v=uqOk2XI_uNw	3 (-)	outdoor	tv
T14	https://www.youtube.com/watch?v=7Q9AXdlcRkl	1 (1)	outdoor	far
T15	https://www.youtube.com/watch?v=0YuHTzoksNQ	2 (2)	outdoor	into
T16	https://www.youtube.com/watch?v=g0-fL4bF3jl	1 (-)	outdoor	tv
T17	https://www.youtube.com/watch?v=ExYrHn8g8o	1 (-)	outdoor	tv
T18	https://youmedia.fanpage.it/video/aa/WTRU3-Sw3YN97pCm	1 (-)	outdoor	far

Figures

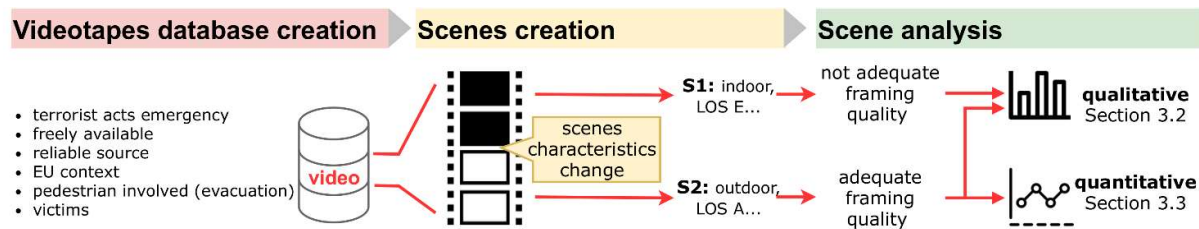


Figure 1. Flowchart of the videotapes database creation and analysis. References to the specific Sections of the methodology are pointed out.

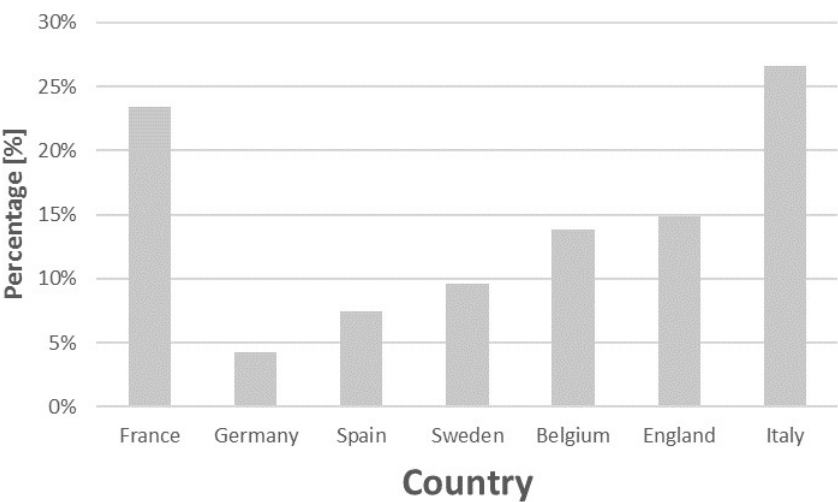


Figure 2. Percentage distribution of Country where the terrorist act occurred within the considered sample.

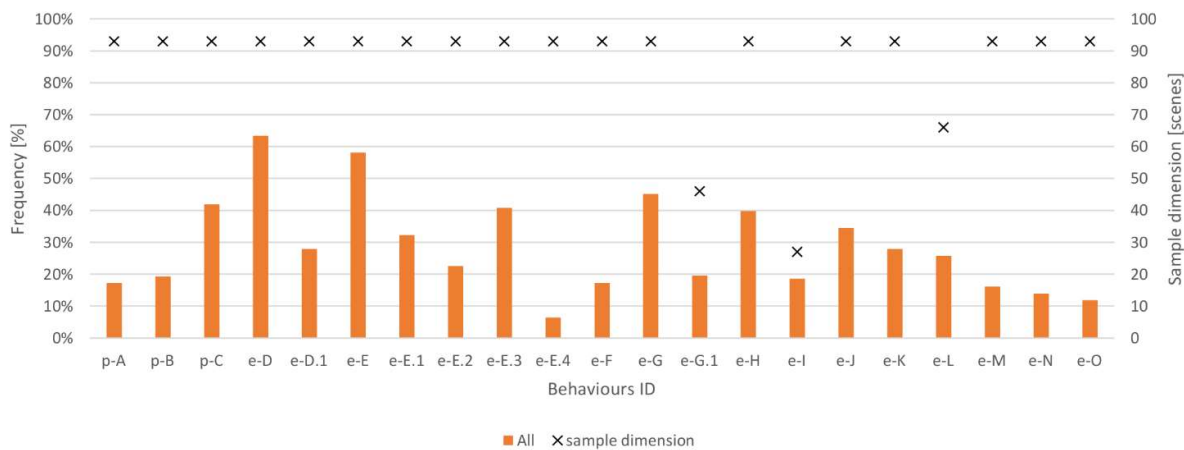


Figure 3. Overall percentage frequency (by colored bars; left y-axis) of noticed behaviours according to Table 1 IDs. The sample dimension is outlined on the right y-axis.

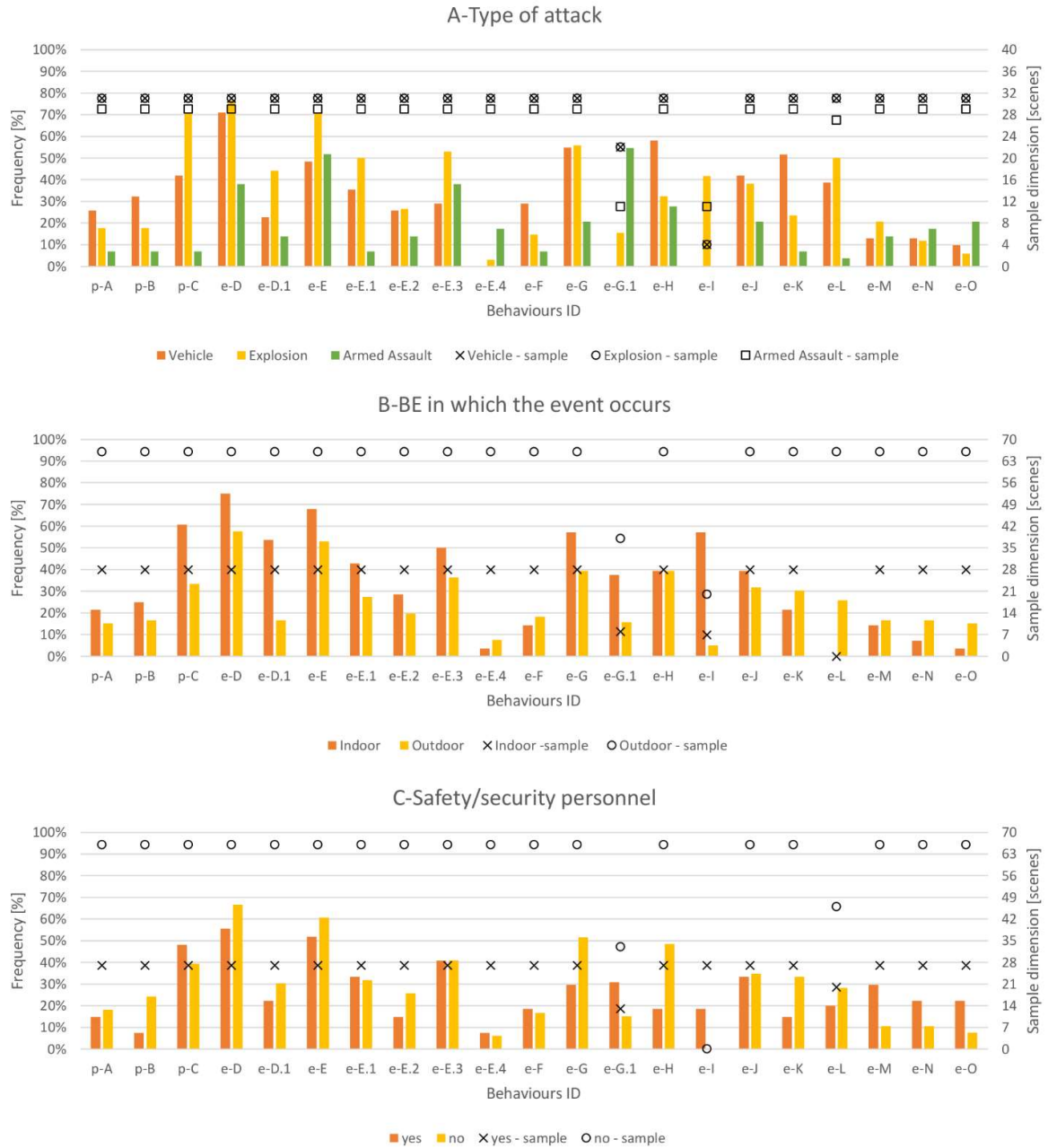


Figure 4. Percentage frequency (by colored bars; left y-axis) of noticed **behaviours** according to Table 1 IDs, in relation to: A- type of attack; B- BE scenario in which the event occurs; C-presence of safety/security personnel. The sample dimension is also outlined according to the right y-axis and considering each **subsample** in the bottom legend.



Figure 5. Percentage frequency (by colored bars; left y axis) of noticed behaviours (according to Table 1 IDs) in relation to: A- presence of obstacles; B- BE scenario modifications due to the attack; C-trigger proximity of the individuals. The sample dimension is also outlined according to the right y-axis and considering each subsample in the bottom legend.

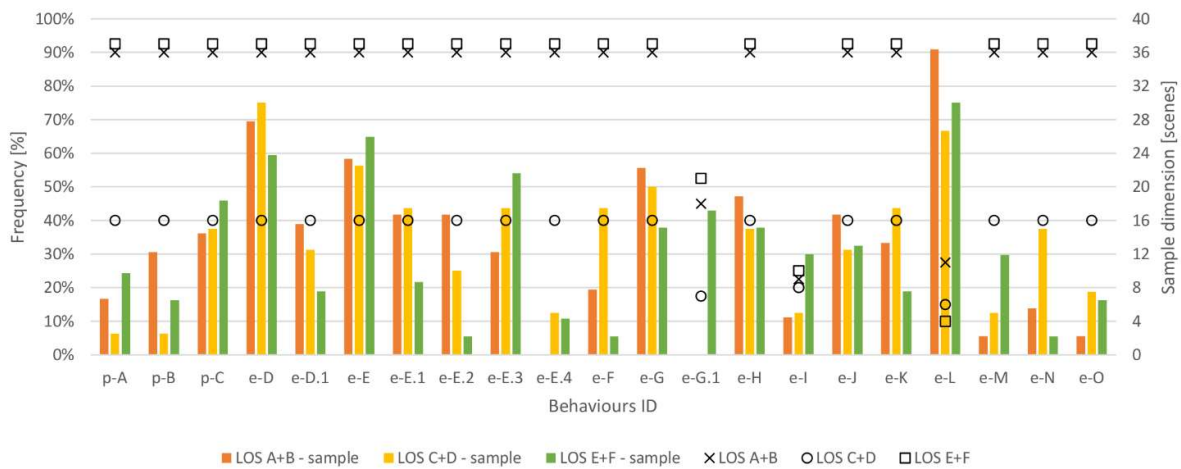


Figure 6. Percentage frequency (by colored bars; left y axis) of noticed behaviours (according to Table 1 IDs) in relation to the Level of Service (LOS) classes. The sample dimension is also outlined according to the right y-axis and considering each subsample in the bottom legend.

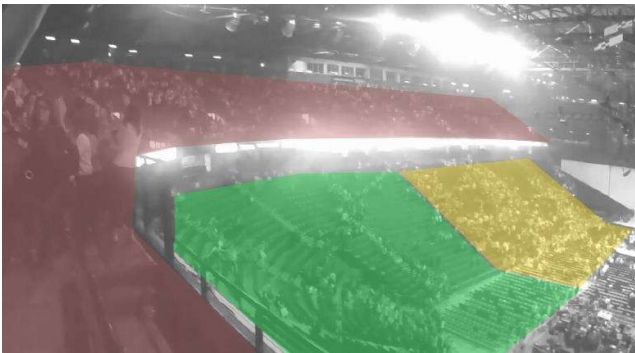


Figure 7. Trigger proximity effects in respect to the response to sensible events {Ma5}: at the view timing (after the attack, timing: 0:07), most of the people near to the trigger has already left their initial position immediately after the attack (green area) or are still performing safety actions, while people farer from the trigger (red area; people placed in the upper gallery) have a limited response.

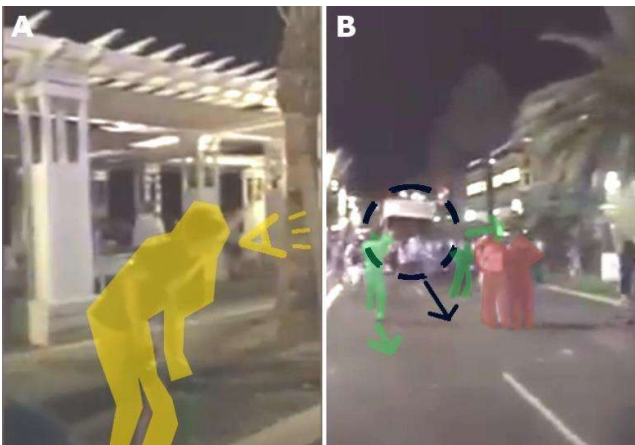


Figure 8. Response to sensible events in vehicle-related attacks {N1}: A-an individual is looking towards the truck (yellow figure) and then I will decide to evacuate (video timing: 0:18); B-people placed along the truck direction (black dashed circle and black arrow) try to start the evacuation (green figures, evacuation direction with green arrows) while someone (red figures) are still unaware of the risk because they are walking along the same truck path placed farther behind them (video timing: 0:20).



Figure 9. Self-protection behaviours in case of explosion {Br2} just after the attack, with people laying on the floor (video timing: 0:08).



Figure 10. People running far from the event trigger (arrows point out the direction in a qualitative manner) in: A- mono-dimensional spaces, as the metro car {Br2}; B-outdoor spaces, with people moving from the middle of the square to the surrounding colonnade (two consecutive views of {T16}).



Figure 11. People running far from the event trigger, reaching a window and then dangling in the void to be safe from terrorist fire guns during the Bataclan attack {P2} (video timing: 2:11). Someone is trying to support the woman hanging at the window.



*Figure 12. The individual **marked** by the arrow should modify his trajectory to avoid people who remain in the same position and does not participate to the evacuation process {T5}.*



Figure 13. Interaction with low obstacles by: A-knocking over fixed railings because of high pressure of crowd (the yellow area points out the missing railings in the immediate aftermath) {T5}; B-climbing low obstacles, including raised platforms, to move far from the stampede scene (red figures marked in two consecutive frames) {T2}.



Figure 14. Qualitative representation of the stampede front in the Turin stampede, at different seconds. The pressure of the crowd is due to the movement of people far from the supposed trigger (direction given by the arrow) {T11}.



Figure 15. Security staff members support the evacuation of people by inviting them to leave their position and move towards the exits {Br2} (video timing: 02:41).



A



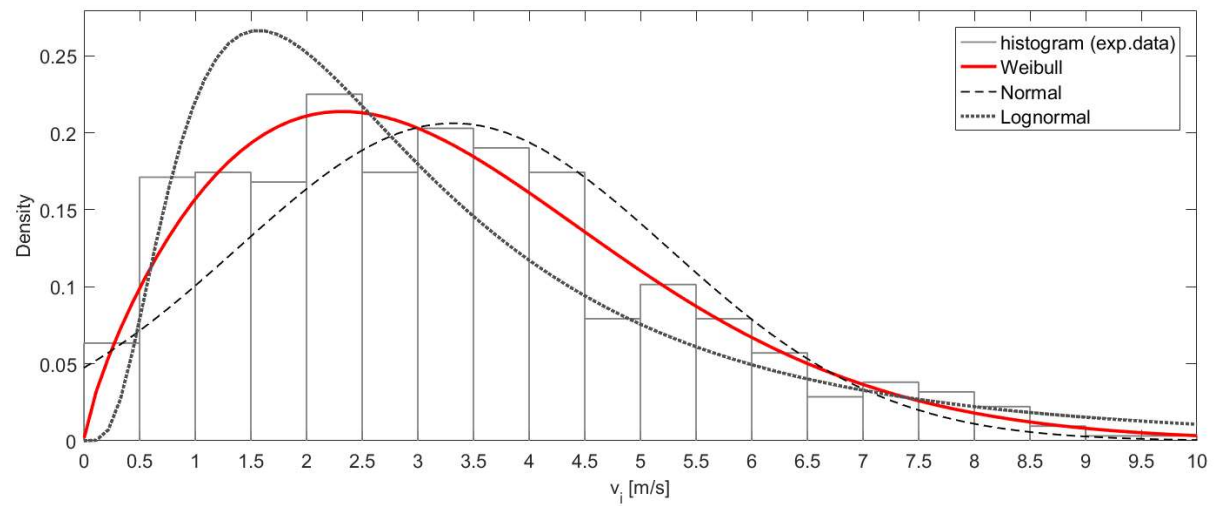
B

Figure 16. Support actions to injured people by: A-safety/security personnel in the immediate aftermath, by being in direct contact of the exposed individuals {T5}; B-the same individuals who previously experienced the emergency conditions {T9}.



Figure 17. Attachment to belongings {T2}: the individual in the red circle runs into the space near the supposed attacker (on the right, with the open arms) to collect the bag (inside the red circle) and then returns back (blue arrows).

A



B

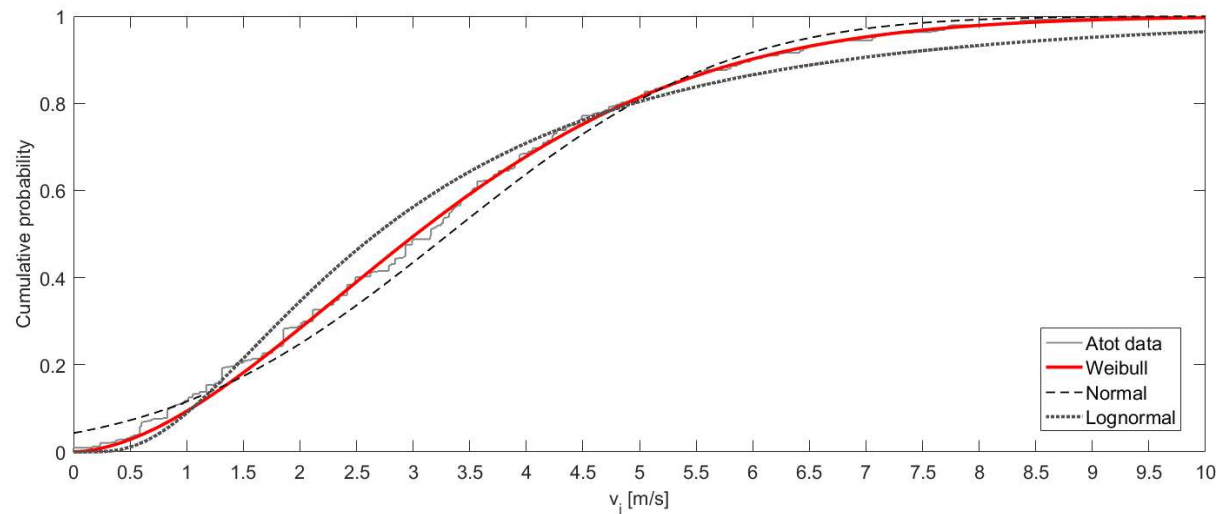


Figure 18. Evacuation speed distribution through Weibull, normal and lognormal distributions based on experimental data, in terms of: A- density (and related experimental data representation through histogram); B- cumulative probability.

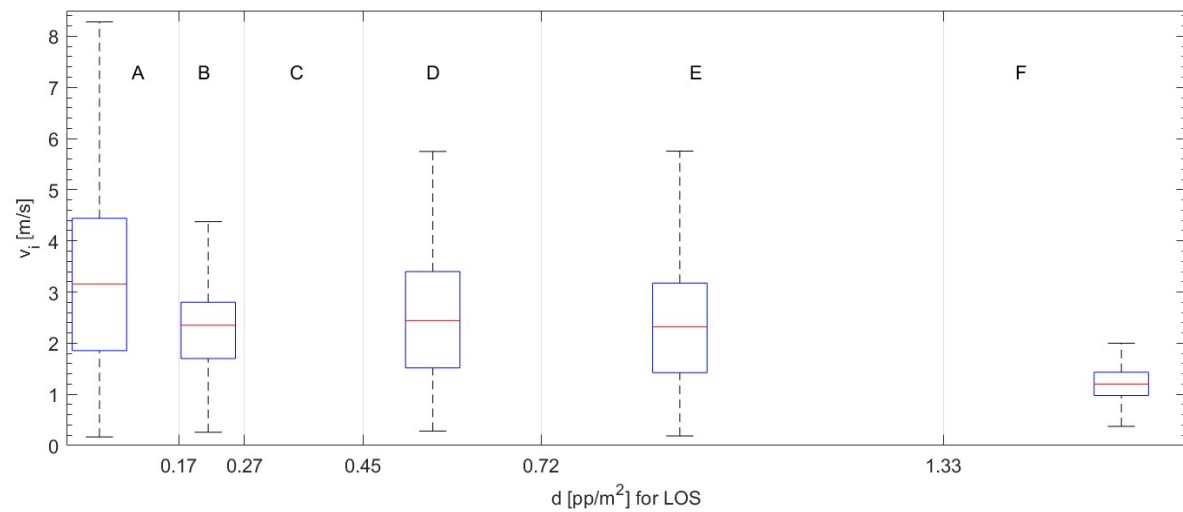


Figure 19. Instantaneous evacuation speed distribution depending on the LOS classifications (all the instantaneous speeds).

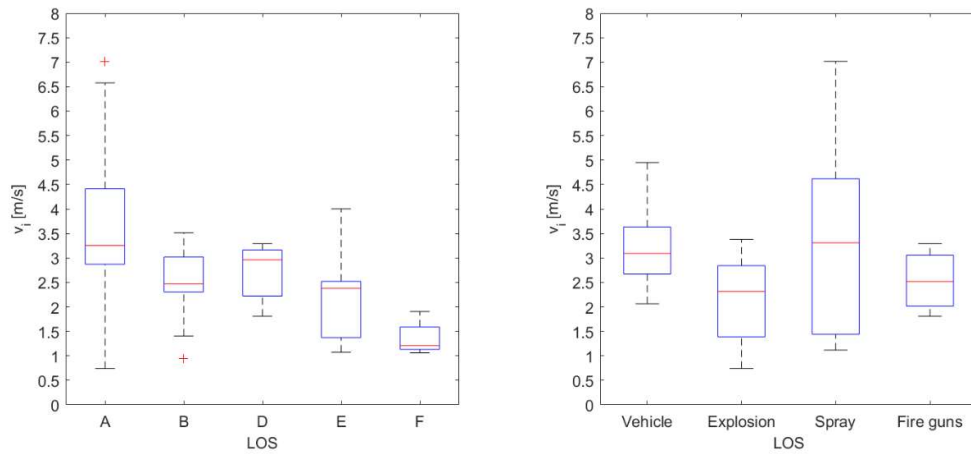


Figure 20. Instantaneous evacuation speed distribution (average speed for each of the tested individual) depending on: A-left, LOS classifications; B- right type of attack (by distinguishing armed assault with fire guns and spray).

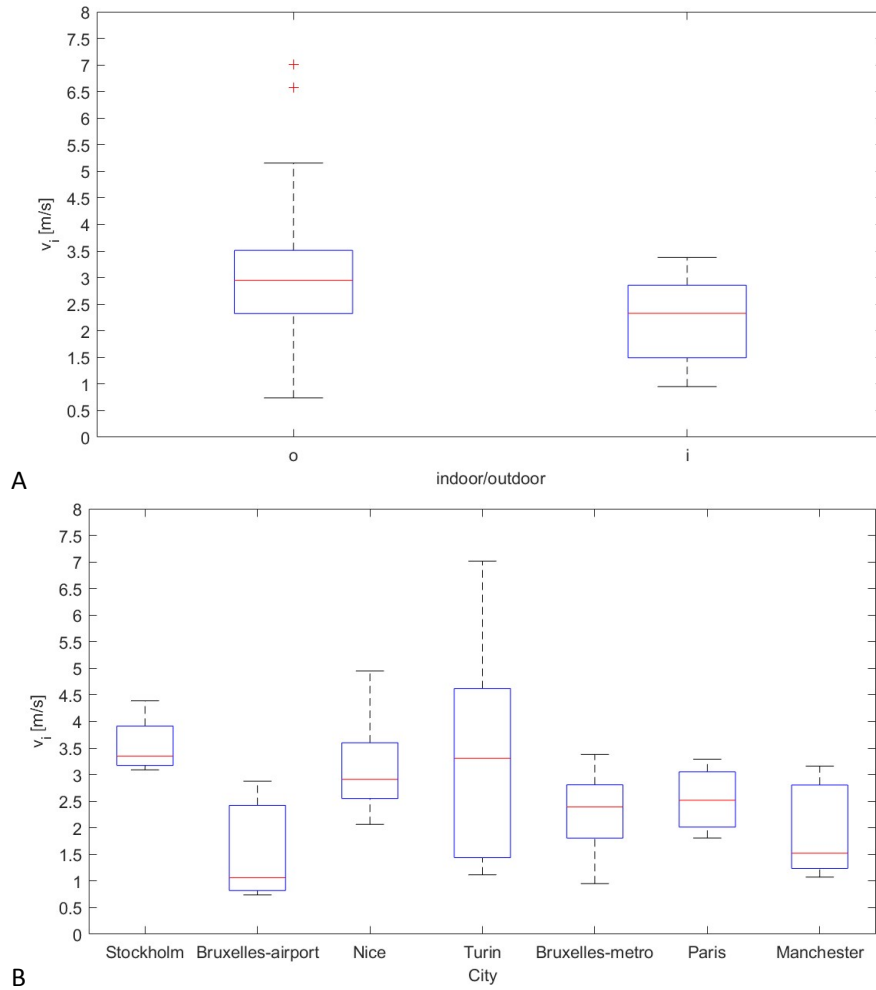


Figure 21. Instantaneous evacuation speed distribution (average speed for each of the tested individual) depending on: A- indoor/outdoor spaces; B- city where the event happened.

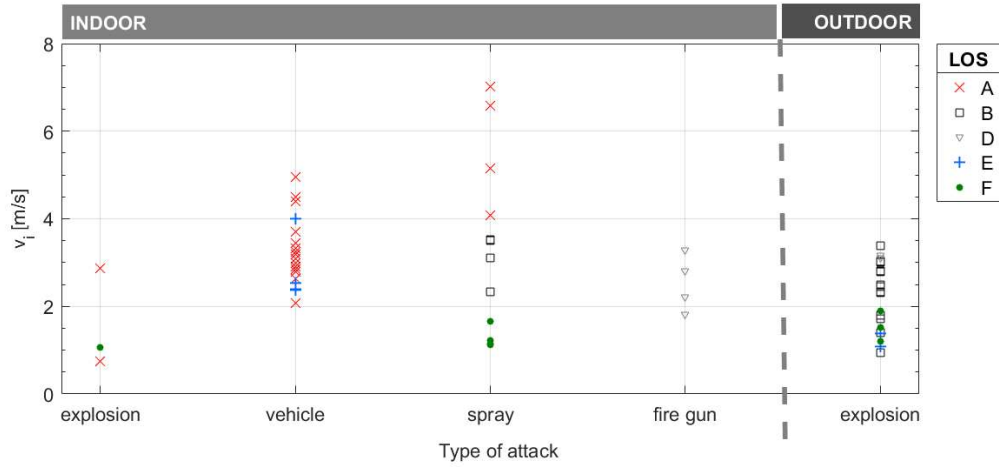


Figure 22. Instantaneous evacuation speed pairs (average speed for each of the tested individual) depending on indoor/outdoor scenarios and on the type of attack, by additionally tracing the related LOS level.

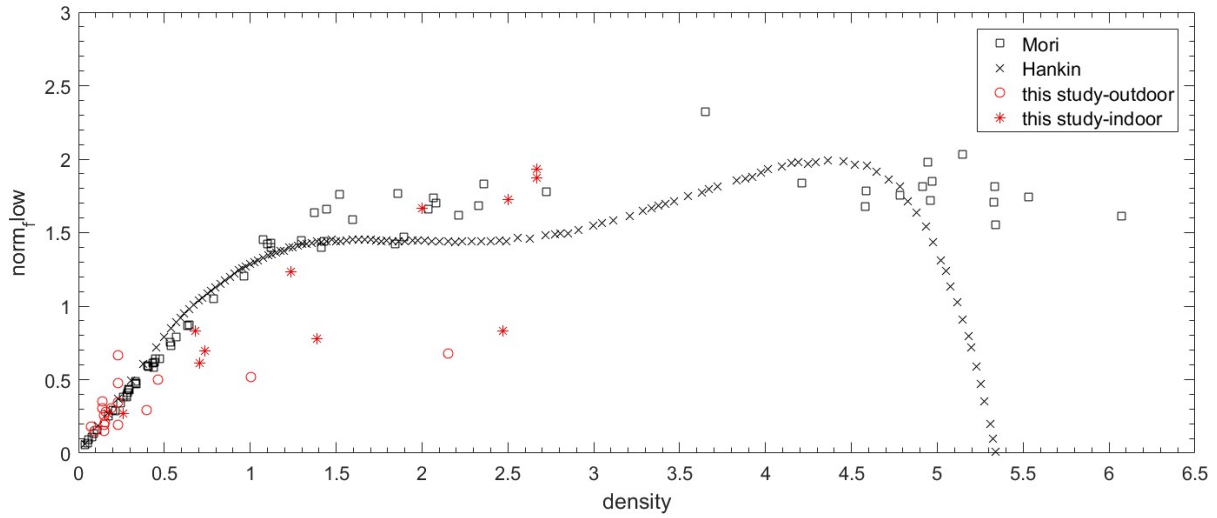


Figure 23. Density-flow pairs in this work and in reference studies (Hankin and Wright, 1958; Mori and Tsukaguchi, 1987), by distinguishing indoor and outdoor data

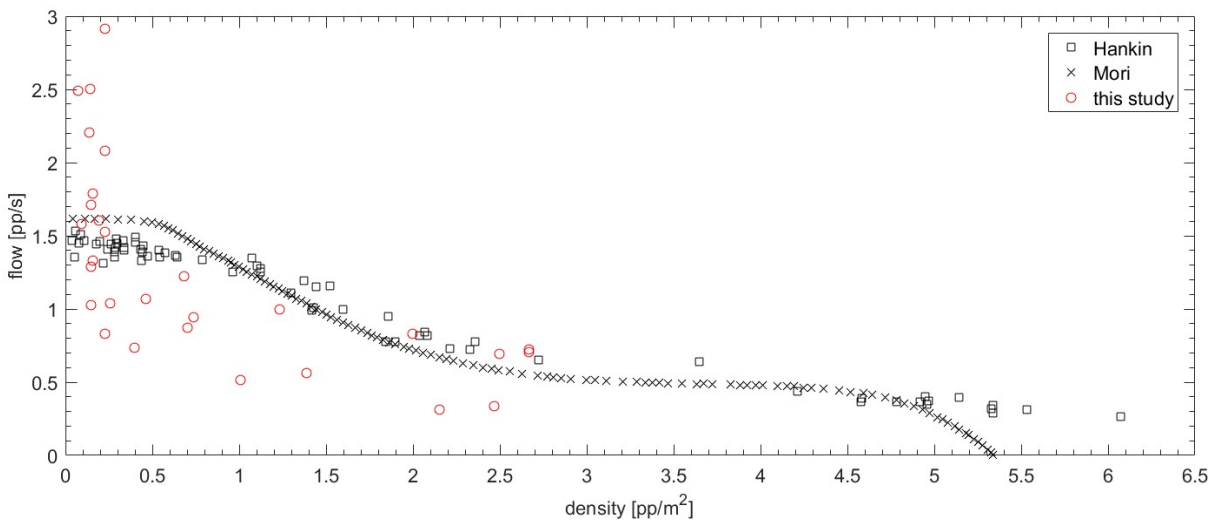


Figure 24. Density-speed pairs in this work and in reference studies (Hankin and Wright, 1958; Mori and Tsukaguchi, 1987)

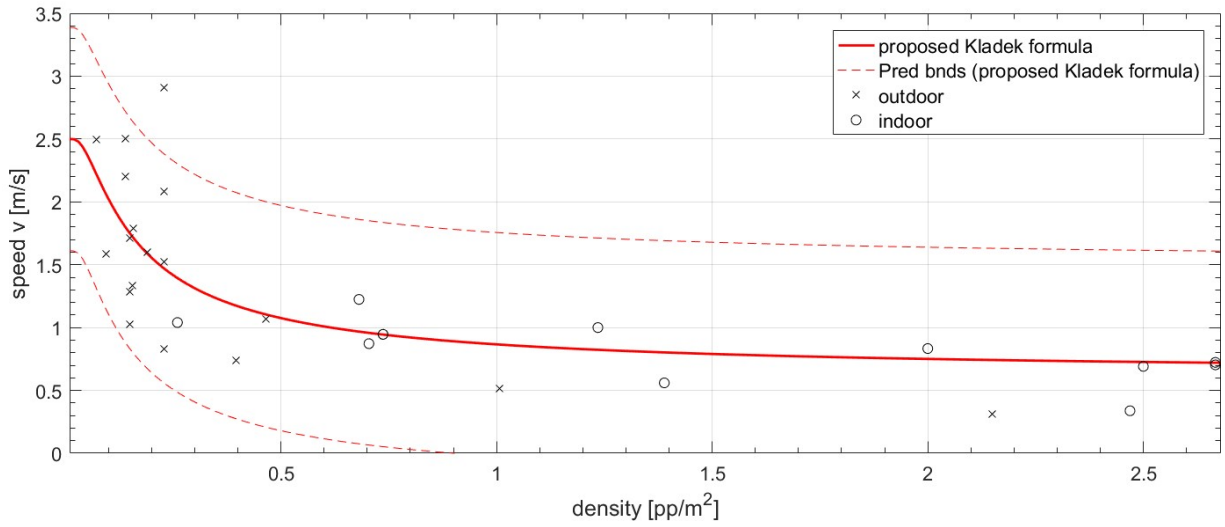


Figure 25. Kladek formula over the investigate sample (fitting on the overall sample), by including prediction boundaries at 95% of confidence (dashed red curves; $v_{F,hf}$, v_{min} , k , ρ_{max} can be respectively considered as equal to: 1.64m/s, 0m/s, 0.088, 0.90pp/m², for the lower boundary; 3.39m/s, 1.60m/s, 0.187, 2.67pp/m², for the upper boundary).

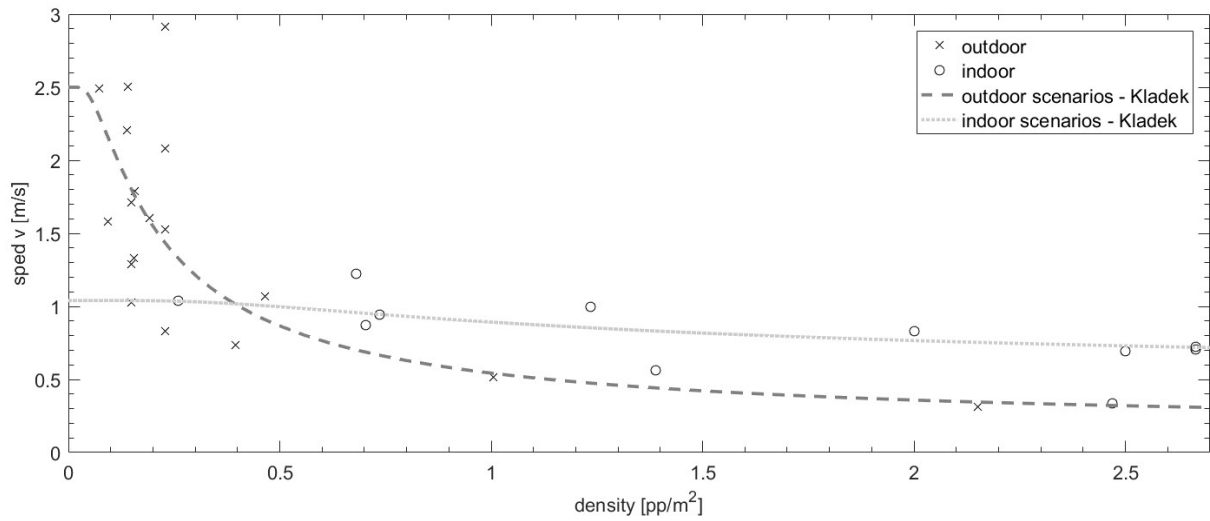


Figure 26. Kladek formula over the investigate sample by distinguishing indoor and outdoor regression pairs-based regressions.

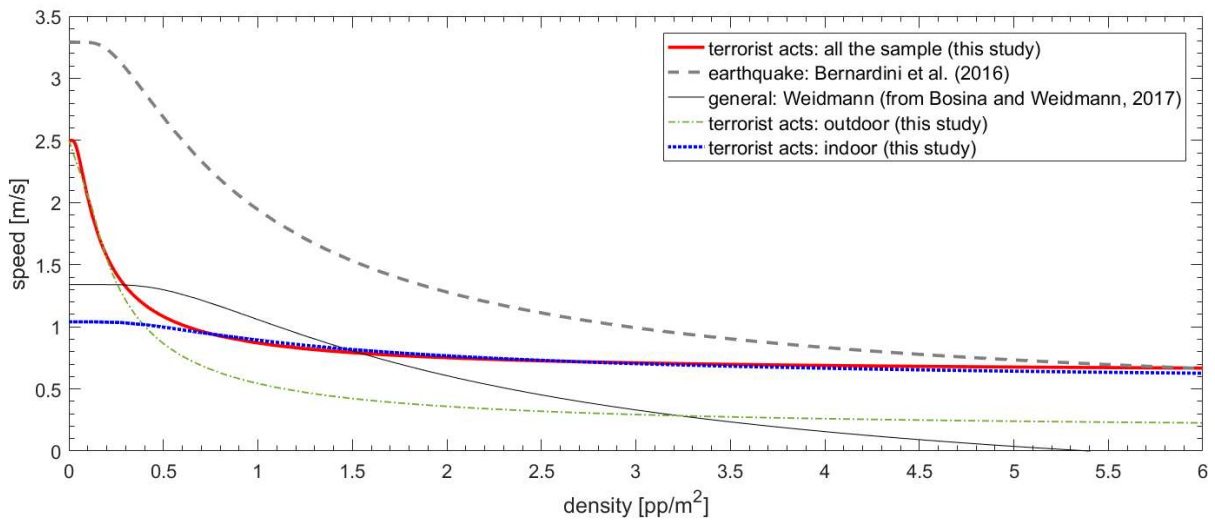


Figure 27. Comparison between Kladek formula proposed in different works for different emergencies and the key findings of this work (for the whole sample and for outdoor sample).

Tables

Table 1. Noticed **behaviours** from the analyzed sample, by including main literature references. Behaviors common to other kind of evacuations are identified by *, while the others are peculiar ones. For each behaviour, the table provides the evacuation phase, the main scenes characteristics, the reference elements for pedestrians' interactions, and, finally, the absolute and relative frequency in respect to the sample dimension due to the number of referring scenes.

Phase	ID	Noticed behaviour (references): Short description	Main scenes characteristics	Reference elements of interaction	Total number of scenes (total number of referring scenes) – related frequency [%]
Pre-movement	p-A	"Pro-Social" Behaviors* (Baňgate et al., 2017; Kuligowski, 2013; Lovreglio et al., 2019; Mawson, 2012; Rao et al., 2011): people interact to perform decisional issues and activate evacuation procedures depending on the state of surrounding BE/individuals, by additionally performing information seeking and exchange	Indoor and outdoor	Pedestrians	16 (93) - 17%
	p-B	Response to sensible events* (Bernardini et al., 2019; Kobes et al., 2010; Lovreglio et al., 2016): individuals who perceive in a direct way what is happening can start the evacuation process before than the ones who are farther from the event trigger (also in an immediate way)	Indoor and outdoor	Attack and BE conditions (including their modifications and to the proximity with the trigger)	18 (93) - 19%
	p-C	Curiosity effects* (Bernardini et al., 2019, 2017a; Kaigo, 2012): people remain near to the initial position, and/or spend time in unsafe areas, and/or walk more slowly to "see what is happening", by also using mobile devices for shooting the emergency scene, thus performing not-evacuation-related actions. People farther from the trigger could also decide not to evacuate to this end.	Indoor and outdoor	Attack and BE conditions (including their modifications and to the proximity with the trigger)	39 (93) - 42%
Evacuation	e-D	Attraction towards safe areas* (Bernardini et al., 2019; Haghani and Sarvi, 2016; Helbing et al., 2002; Liu, 2018): Pedestrians move towards safe areas, that is far from the event trigger (thus, in relation to the type of attack and to the BE contest). It mainly includes:	Indoor and outdoor	BE conditions (including their modifications and to the proximity with the trigger) and Attack	59 (93) - 63%
	e-D.1	Running far from the event trigger* (Bernardini et al., 2019; van der Wal et al., 2021): pedestrians can start moving far from the event trigger, by selecting the first available direction (including dead end paths; paths with complex layout). In this sense, the path selection can be considered as peculiar of the terrorist act conditions	Indoor and outdoor	BE conditions (including their modifications and to the proximity with the trigger), Attack, Pedestrians (due to "pro-social" behaviours)	26 (93) - 28%
	e-E	"Pro-Social" Behaviors* (Alnabulsi et al., 2018; Baňgate et al., 2017; Helbing and Johansson, 2010; Johansson et al., 2008; Lakoba et al., 2005; Mawson, 2012; von Sivers et al., 2016; Yang et al., 2016): interactions during the motion process include the formation of evacuation groups, also due to herding and social shared identity issues (including group ties). This phenomenon can also promote information seeking and exchange during the evacuation. In such groups, the individuals' velocity can be affected by "collective" velocity (besides pedestrians' density). They also include:	Indoor and outdoor	Pedestrians	54 (93) - 58%
	e-E.1	attraction for group ties*	Indoor and outdoor	Pedestrians	30 (93) - 32%
	e-E.2	supporting more vulnerable pedestrians* e.g. (hand)assisted evacuation	Indoor and outdoor	Pedestrians	21 (93) - 23%
	e-E.3	formation of evacuation groups in view of herding behaviours*			38 (93) - 41%
	e-E.4	stop-and-go waves*	Indoor and outdoor	Pedestrians	6 (93) - 6%

e-F	<i>Repulsive mechanisms to avoid physical contact*</i> (Helbing et al., 2002; Helbing and Johansson, 2010): Pedestrians try to modify their trajectory by avoiding collisions with other individuals and with the BE elements	Indoor and outdoor	Pedestrians and environment	16 (93) - 17%
e-G	<i>Not keeping a "safety distance" from "low obstacles"</i> * (Bernardini et al., 2019; Nelson and Mowrer, 2002): Pedestrians allow physical contacts in motion with "low obstacles" including walls, fences, trees, street furniture, railings and chairs (also in indoor), movable elements (e.g. metal barriers). It mainly includes:	Indoor and outdoor with low obstacles	Environment	42 (93) - 45%
e-G.1	<i>People climbing over low obstacles/knock over mobile obstacles</i> while moving, to minimize variations in the evacuation direction (also in view of e-D.1 behaviours)	Indoor and outdoor with low obstacles that can be climbed/knocked over	BE, i.e. low obstacles	9 (46) - 20%
e-H	<i>"selfish" and competitive behaviours*</i> (Drury and Cocking, 2007; Haghani and Sarvi, 2018; Yang et al., 2016): people can activate actions such as pushing and trampling others to reach safety, essentially in view of the possible pressure-increasing elements	Indoor and outdoor	Pedestrians, BE (including its modifications), Attack	37 (93) - 40%
e-I	<i>Increased guide effect for presence of rescuers*</i> (Averill et al., 2005; Bernardini et al., 2019; Drury and Cocking, 2007; Ji and Gao, 2007; Li et al., 2015; van der Wal et al., 2021): safety/security personnel in the BE (including police officers and first responders) can support the evacuating pedestrians in performing "safe" behaviours and prompt reaction to evacuation tasks (e.g. path selection uncertainties reduction, adoption of safety behaviours), in view of a leader-follower effect	Indoor and outdoor with presence of rescuers	BE	6 (27) - 22%
e-J	<i>Avoidance of evacuation procedure performing</i> : Individuals can also not participate to the whole evacuation process, performing milling behaviours and becoming an obstacle of the other pedestrians' evacuation. They can also perform pro-social or curiosity-related behaviours	Indoor and outdoor	Pedestrians	32 (93) - 34%
e-K	<i>Counterflow in evacuation motion*</i> (Fang et al., 2016; Templeton et al., 2020): collective behaviours or safe areas identification (and related path selection) could lead groups of pedestrians to walk in opposite directions, by shaping the group to reduce movements efforts and collisions	Indoor and outdoor	Pedestrians, BE	26 (93) - 28%
s-L	<i>Safe area definition</i> : people tend to gather as far as possible from the event trigger/of the attack-damaged BE.	Outdoor	Pedestrians and environment	17 (66) - 26%
s-M	<i>Evacuation end for influence of not immediate danger feelings or helplessness conditions*</i> (Bernardini et al., 2019): pedestrians can interrupt their evacuation process in the first available safe area (compare to s-L), by not ending the evacuation process and not performing possible personal safety actions, similarly to what is noticed in earthquake evacuation .	Indoor and outdoor	BE, Attack	15 (93) - 16%
s-N	<i>"Pro-social" behaviours in post-evacuation*</i> (Averill et al., 2005; Bartolucci and Magni, 2017; Drury et al., 2016; Rao et al., 2011): individuals help each other in the immediate aftermath, also in direct relation with injured people, as in wide-scale sudden onset disasters (e.g. earthquake, typhoon)	Indoor and outdoor	Pedestrians, Attack and BE (depending on the possibility to have different injuries levels for people)	13 (93) - 14%

s-O	<i>Attachment to things effect*</i> (Rao et al., 2011; Riad and Norris, 1996): people try to collect personal belongings by also allowing returning towards the event site, as for other kinds of wide-scale sudden onset disasters (e.g. earthquake, flood)	Indoor and outdoor	BE, Attack (towards the possibility to return at the initial position)	11 (93) - 12%
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Table 2. Summary of basic statistics for quantitative analysis on individual's instantaneous evacuation speed v_i [m/s] for the whole sample and for separated outdoor and indoor samples, depending on the classification criteria (LOS). Values with n.a. are not assessed in the original sample, while * implies that data can be affected by the scarce sample dimension.

Statistics	LOS A	LOS B	LOS D	LOS E	LOS F
v_i data [m/s]	all the sample (outdoor; indoor)				
Minimum (IQR-based)	0.17 (0.17; n.a.)	0.26 (1.76*; 0.26)	0.28 (0.28; 2.41*)	0.19 (0.19; 0.56*)	0.37 (0.37; 0.89*)
Q1	1.85 (1.85; n.a.)	1.75 (2.54*; 1.70)	1.52 (1.44; 2.69*)	1.42 (1.83; 1.03*)	0.98 (0.97; 1.15*)
Q2 (median)	3.16 (3.16; n.a.)	2.35 (3.10*; 2.35)	2.44 (2.39; 2.75*)	2.32 (2.53; 1.19*)	1.20 (1.18; 1.43*)
Arithmetic mean	3.32 (3.32; n.a.)	2.31 (3.09*; 2.26)	2.54 (2.49; 3.13*)	2.62 (2.86; 1.25*)	1.25 (1.19; 1.58*)
St. dev	1.93 (1.93; n.a.)	0.88 (0.75*; 0.86)	1.24 (1.26; 0.73*)	1.66 (1.68; 0.39*)	0.42 (0.39; 0.46*)
Q3	4.44 (4.44; n.a.)	2.80 (3.68*; 2.75)	3.40 (3.39; 3.70*)	3.17 (3.50; 1.68*)	1.43 (1.37; 1.93*)
99th percentile	8.40 (8.40; n.a.)	4.83 (4.83*; 4.81)	5.60 (5.61; 4.73*)	8.50 (8.50; 2.02*)	2.28 (2.26; 2.38*)
Maximum (IQR-based)	10.26 (10.26; n.a.)	6.05 (4.84*; 6.05)	5.75 (5.75; 4.73*)	8.51 (8.51; 2.02*)	2.38 (2.26; 2.38*)
Sample dimension	625 (625; n.a.)	879 (56*; 823)	272 (252; 20*)	148 (126; 22*)	133 (114; 19*)

Table 3. Summary of sample dimension and average speed (aggregate sample) for quantitative analysis on average evacuation speeds calculated starting from v_i , depending on main scenario characterization elements.

Classification	Sample dimension [pp]	Average speed [m/s]
LOS		
A	21	3.64
B	18	2.51
D	6	2.73
E	6	2.29
F	8	1.35
Type of attack		
Vehicle	19	3.23
Fire guns	4	2.53
Spray	12	3.37
Explosion	24	2.12
Type of scenario		
Outdoor scenarios	38	3.07
Indoor scenarios	21	2.2
City		
Stockholm	4	3.54
Paris	4	2.53
Brussels-airport	3	1.56
Brussels-metro	14	2.34
Nice	15	3.14
Turin	12	3.37