Individual accidents at the interface between platform, train and tracks (PT 2 I) in the subway: a literature review

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Abstract

The subway context is a risky environment. Hundreds of individual incidents occur every year in this environment, entailing a safety issue for subway companies and safety organizations. This review deals with individual incidents at the platform-train-tracks interface (PT²I) with a particular focus on accidents and precursor analysis and on preventive measures. 42 articles ranging from 1984 to 2018 were selected and analysed to understand this issue. Our results suggest that the existing literature provides a relatively comprehensive picture of the individual factors involved in accidents, but that there is a lack of knowledge on the impact of the socio-cultural environment, the equipment and surroundings, and the organisational factors. Concerning preventive measures, although 19 measures covering all levels and types of prevention are presented, only 6 have been evaluated. Research areas of particular interest are real user behaviours, systemic approaches to behavioural determinants, and evaluations of preventive measures.

1 Introduction

Subway networks have developed continuously ever since the first one was built in London in 1863, and they currently serve many of the world's major cities (Kyriakidis et al. 2012). In 2017, there were 178 subway systems distributed in 56 countries. They transported 53,768 million passengers in the world. In the six years between 2012 and 2017, ridership grew globally by 19.5% (UITP 2018). Four main types of subway infrastructures exist worldwide: stations are mostly underground (67%), elevated (20%) or at-grade (12%) while in-trench stations (1%) are uncommon (UITP 2018).

Subway networks experience several incidents and accidents, some of them resulting in injury or death to both staff members and to users. The most widely publicized accidents are those involving a large number of casualties, such as the derailment of a train in Chicago in 2014 (30 injured) or in Moscow the same year (21 fatalities and more than 160 injured). Globally, however, subway networks have recorded very few collective accidents, (i.e accidents implying multiple victims), and those that have occurred have caused few casualties; individual incidents and accidents are largely predominant. For example in France, subway companies report annually more than 1,200 individual safety incidents on their systems (STRMTG 2018) although most of them did not result in any severe consequences for humans. These incidents resulted on average in more than 10 fatalities and 700 injuries per year over a five-year period (STRMTG 2017) while twenty-eight suicide-related deaths occurred on average each year between 2007 and 2015 (STRMTG 2017). The London Underground reported on average about 3,000 incidents each year including assaults, slips, on board injuries, etc. (e.g. LUL 2019), that resulted in about 40 deaths per year of voluntary or involuntary origin between 2000 and 2010 (Martin and Rawala 2017).

In addition to the human loss, subway accidents cause trauma and work-related stress to the rail staff and rescue employees, severe consequences for train drivers (e.g. somatic problems, anxiety, sleep disruption, etc.) as well as for passengers and eyewitnesses (Havârneanu et al. 2015). Subway drivers who experienced a "person under train" (PUT) event had higher sick leave absenteeism, smoking habits and alcohol habits, and these problems worsened when the victims when the victims were severely injured (Theorell et al. 1994).

The platform-train interface (PTI) has been identified for a long time as a hotspot of individual injuries and fatalities in subway networks (Santoso et al. 2013). This interface encompasses the train door and the corresponding adjacent spaces on the platform and on the trains, and includes any devices and information provided to the passengers during their interactions in this phase of their trip. Passenger interactions are mostly concerned with moving, waiting, boarding and alighting. In fact, since the tracks are also a critical component in relation to injuries and fatalities, it would be more correct to refer to the platform-train-tracks interface (PT²I) rather than to the platform-train interface (PTI).

The aim of this paper was to review research on individual accidents[1] leading to injuries and fatalities at the PT²I with a focus on their individual, contextual, spatio-temporal and behavioural determinants, as well as on existing and prospective means to prevent their occurrence. It updates and extends two previous literature reviews. The review by Gershon et al. (2005) covered all subway hazards (including crimes) without much detail on subway accidents and was not specific to the PT²I. We share three references (Mishara 1999; O'Donnell and Farmer 1994; Sonneck et al. 1994) with this review and have added 39 references mostly posterior to 2005. The review by Havârneanu et al. (2015) concentrated on the prevention of accidents and suicides in the railway context with some marginal references to the subway context. Furthermore, Havârneanu et al. (2015) did not review the knowledge about user behaviours and other determinants associated with accidents. Our review includes this topic and shares six references (Coats and Walter 1999; Law and Yip 2011; Mishara 1999, 2007; Niederkrotenthaler et al. 2012; O'Donnell and Farmer 1992, 1994).

It is not easy to conduct a literature review on accidents as no international standardized classification of individual accidents in subways has been adopted. Thus, research dealing with accidents is not fully comparable. Moreover, current knowledge on victims' profiles, the context of accidents (e.g. time, location) and their determinants is sparse and scattered throughout the literature. User behaviour at the PT²I is sparsely documented and poorly understood, especially in relation to the occurrence of individual accidents.

Furthermore, some of our references include information about both accidents and suicides for the following reasons, although the literature search did not include keywords related to suicide or incidents. First, the way in which injuries or fatalities are classified as accidents or suicides is not always clear or consistent across the different sources. While the presence or

[1] The term accident will be used exclusively to describe events that led to unintentional injury or death. The term suicide is used when injuries or deaths due to intentional events (excluding crimes), suicide attempts are included. The term incident will be used to all types of events (accidents, suicides, crimes).

absence of intent to kill oneself is the common criterion to distinguish between suicides and accidents (Lin and Gill 2009; Mishara 2007), this intention is not always easy to determine. Second, most of the existing references address fatalities and injuries either in an undifferentiated manner (Coats and Walter 1999; Cocks 1987; Guth et al. 2006; O'Donnell and Farmer 1994) or separately (Gershon et al. 2008; Lin and Gill 2009; Uittenbogaard and Ceccato 2015). Finally, existing preventive measures may, in some cases, apply to both suicides and accidents.

This review is split in four parts. We first present the method used to select, classify and analyse the articles. The second part is dedicated to the two-step analysis of the articles. The quantitative analysis covers the country and time distribution, the methodologies used and the types of data in each article. The qualitative analysis addresses two main topics: accident analysis/description and prevention. The last part discusses the contributions of existing research in order to identify gaps that need to be filled in future research.

2 Method

This review used a three-step methodology based on the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement (Moher 2009) (Fig. 1).

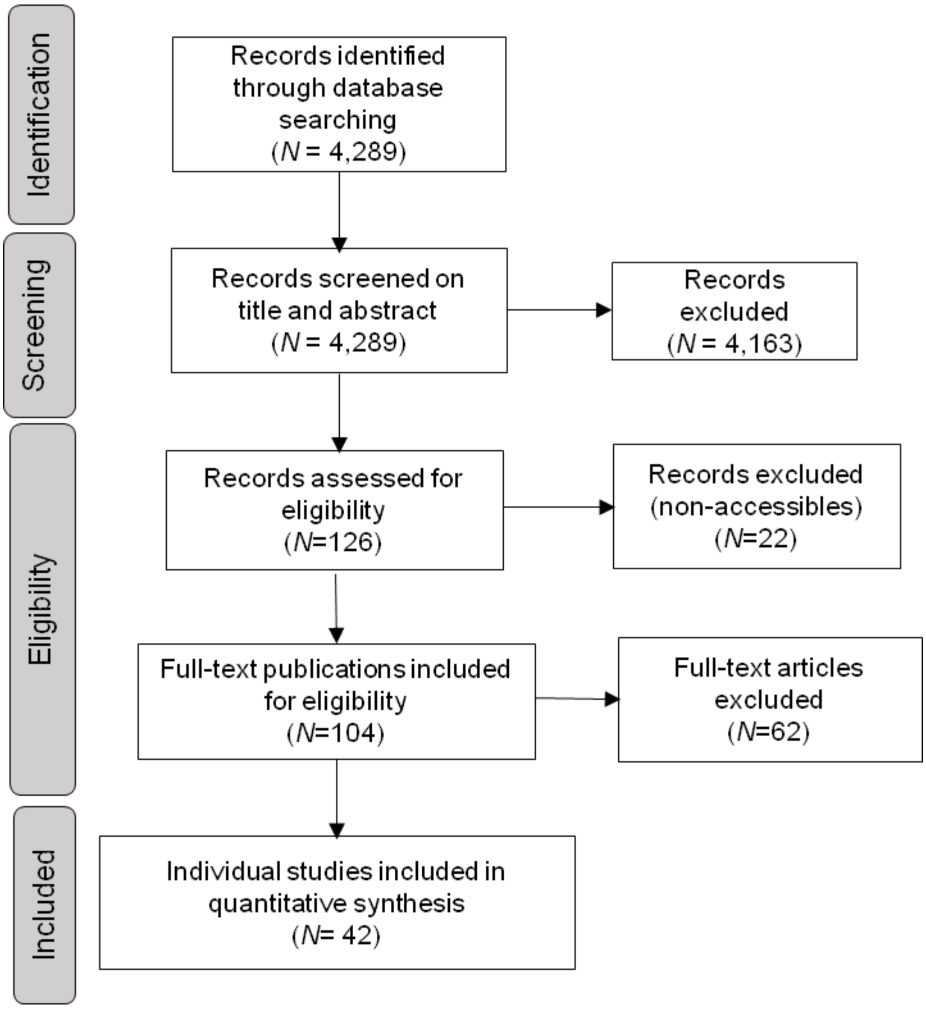

Fig. 1 PRISMA flow chart

Studies were identified by searching through several scientific databases covering peer-reviewed journal papers published in French and English up to January 2019 in behavioural science, social science and medicine (Scopus, PsychINFO, and Google Scholar). The search was applied to title, keywords and abstract using the following terms: “Metro” or “Subway” or “Underground” completed with “Injur*” or “Fatalit*” or “Accident*”. In addition, we also looked at the “grey literature” such as practical safety guidance documents, conference proceedings, accident reports, statistical reports, and official publications of subway companies. Several subway companies, as well as national and international administrations, publish reports on safety, incidents, and the organisation of subway systems on their own websites. This step resulted in 4,289 references.

We read through all the titles and abstracts. To be included, the document had to provide evidence about the subway system, station design and user behaviours, safety performance of measures dedicated to the subway, or subway accidents. This process resulted in a subset of 126 documents, of which 22 were not included because we could not access to the full document (e.g. unpublished conference presentation) or only the summary was written in English or French.

The content of the remaining 104 documents was analysed in depth to determine their eligibility. To be included, references needed to address at least one of the following themes: 1) preventive measures against PT²I incidents (suicides or accidents), 2) users' behaviours at the PT²I, 3) precursors of PT²I incidents, 4) victimology (context and victims' profiles) on PT²I incidents. We obtained 42 articles that met these criteria. Our analytical approach was twofold. We first carried out a quantitative synthesis of the 42 eligible publications using the following descriptive schema: 1) type of publication (conference proceedings or journal article), 2) country and year of publication, 3) main topic (prevention or accident), 4) type of data (empirical, theoretical or technical), 5) methodology used, 6) preventive measures (none, proposed, or evaluated). Second, we conducted a content analysis, adopting a qualitative perspective on accidents, the description and explanation of human behaviour at the PT² interface, existing evidence related to general and specific preventive measures proposed by different authors, and possibly unique measures to prevent individual incidents and accidents in subway networks.

3 Results

3.1 Quantitative analysis

This first section describes the 42 selected papers published between 1984 and 2018 based on the criteria mentioned above. Most of the publications come from scientific journals (n=34), the rest from conference proceedings (n=8). The scientific journals are all peer-reviewed and correspond to Q1 or Q2 in the SCIMAGO classification. All the conference papers except the one by Zhou and Yan (2018) were presented at international conferences based on a peer-reviewed selection process.

3.1.1 Spatial and temporal distribution of our corpus

The data used in these publications usually came from a single country although three documents reported on data and results within an international scope (Kyriakidis et al. 2012; 2013; O'Donnell and Farmer 1992). Most of the papers came from three regions (Table 1): Asia (*n*=16) followed by Europe (*n*=12) and North America (*n*=9). Less well represented areas were Latin America (*n*=2) and the Middle East (n=1). The most represented countries were China (*n*=10), the United-States (*n*=6) and the United Kingdom (*n*=5). Other countries had less than four publications. The number of publications increased between 1984 to 2018 (χ^2 (2, N=42)=19.5; *p*<.01) (Table 1) with the development of Asian research on this topic, in line with the growth of subway networks in this area.

Table°1 Distribution of references by country and time period

World region	Country	Time Period			Tot.
		1984-1995	1996-2007	2008-2018	
Asia	China			10	10
	Singapore			1	1
	South Korea			4	4
	Thailand			1	1
Europe	United Kingdom	4	1	1	6
	Austria	1		1	2
	Germany		1		1
	Portugal			1	1
	Sweden			1	1
North-America	USA		4	2	6
	Canada	1	1	1	3
Latin-America	Chile			1	1
	Mexico			1	1
Middle East	Iran			1	1
International		1		2	3
	Tot.	7	7	28	42

3.1.2 Topic evolution: accident description vs. preventive means

All the publications were classified according to the main topic they addressed, either prevention (*n*=18) or accidents and precursor analysis/descriptions (*n*=24) (Table 2). They were classified as oriented towards prevention when most of the text was about the design and/or evaluation of one or more preventive measures against individual accidents at the PT²I. They were classified as accident analysis when the text was mostly oriented towards describing the characteristics of accidents and victims (toxicology, location, time, etc.) or investigating some accident precursors such as user behaviours, knowledge or perception of risk at the PT²I. It is worth noting that preventive measures were sometimes mentioned in papers oriented towards accident analysis, but usually in a marginal and cursory manner, for example as a suggestion for possible preventive solutions in the conclusion or discussion section.

Table 2 Distribution of references by main topic and design

Time	Main topic	Design	Tot.

period		Empirical	Theoretical	Technical	
1984-	Accident Report	5			5
1995	Prevention	3			3
1996-	Accident Report	4	2		6
2007	Prevention	2		1	3
2008-	Accident Report	13			13
2018	Prevention	8		4	12

Accident reports were the main topic in the literature on subway issues before 2007. After this date, prevention and accidents were given equal importance. The temporal evolution of these two topics was the same ($\chi^2(2, N=42)=0.9$; $p<n.s$).

3.1.3 Nature of contributions and methods used

Three types of papers can be distinguished according to the nature of the evidence on which they are grounded: empirical, technical and theoretical contributions (Table 2).

Empirical studies

Empirical papers are based on the collection and analysis of data from the field or from the laboratory through observation, experiments, surveys or accident/incident reports. Various data collection and analysis methods are used, and sometimes combined, in our subset of 35 empirical papers.

Descriptive analysis (n=26) refers to the analysis of data on accidents, fatalities and incidents from different sources (police, medical services, transport agencies, subway operator reports).

Questionnaires were used with one or two target populations: professionals (*n*=3) and users/passengers (*n*=6). Various topics were investigated: the perception of platform safety and risky behaviours (Santoso et al. 2013; Wan et al. 2015; Wan et al. 2016), the risk of accidents in general (Kim et al. 2017), the acceptance of subway incidents (Chen et al. 2018; Jones-Lee and Loomes 1995). Preventive measures were also investigated or described through questionnaires (Kyriakidis et al. 2012; Santoso et al. 2013).

Experimental design characterized four papers. Three papers evaluated a preventive measure (Duarte et al. 2014; Muñoz et al. 2018; Yang and Long Lim 2018), while the fourth assessed users' perception and beliefs of risks in several scenarios in the PT^2I context (Wan et al. 2016).

Observation was reported in only four studies, either as the main (Clarke and Poyner 1984; Zhang et al. 2012) or as a preliminary approach for gathering data (Santoso et al. 2013; Wan et al. 2015).

Three papers used interviews as a pilot study to create questionnaires (Wan et al. 2016; Wan et al. 2015) or to prepare observations (Clarke and Poyner 1984) by listing risky behaviours with participants.

Technical studies

We considered as technical papers (n=5) those that used computer-based simulation instead of studying real users or that described the organizational and technological measures for the prevention of PT^{2}I accidents.

Two papers used computer-based simulations to create the station environment with the aim of mimicking passengers' behaviours or testing preventive measures (Baee et al. 2012; Portillo-Villasana et al. 2017). Three papers described technical devices for the PT^{2}I (Joung 2010; Mathew 2005; Zhang et al. 2010).

Literature review

Two papers present literature review about safety in railway contexts (including the subway) in the sense that they are based on assertions about human behaviours and descriptions about subway safety, rather than on the collection and analysis of empirical data. Mishara (2007) proposed a theoretical description and analysis of incidents, focusing on suicides in the railway context (including the subway). Gershon et al. (2005) reviewed the literature about various dimensions of passengers' health and safety in the subway.

3.1.5 Preventive measures found in the corpus

Thirty-eight of the 42 papers mention one or more preventive measures, from which we identified 19 distinct specific measures (Table 3).

Table 3 Distribution of preventive measures in the corpus (() number of evaluations included)

Type of measures		Time period			Tot.
		1984-1995	1996-2007	2008-2018	
Physical and technical	PSD	3	3	8(4)	14
	CCTV	2	3	3	8
	Suicide pit	4(2)	3(1)	1	8
	Sliding step			1	1
	System to detect intrusions in the gaps between train and PSDs			1	1
	Door on the platform/Unidirectional door			2(2)	2
	Alarm			1	1
	Infra Red beams	1			1
	Lighting			1	1
	Platform design		1		1
	Front train material	1			1
Organisational and procedural	Speed limit	1	3		4
	Surveillance units		2	3(1)	5

	Preferential tariff			1(1)	1
	Accident causation analysis			2(2)	2
Communicational and educational	Training	2	1	1	4
	Education program	1	2	1	4
	Communication		1	3	4
	Media guidelines	2		1	3
	Video spot			1(1)	1
Total		17	19	31	67

These preventive measures were described with various levels of detail and evidence. Some papers (*n*=9) proposed only one or more measures, sometimes at a very general level. Another set of papers reported on some assessments of preventive measures (*n*=13). A third set proposed and detailed the content of preventive measures without any evaluation (*n*=12).

A third of these measures (7/20) were subjected to evaluation. Platform screen doors (PSD) (n=4) was the most frequently evaluated measure, followed by suicide pits (*n*=3), unidirectional gates on the platform (*n*=2), an accident analysis method (n=2), the presence of surveillance units (n=1), video spots (n=1), and preferential tariffs (n=1).

3.2 Qualitative analysis

3.2.1 Characteristics of incidents and accidents

Fourteen studies investigated the consequences of subway incidents on victims. They used various sources and types of data and examined the issues at various levels of detail (Tables 4, 5 and 6).

While some papers focus on fatality records, the others adopt a broader scope and consider patients admitted after a subway-related accident, or incident databases. In the case of incident databases, accidents are often one of the different items surveyed and few, if no, details are given about the context and the explanatory factors. Furthermore, the classification of occurrences is not always consistent between authorities or sources. For example, only a subset of the studies make a clear distinction between intentional (suicide) and unintentional incidents (accidents) (Gershon et al. 2008; Lin and Gill 2009; Rodier et al. 2018; Uittenbogaard and Ceccato 2015). This makes it difficult to aggregate outcomes based on existing data because of their lack of consistency and incompleteness. A further difficulty is that subway networks exhibit highly distinctive characteristics depending on the world region, the country and the moment of the study in terms of infrastructure, degree of automation, ridership etc. This means that the outcomes are not applicable between countries or even between regions, as well as over time. In addition, these data are associated with a limited range of identifiable risk factors, and in particular those relative to individual behaviours and motivations.

Four main classes of individual incidents with wide variations in accident and other event rates

The literature identifies up to four main classes of individual incidents depending on the intentionality criterion: accidents, suicides, homicides, and undetermined.

The proportion of subway fatalities (Table 4) classified as accidental ranges from 5% (Johnston and Waddell 1984) in Toronto between 1954 and 1980, 11% in Montreal between 1986-1995 (Mishara 1999) to 47% in the New York city subway between 1990 and 2003 (Gershon et al. 2008). An even higher rate of 50% of accidents is reported by He, Fang, Lin, Ma, and Li (2015) for the Shanghai subway between 2000 and 2009. However, a particularly low number of fatalities in comparison to any other network characterises the latter. Suicide rates vary in a complementary fashion between 95% to 51% depending on the city and the period. One hypothesis could be that accidents are more prone to occur in large networks with a high ridership (e.g. NY City), whereas a lower prevalence of accidents in smaller subway networks (e.g. Toronto, Montreal or Stockholm) would increase the proportion of suicides. Another explanation may lie in differences related to the stations' infrastructure, the rolling stock and the preventive measures implemented. It is worth noting that the ratio between accidents and suicides differs depending on the sources and the nature of the data (medical reports, death reports, etc.). For example, in New York city, medical records of patients admitted after subway-related injury to Bellevue Hospital show only 17% (Rodier et al. 2018) or 25% (Guth et al. 2006) of suicides whereas an average of 51% of suicides was found when death certificates were consulted (Gershon et al. 2008; Lin and Gill 2009). This may be due to a greater proportion of fatal outcomes in the case of suicides as compared to any other incident.

Depending on the papers, there can be also up to 17% of "undetermined" fatality cases, highlighting that this four-part classification is not straightforward, in particular when information about the person's intention is missing. Finally, homicides represent between 0.2% (Johnston and Waddell, 1984) and 0.3% of patients admitted after subway-related injuries (Rodier et al. 2018) and between 2% (Gershon et al. 2008; Lin and Gill 2009) and 3% (Mishara 1999) of fatalities in North America.

Table 4 Summary of the studies that provide empirical results about subway incidents with different causes

Reference (authors, date)	Data description and main results	Sample
Studies using fatality records		
Gershon et al. (2008)	*Location:* New York city subway *Source:* Review of medical files at the Office of the Chief Medical Examiner of NYC (OCME) *Period:* 1990-2003	315 fatal accidents: 91% male, 35-44 years, 46% with alcohol, 31% with drugs, 71 % of non-white victims 343 suicides: 78% male, 25-34 years, 18% with alcohol, 21% with drugs, 62% of non-white victims 10 homicides: 60% male, 35-44 years, 0% with alcohol, 60% with drugs, 90% of non-white victims
He et al. (2015)	*Location:* Shanghai subway *Source:* Review of unnatural deaths at the Shanghai Public Security Bureau *Period:* 2000-2009 *Results:* All decedents were males with an average age of 36 years	3 fatal accidents, 2 suicides, 1 undetermined death
Lin and Gill (2009)	*Location:* New York city subway *Source:* Death certificates of OCME with the words "subway", "train" or "tracks" *Period:* Jan. 1, 2003-May 31, 2007 *Results:* 2% of deaths are caused by electrocution and the others by blunt force. Greatest number of suicide deaths occurred in May and on Tuesday. Accidental deaths occurred most in March and December with low day-to-day variability.	76 fatal accidents: 86% male, mean age 44, 42% with alcohol, 25% with drugs, 8% with antidepressant medication 111 suicides: 81% male, mean age 45, 14% with alcohol, 3% with drugs, 21% with antidepressant medication 20 undetermined deaths 4 homicides
Mishara (1999)	*Location:* Montreal subway *Source:* Reports from the Quebec Chief Coroner's office *Period:* March 1986- Dec. 1995 *Results:* Suicides occurred between 9:00 to 16:00. 61% of suicide victims were men with average age of 38 years, 27% lived in a mental health facility at the time of their death, only 14% of suicide victims indicated no previously diagnosed mental illness Alcohol was found in 25% of suicides.	17 fatal accidents, 120 suicides, 9 fatalities undetermined, 5 homicides
Study using medical records		
Rodier et al. (2018)	*Location:* New York city subway *Source:* Medical records of patients admitted after subway- related trauma to Bellevue Hospital *Period:* Jan. 1, 2001- Dec. 31, 2015 *Results:* Mean age of cohort was 41 years, of which 80% were male. Cases occurred most in winter and spring and alcohol was detected in 42% of patients.	177 accidents, 43 suicide attempts, 27 undetermined, 7 homicides
Study using incident records		
Johnston and Waddell	*Location:* Toronto subway *Source:* Records of Toronto Transit	36 accidents: 31% of deaths 430 suicides: 48% of deaths, 20-30 years

(1984)	Commission *Period:* 1954-1980 *Results:* November and December had the highest suicide rates. Midday is the time when most suicide attempts were made. Transfer stations had most suicide attempts.	1 homicide
Uittenbogaard and Ceccato (2015)	*Location:* Stockholm metro *Source:* Data from MTR Stockholm and Stockholm public transport *Period:* 2000-2013 *Results:* The number of suicides was slightly higher on weekdays with a peak in the afternoon (15:00 and 16:00). Accidents were most frequent during the evening and night and during weekends. Highest incidence of suicides was in spring and highest incidence of accidents was in autumn and winter. Highest rates of suicide were observed in the periphery while highest rates of accidents were found adjacent to the city center.	88 fatal accidents, 162 suicides

Fatality rate and causes of injury

To the best of our knowledge, and in contrast with other transport modes (e.g. road, rail), there are no published data on death rates and passenger injuries in subway systems at an international level. The few existing sources concern a specific network or a country - over a given period - and provide limited information on the incidence and mortality of passenger incidents in subways. These studies based on incidents and patient records (Table 5) showed a fatality rate between 10% (Guth et al. 2006) and 57% (Coats and Walter 1999). At a wider scale, data from the U.S. subway showed a fatality rate of 0.33 deaths per billion passenger-miles between 2000 and 2014. This is higher than the fatality rate for bus transport (transit, intercity, school, charter) (0.2 deaths per billion passenger-miles) but slightly lower than commuter rail and Amtrak (0.36 deaths per billion passenger-miles) and far safer than roads (6.53 deaths per billion passenger-miles) (APTA 2016).

Table 5 Summary of the studies that provide empirical results about subway incidents and patients after subway-related incidents.

Reference (authors, date)	Data description and main results	Sample
Studies using incident records		
Coats & Walter (1999)	*Location:* London underground *Source:* Records of incidents *Period:* Jan. 1996- March 1997	58 incidents % deaths: 57
O'Donnell, & Farmer	*Location:* London underground *Source:* Records of railway operations and passenger services	3240 incidents % deaths: 10

(1994)	departments of LUL *Period:* 1940-1990 *Results:* 7% of deliberate acts between 1985-1989 (n= 409), Suicide rate was highest in spring and lower on Sunday, 41% of incidents occurred between 10:00 and 16:00, Most risky stations were near a psychiatric hospital	% male: 64 Mean age: 41
Studies using medical records		
Cocks (1987)	*Location:* London underground *Source:* Records of police, emergency services, hospital and coroner *Period:* 1981-1986	100 patients % deaths: 43 % male: 49 Mean age: 40
Guth et al. (2006)	*Location:* New York city subway *Source:* The Bellevue hospital registry US department of labor Bureau of Labor Statistics Data *Period:* Jan. 1, 1990- Dec. 31, 2003 *Results:* 45.5% of patients were unemployed, 25% of cases were suicide attempts, Similar pattern between unemployment rates, homeless rates and subway injuries.	208 patients % deaths: 10 % male: 80 Mean age: 39

Subway-related injuries and fatalities are associated with two main causes: mechanical when a collision occurs and/or electrical when there is contact with the third rail that delivers electrical power to the train. Lin and Gill (2009) give the only available evidence regarding the prevalence of these two causes. They report that between 2003 and 2007, most of the 211 fatalities registered in the New York City subway were caused by blunt trauma (98%) and very few by electrocution (2%).

Accidents and suicide-related fatalities differ in their daytime and weekday distribution

The time distribution of fatalities in the subway differs depending on whether they are intentional (suicide) or unintentional (accident) in nature. Data from two networks (New York and Stockholm) show that accidents occur most frequently during the afternoon rush (17:00 to 20:00), in the evening (20:00 to 24:00), and early in the morning (4:00 to 8:00) (Lin and Gill 2009; Uittenbogaard and Ceccato 2015). In addition, there is no difference in the accident rate by day of the week in London, New York and Stockholm subway networks (Lin and Gill 2009; O'Donnell and Walter 1994; Uittenbogaard and Ceccato 2015).

In contrast, the suicide rate (Table 4 and 6) is the highest in the middle of the day, i.e. between 10:00 and 16:00 (Johnston and Waddell 1984; Ladwig 2004; Mishara 1999; O'Donnell and Walter 1994; Uittenbogaard and Ceccato 2015), and on weekdays (Lin and Gill 2009; Sonneck et al. 1994; Uittenbogaard and Ceccato 2015). More precisely, the highest suicide rates are at the beginning of the week, on Monday and Tuesday (Lin and Gill 2009; Sonneck et al. 1994).

Table 6 Summary of the studies that provide empirical results about subway suicides

Reference (authors, date)	Data description and main results	Sample
Studies using fatality records		
Martin and Rawala (2017)	*Location:* London underground *Source:* British Transport Police *Period:* 2004-2010 *Results:* Suicide deaths occurred most in May and June and the majority of victims (80%) were white North European	132 suicides % male : 66 Mean age : 43
Study using incident records		
Ladwig (2004)	*Location:* Munich subway *Source:* MVG case registry *Period:* 1980-1999 *Results:* Suicides occurred the most between 9:00 to 12:00, and most at the beginning of the week and least on Sunday, The sample did not reveal a consistent seasonal pattern.	306 suicide attempts % deaths: 66 % male: 53 Mean age: 38
Studies using media records		
Sonneck et al. (1994)	*Location:* Vienna subway *Source:* Records of Austrian daily newspapers *Period:* 1984-1987 *Results:* Weekday with the most suicides was Monday.	89 suicide attempts % deaths: 63 Ratio male: 2.1 :1 Mean age: 37
Zhang et al. (2016)	*Location:* Shanghai subway *Source:* Data collected in literature and media *Period:* Jan. 2005-May 2013 *Results:* Most incidents occurred in the morning and afternoon rush hours (7:00 to 9:00 and 17:00 to 19:00)	240 other causes 9 suicide attempts % deaths: 19

Distribution of accidents across seasons and places varies depending on the network

Some variations across seasons are specific to the network: whereas the winter is the highest accident-prone period in New York (Lin and Gill 2009; Rodier et al. 2018), most accidents are observed in autumn in Stockholm (Uittenbogaard and Ceccato 2015). Suicides occur less at the beginning of autumn (September and October) and more in spring and winter on three networks: New York city, London and Stockholm (Lin and Gill 2009; Martin and Rawala 2017; Uittenbogaard and Ceccato 2015). Conversely, in the Munich subway, the number of deaths due to suicide does not vary with the season (Ladwig, 2004).

In New York, London and Stockholm, fatalities due to accidents are mainly concentrated in the city centre area while suicides are more frequent in suburban stations (Gershon et al. 2008; Uittenbogaard and Ceccato 2015) or in proximity to psychiatric hospitals (O'Donnell and Farmer 1994).

Victims are predominantly male and middle-aged

Medical and coronary records provide information about the victims' characteristics (Table 4 and 6). The study of cohorts of patients admitted after a subway related injury showed that 49 to 80% of them are male (Cocks 1987; Guth et al. 2006; Rodier et al. 2018). However, the male/female distribution between accident and suicide victims appears to differ: the victims of fatal accidents in the subway are predominantly male (Gershon et al. 2008; He et al. 2015; Lin and Gill 2009), accounting for 88% on average. When only deaths by suicide are considered, the male-to-female ratio is slightly lower but men still account for the vast majority with on average 66 to 81% (Gershon et al. 2008; Lin and Gill 2009; Martin and Rawala 2017; Mishara 1999).

Generally, the age of victims appears to be similar in subway-related accidents and suicide fatalities (Gershon et al. 2008; Lin and Gill 2009). The victims of subway incidents are predominantly middle-aged, with an average age of about 40 (Cocks 1987; Guth et al. 2006; He et al. 2015; Martin and Rawala 2017; Lin and Gill 2009; Rodier et al. 2018; Sonneck et al. 1994).

Alcohol and cocaine are associated with accidents, antidepressants with suicides

Alcohol or drug intoxication is frequently associated with accidents and suicides (Gershon 2005; Lin and Gill 2009; Rodier et al. 2018). Gershon et al. (2008) and Lin and Gill (2009) report toxicological evidence of drugs in 63% of victims. The substances identified appear to differ depending on the type of incident. In the New York City subway, alcohol was detected on average in 40% of fatal accidents and 15% of suicides (Gershon et al. 2008; Lin and Gill 2009; Rodier et al. 2018). In New York, drugs were detected on average in 20% of fatalities (suicides and accidents) but the types of drugs used differ between accidents and suicides. Lin and Gill (2009) found that antidepressant medications are more frequently detected in suicides (21% vs. 8% in accidents) whereas cocaine is more frequent in accidents (Gershon et al. 2008; Lin and Gill 2009).

Psychiatric and socio-economic characteristics of victims

Rodier et al. (2018) found that 39% of patients admitted after a subway related injury had a history of psychiatric illness and Cocks (1987) found that 58% of patients injured on the London underground system had a previous history of psychiatric illness. In contrast, Lin and Gill (2009) reported differences in the number of victims of subway-related fatalities with psychiatric illness: 34% of suicide victims vs. 3% of accident victims.

A few studies have investigated the impact of socio-economic factors on the occurrence of incidents. Guth et al. (2006) observed that the higher the number of accidents at a station, the higher the unemployment rate in the corresponding area. They found that slightly less than half of 46% of patients admitted after subway injuries in the New York city subway between 1990 and 2003 were unemployed. In the same network, Gershon et al. (2008) and Lin and Gill (2009) found that most of the subway-related accident and suicide fatalities concerned minorities (71% of “non-white race”). In contrast, Martin and Rawala (2017) observed more white North European victims (80%) in suicide cases on the London underground between 2000 and 2010.

3.2.2 Characteristics of risky behaviours in relation to incidents and accidents

Based on the declared frequency of several risky behaviours by passengers in the Shanghai subway network, Wan et al. (2015) distinguished between three main categories of risky behaviours in relation to accidents: transgressions (transgression of subway riding rules, violations and errors), self-willed inattention (more frequent but less risky behaviours implemented for convenience, comfort, etc.) and abrupt violations (deviation from normal behaviour). They reported that transgressions and abrupt violations were significant predictors of incident and accident involvement.

There is a partial consensus among authors on the most specific risky behaviours. Estimating the incidence and the potential severity of the consequences associated with 19 pre-identified behaviours occurring at the PT²I, Wan et al. (2015) highlighted four specific behaviours as being more risky than others: boarding or alighting when the door-close alarm sounded, squeezing into the train before alighting had finished, forcing the doors to board or alight, and finally crossing the yellow line when waiting on the platform. Likewise, Zhang et al. (2012) characterized "stepping on the yellow line" and "pushy riding" as the twin behavioural indicators of risk in the only published study based on the observation of real passengers' behaviours (although carried out at a single station). Wan et al. (2015) added the use of smartphones as another frequent risky behaviour, although direct evidence was lacking. Existing indirect evidence is provided by Kim et al. (2017) showing that students who are smartphone addicts have overall more accidents (of different types) than other students do, although they do not exhibit statistically more accidents in the subway (they studied the accident of being trapped in the subway). However, the lack of a significant difference could be due to the low levels of prevalence of this kind of accident (1.8% for smartphone-addicted students vs. 0.78% for non-addicted students).

3.3 Factors explaining risky behaviours

The existing literature on subway accidents focuses mostly on individual explanatory factors of risky behaviour at the PT²I. Zhang et al. (2012) argued that the emergence of risky behaviours could be explained by the lack of knowledge or understanding of the dangers related to the subway environment. Other authors suggested that risky behaviours could relate to the false perception of how risky the behaviour actually is (Wan et al. 2015). The latter idea is debated, however. For example Santoso et al. (2013) showed that users are well aware of the safety concerns associated with some behaviours such as teasing or playing on the platform. In general, users correctly consider the platform zone and especially the space near the platform edge as risky.

Rather than implicating the cognitive level, Wan et al. (2016) proposed that passengers' risky behaviour may be better explained by social norms and beliefs. Grounded on the extended theory of planned behaviour (TPB; Ajzen 2002), they surveyed a sample of habitual subway users on three specific behaviours: last-second riding, pushy riding (boarding before alighting ends) and door forcing. They found an effect of the different beliefs on the prediction of an intention to ride dangerously. Behavioural and control beliefs are consistently predictive across the behaviours surveyed (saving time, getting a seat and being late/in a hurry). Other factors increase the explanatory power of the model: moral norms, past behaviour, perceived risk and self-identity. TPB factors (Ajzen 2002) on average accounted for 56% of variation in intentions to commit the three risky behaviours studied. However, as with all the studies using TPB as theoretical framework, the focus is on intentions instead of actual behaviours and comprises self-reporting biases.

The literature also reports the impact of contextual factors. Zhang et al. (2012) identified in particular the effect of crowd density, speed and flow on the level of risk. With measurements at morning, noon and evening peak times, they observed the highest rate of late boarding and alighting in the evening (3% of the observed passengers) and the lowest in both morning and noon hours (less than 1%). They hypothesized that, in the evening, the subway is so overcrowded that no space is left to jump onto the train, and at noon, there is no need to crush in the train because there are very few passengers. In contrast, Wan et al. (2015) showed that those passengers that ride the subway during peak periods declare more frequent transgressions of subway riding rules, inattentive behaviour and high risk behaviour. They also report that the characteristics of the trip, of the riding area and the increase in the number of stops, predict the involvement in incidents, although no clear interpretation can be provided. Finally, Zhang et al. (2012) explained the near to zero rate of stepping on the yellow line (on the edge of the platform) observed in their study by the presence of subway staff who stop passengers effectively and in a timely manner. The difference in the results of these two studies (Zhang et al. 2012; Wan et al. 2015) may be due to a difference in the methodologies used. Zhang et al. (2012) observed passengers' behaviour at a single station of the Beijing subway, whereas Wan et al. (2015) used self-report questionnaires published on the homepage of some popular forums. Self-report questionnaires may be biased by social representations, while observations are limited to a single location and can also be biased due to physical constraints in the station environment.

3.4 Preventive measures against PT²I incidents

Within our selected set of studies, several preventive measures are adapted against PT²I incidents and their consequences for victims. In a study on the prevention of trespass-related railway accidents and suicide, Havârneanu et al. (2017) distinguished between three families of preventive measures based on their nature and the mechanisms underlying their effect: technological and physical measures, organizational measures, and finally educational and communicational measures.

3.4.1 Technological and physical measures

Technological and physical measures refer to technical means and physical barriers to avoid the occurrence of an accident or to reduce its gravity. These measures can be implemented on the station environment (e.g. CCTV, PSD, etc.) as well as on the tracks (e.g. suicide pits, fall detector systems, etc.) or on the train (e.g. airbag, protective skirt, etc.). Eleven distinct technological and physical measures are mentioned in 23 of our papers (Tables 3 and 7).

Table 7 Summary of the studies that provide evaluation of technical and physical measures

Reference (authors, date)	Study design and measures	Significant results reported
Platform screen doors		
Chung et al. (2016)	*Location:* Seoul Metro *Intervention:* Half- height PSDs (1.65m) at two stations and full-height PSDs on 119 stations *Study design:* Quasi-experimental, ecological study with before and after measurements, based on the number of suicides *Data:* 135 suicides on 121 stations *Period :* 2003 to 2012	Suicides in subway stations decreased significantly after installation of PSDs (-89%)
Law and Yip (2011)	*Location:* Hong Kong railway system *Intervention:* PSDs in 30 stations in 2002 *Study design:* Quasi-experimental, ecological study with before and after measurements, based on injury data *Data:* 402 casualties (154 suicidal, 248 accidental) *Period:* 1997 to 2007	Installation of PSDs reduced casualties (-67.5% suicidal; -69.5 accidental)
Portillo-Villasana et al. (2017)	*Location:* Zocalo subway station (Mexico City) *Intervention:* PSDs *Study design:* Simulation software ("AnyLogic"), Analysis of the effectiveness of physical barriers with two scenarios (with or without PSDs) *Data:* 100 simulations	84% of subway passengers who have the intention to commit suicide succeed without PSDs against 24% with PSDs
Santoso et al. (2013)	*Location:* Bangkok subway *Intervention :* PSDs *Study design:* Questionnaire survey about platform safety by users (21 items), four items on the perception of PSD installations *Data:* 120 valid questionnaires (65% female, 54.17% aged 26-60 years) *Period*: Nov. 2012	Installation of PSDs was perceived positively (76.67% agree) provided it does not imply any increase in the fare
Doors on the platform		

Munoz et al.(2018)	*Location:* Tobalaba Station (Santiago metro) *Intervention:* Door placed at the center of the arrival platform, to traverse the platform uniquely from South to North, 3 removable unidirectional doors on weekdays between 7 and 9 a.m. *Study design:* Quasi-experimental, ecological study with before and after measurements, based on several performance indicators: Time to clear the platform; Frequency of trains; Operational speed of trains; Passenger opinion *Data*: One station, 400 random users	Transport capacity grew 5%, trains were more frequent and more reliable. Travel times decreased by 6.5%. Platform clearing time decreased by 7%. Passenger counter-flows on the platform disappeared.
Baee et al. (2012)	*Intervention:* Different boarding/alighting scenarios: BASD: Entrance to and exit out of wagons are isolated through a separator BADD: Inflow and outflow of passengers are directed through different doors BATD: inflow and outflow of passengers are scheduled at different times Control: De facto *Study design:* Simulation using MATLAB: - Train stopping time at the platform - Service Success Rate - Satisfaction Level *Data*: Nine stations (start station: all in flow; end station: all out flow; six regular stations and one inter-change station)	BASD scenario shows higher satisfaction levels and a lower failure rate in boarding/alighting than with other scenarios. Train stopping time at the platform was shorter with the BASD scenario than with three others.
Suicide pit		
Coats and Walters (1999)	*Location:* London underground *Intervention:* Drainage pit or suicide pit *Study design:* Quasi-experimental, ecological study, based on incident records of patients hit by a train at the platform with or without a suicide pit *Data:* 58 cases (57% of deaths) *Period:* Jan. 1996-March 1997	Suicide pit reduced fatalities (44% of mortality with a pit compared to 76% without a pit, p=.026)
O'Donnel and Farmer (1992, 1994)	*Location:* London underground *Intervention:* Suicide pit *Study design:* Quasi-experimental, ecological study, based on incident records of patients hit by a train at the platform with or without a suicide pit *Data:* 1606 suicidal acts *Period:* 1973-1990	More deaths without a pit (66%) than the station has a pit (45%, $x^2(1) = 72.1$, $p<.001$)

Measures to reduce the occurrence of incidents (PSDs, sliding steps)

The Platform Screen Door (PSD) is the most widely documented measure in our corpus, and references to this measure have recently increased even further. Already in 1984, Johnston and Waddell proposed this measure to prevent accidental or deliberate injuries involving moving subway trains. PSDs are physical barriers that limit passengers' access to the tracks by separating the rail from the platform (Gershon et al. 2008). They can be full or half-height. PSDs open only when the train stops at the station (Chung et al. 2016; Gershon et al. 2008). PSDs have already been installed in several subway networks around the world (Clarks and Poyner 1994; Kyriakidis et al. 2013). Their primary objective is to reduce falls, trespassing and suicides (Chung et al. 2016; Kyriakidis et al. 2012). Several studies have evaluated this measure and have confirmed its effectiveness (Table 7). PSDs reduce suicide attempts by around -80% on average (Chung et al. 2016; Law and Yip 2011, Portillo-Villasana et al. 2017) and accidents by -69.5% (Law and Yip 2011), thereby contributing to reducing the time of service disruption by 64% (Law and Yip 2011). These studies do not distinguish the use of full-height and half-height PSDs. The height of the doors can have an impact on the effectiveness of this measure. However, new risks have emerged with PSDs, passengers could be unfortunately restrained and killed in the gaps between PSDs and the doors of the train. To reduce these risks, Zhang et al. (2010) propose to install a sensor system to monitor passengers and intrusion at the gaps based on optical time domain reflectrometer (OTDR). The presence of intrusions will be detected if the abrupt power loss at the locations of gaps is over a predetermined value. In their study, authors did not propose any data on the effectiveness of this system.

PSDs may also increase the perception of safety on the platform. In the Bangkok subway, passengers perceived this measure positively (mean of ⅘) provided that it did not imply any increase in the fare (Santoso et al. 2013). However, the installation of PSDs represents a huge cost of several million dollars for operators (Chung et al. 2008; Law and Yip 2011). Law and Yip (2011) examined the effectiveness and cost-effectiveness of PSDs in preventing injuries in the mass transit railway of Hong Kong with the "WHO-CHOICE" method (Table 7). With their approach, PSDs become cost-effective when the expected useful life is extended by two additional years to 27 years. Furthermore, this analysis did not include the cost saving of energy conservation.

Another system can reduce the occurrence of PT^{2}I incidents. The gaps between platforms and trains could also provoque incidents. This gap may be due to station design (curved area) or train characteristics. Sliding steps exist either on platforms or trains (Table 3). They fill the gap between the train and the platform. If the sliding step is installed on the vehicle, it is possible to respond to the various platform typed. This system has been validated as safe to use on subways but is not systematically used in existing networks (Joung 2010).

Measures reducing the consequences of incidents (suicide pit, front train material)

The first mention of a suicide pit was in 1936 in the London underground (Cocks 1987). A suicide pit is a drainage pit under the tracks, usually about a meter deep (Coats and Walter 1999). These pits increase the clearance between the train and the ground. As a result, after falling, an individual can lie safely underneath the train (Gershon et al. 2008). Studies found that suicide pits did not reduce the number of incidents but the mortality rate decreased (Coats and Walters 1999; O'Donnell and Farmer 1992). In the London underground, the fatality rate was on average 70% without pits and 45% at stations equipped with pits (Table 7) (Coats and Walters 1999; O'Donnell and Farmer 1992, 1994). Nevertheless, references to suicide pits as a preventive measure have declined since 2007.

In the nineties, Clarke and Poyner (1994) proposed other mechanisms on the front of the train to reduce injury such as an air bag or protective skirt. These mechanisms are not effective at high speeds but could avoid some fatalities in stations (Clarke and Poyner 1994). However, these systems have not been tested and changes in train design may make such additional devices unnecessary.

Measures avoiding passenger congestion (gates on the platform, platform design)

Passenger flow and congestion can be precursors of accidents. In the Santiago subway, unidirectional gates were installed in the middle of the arrival platform to constrain passenger flow on the platform to the South to North direction. The objective was to avoid counterflow on the platform. This installation decreased the platform's clearing time, generating a higher transport capacity - trains were more frequent and more reliable - and a higher level of safety as it eliminated passenger counterflow (Table 7). A few days after installation, users approved this initiative (Munoz et al. 2018). This installation has been preceded by public relations campaign and campaign reinforcement to requesting changes in boarding behaviour. Two policemen stood next to the gate during the first two weeks of the installation to ensure its proper operation but subway personnel still stated the passenger counter-flow once a day (Munoz et al. 2018). Authors do not indicate the duration of the experiment; the effects of this intervention could change over time.

To clear platforms faster, Baee et al. (2012) simulated several scenarios. When the entrance to and exit out of wagons were isolated through a separator (Boarding/Alighting Space Division; BASD), simulations showed fewer passenger collisions with a lower failure rate in boarding/alighting. The train stopping time at the platform was shorter with the BASD scenario than with the other three scenarios (Table 7).

Platform design can also change passengers' habits to reduce congestion in subway stations. Matthew (2005) described environmental persuasion with artwork on the walls and screens to increase social interaction and users' attention. These environments did not avoid PT²I incidents but they may create positive behaviours.

Measures to increase safety in stations (CCTV, alarms, lighting, infrared beams)

Some incidents at the PT²I are caused by malicious and illegal action (Kyriakidis et al. 2012). Closed circuit television (CCTV) will not necessarily stop intrusions or accidents at the PT²I but it could play a critical role in apprehending miscreants and reducing vandalism and antisocial behavior (Kyriakidis et al. 2012, 2013). With CCTV, staff can detect falls or jumping onto the tracks (Clarke and Poyner 1994; Yeo et al. 2006). The passengers' perceptions that they are being watched may reduce crime and suicides (Clarke and Poyner 1994). In addition, the cost of installation is relatively low (Yeo et al. 2006). The quality of lighting in the station could also increase safety, Gershon et al. (2008) mentioned adequate lighting to improve safety outcomes. However, lighting has never been tested as an preventive measure in its own right in subway systems.

With the same objective, O'Donnell and Farmer (1992) presented infra-red beams as a preventive measure to avoid intrusions. They alerted the station staff if an unauthorized person attempts to enter the tunnel in Prague. The infra-red beams are rarely mentioned and do not appear to be evaluated in the literature.

3.4.2 Educational and communication measures

Educational and communication measures correspond mainly to primary prevention (OMS 1948). The objective is to use communication or educational programs in order to change behaviours and/or to increase attention, as well as to avoid a copycat effect related to suicide media reports. There are 5 specific educational and communicational measures distributed across 22 papers in our corpus (Table 3 and 8).

Measures of public awareness (educational and communication campaign, media guidelines)

To strengthen global safety in the subway context, poster campaigns are launched to reduce risky behaviours by passengers (Kyriakidis et al. 2012, 2013). Public messages and information similar to what is provided for road traffic (e.g. drunk driving) could be effective in raising public awareness of risk in the subway (Gershon et al. 2008).

Communication about suicides in the subway is managed in various ways. Publicity campaigns may be counterproductive in suicide cases (Clarke and Poyner 1994). It is necessary to monitor the media very carefully. To avoid imitative effects after a subway suicide, guidelines are proposed to newspapers (Gershon et al. 2008; Sonnecks et al. 1994).

The emotion induced by a communicational campaign is also important to change passengers' perceptions of risk. Duarte et al. (2014) examined the effect of two different approaches, dramatic vs. humoristic animation-based warnings, for conveying the consequences of non-compliance. The authors showed that a video spot with a dramatic ending improved attention and risk perception, while willingness to comply was higher for the humoristic version as compared to the dramatic version (Table 8). As this study only took place on students, it seems questionable to generalize these results to all subway users.

Table 8 Summary of study that provides evaluation of communicational measures

Reference (authors, date)	Study design and measures	Significant results reported
Video-spot		
Duarte et al. (2014)	*Intervention:* Dramatic finale versus humoristic finale of animation-based warnings to convey the consequences of non-compliance *Study design:* Experimental, comparing questionnaires (attention, understandability, compliance, explicitness, risky behavior, hazard injury, injury likelihood, injury severity, drama, humor, duration), participants randomly assigned to dramatic or humoristic finale *Data:* 60 students (Mage = 22.6): 30 in each group Period: not specified	Attention capture, understandability, explicitness are statistically higher with dramatic finale than with humoristic one. The willingness to comply is higher with the humoristic finale than with the dramatic one.

To prevent a PT²I incident before it occurs, an educational program can be used. Educational campaigns should teach subway users about risky behaviors (Wan et al. 2016), they could teach commuters to leave enough commuting time and stress the hazardous outcomes related to risky riding behaviors, especially those highlighted ones. To prevent suicide, programs may specifically affect suicide rates (Mishara 1999; 2007; Johnston and Waddell 1984). In subway context, educational campaigns were not evaluated in the literature. With regard to the presentation made in the literature, campaign content should be adapted to targeted incidents and behaviours (Mishara 1999; 2007; Johnston and Waddell 1984; Wan et al. 2016)

Staff training measures

In addition to public campaigns and educational programs, specific employee education about risky behaviours and subway suicides may also reduce subway incidents (Guth et al. 2006; Johnston and Waddell 1984). Guidelines to staff and police exist on how to approach a suspect or passenger in the subway in order to avoid incidents (Gaylord and Lester 1994; Gershon et al. 2008). For example, the Mass Transit Railway (MTR) district in China suggested guidelines to prevent suicides (Gaylord and Lester 1994) including : surprise approach, direct approach, indirect approach. The effectiveness of different approaches to transit policing are difficult to assess due to limited available data (Gershon et al. 2008).

3.4.3 Organizational measures

Organizational measures refer to measures that aim to analyse and identify the precursors and risks of accidents. Policies and relations with the media are in this category of measures, as well as procedures to avoid or to manage an accident or risky situation. We found 4 specific measures cited in 11 articles (Table 3 and 9).

Table 9 Summary of the studies that provide evaluation of organizational measures

Reference (authors, date)	Study design and measures	Significant results reported
Presence of surveillance units		

Niederkrotenthaler et al. (2012)	*Location:* Vienna subway *Intervention:* Presence of surveillance unit in the station *Study design:* Quasi-experimental, ecological study, based on data of the type and date of the suicidal incident from subway operator and date on station *Data:* 292 cases (107 attempts and 185 suicides) *Period :* 1979-2009	Positive effect of surveillance unit presence on suicide rate (N= 68 without unit and N=16 surveillance unit present)
Preferential tariff		
Yang and Long Lim (2017)	*Location:* Singapore subways *Intervention:* 10 weeks (September 22 to November 28) of promotional fare period with 3 conditions: -Earlier treatment (ET): exited before 7:45 = full rebate; between 7:45 and 8:00= 50-cent rebate -Later treatment (LT): exited before 8:00 = full rebate; 8:00-8:15 = 50-cent rebate -Control *Study design:* Experimental, Data analysis on 60 weeks' worth of travel records from each subject's travel card, 20 weeks before, 10 weeks during and 30 weeks after *Data*: 348 participants (Control = 119, ET= 120, LT=109) *Period:* 60 weeks	Before promotion only 5-10% of morning trips ended before 8:00, 15% during the promotional period for ET and LT. The post promotion percentages for ET and LT were consistently higher than that of the control group.
Accident causation analysis		
Zhou and Yan (2018)	*Location:* London underground *Intervention:* Rail Accident Investigation Branch (RAIB) and System-Theoretic Accident Modelling and Processes (STAMP) method *Study design:* Quasi-experimental, compared two methods in accident analysis *Data*: One accident of passenger trapped in the door in London underground *Period:* March 2015	RAIB analyses all events and associated details but cannot identify causal link. STAMP analyses relationship between several causal factors.
Zhang et al. (2016)	*Location:* Shanghai subway *Intervention:* Metro Operation Incident Database (MOID) *Study design:* Quasi-experimental, ecological study, Compared three types of incidents: serious accidents, non-serious accidents and near misses, based on data of subway incidents collected in the literature and media *Data*: 249 incidents *Period:* Jan. 2005-May 2013	MOID identified 24 accident precursors in the Shanghai subway

Measures aiming to change passengers' habits (preferential tariff)

Passenger flow and congestion could be managed before the passengers arrive at the platform. Yang and Long Lim (2018) proposed the use of promotional fares in order to change passengers' habits, with the idea of reducing platform congestion, conflicts and thus potential accidents. They tested a promotional fare period in the Singapore subway during 10 weeks. Before the promotion (during 20 weeks), only 5-10% of morning trips ended before 8:00, against 15% for the early treatment (ET) and late treatment (LT) groups during the promotional period. The post promotion (during 30 weeks) percentages for ET and LT were consistently higher than that of the control group (Table 9).

Measures to increase station safety (presence of surveillance units)

Niederkrotenthaler et al. (2012) showed that the presence of surveillance units in Vienna subway stations reduced the number of suicide attempts (Table 9). Station agents maintain order, and passengers engage in less risky behaviours when they are present in the station. They help to discipline passenger behaviour and prevent risky ridings (Wan et al. 2016). Guth et al. (2006) considered that it is necessary to increase surveillance by station staff since increasing the visibility of police is an important component in reducing the overall climate conducive to violent crime (Gershon et al. 2008) and suicides (Mishara 1999). However, the effect of the presence of surveillance units on the number of suicide attempts could be due to others variables (e.g. crowdedness of stations) but a more frequent assessment was not possible due to the lack of data (Niederkrotenthaler et al. 2012).

Measures to adapt the speed limit of trains

Another suggestion to reduce injuries after PT²I incidents without engineering is to change the speed limit of trains entering a station (Mishara 1999, 2007). In 1984, Johnston and Waddell proposed an entrance speed of 10 miles per hour instead of 45 mph after analysis of death and injury patterns in the Toronto subway. Several years after this publication, Guth et al. (2006) also proposed to reduce the speed at which trains enter the station, which could decrease the severity and lethality of injury and allow the driver more time to notice a person on the tracks. However, for authors at 10 miles per hours, it would take a considerable distance to train to stop and the severity of the body still be considerable (Johnston and Waddell 1984). However, reducing speed means reducing the frequency of trains, which affects the available transport supply and increases congestion; this congestion can lead to an increase in the risk of accidents. Although a reduced entry speed in station is necessary, too much speed reduction may not be an appropriate solution to avoid PT²I incidents. Further studies are needed to anticipate the beneficial and negative consequences of a possible reduction in the speed of trains entering a station

Measures using incidents feedback (MOID, STAMP, RAIB)

Zhou and Yan (2018) compared the analysis results of RAIB with that of STAMP of one accident (the passenger trapped in train doors and dragged at station) on the London underground (Table 9). The rail accident investigation branch (RAIB) is a British government agency, created in 2005, that investigates fatal accidents causing death in the UK main line networks, the London underground and other subway systems, and tramways. RAIB investigation aims to increase railway safety by preventing future railway accidents or by mitigating their consequences. STAMP is an accident causation model. It analyses each component and controller of the system according to the safety control structure. With the result of RAIB investigations and STAMP analysis of the same incident, the authors concluded that the analysis and the explanations are more objective with RAIB investigation. RAIB investigations help to identify the events that have led to an accident, but do not identify the relationship between these events and the cause(s) of the accidents. This RAIB investigation could be used as an information source. STAMP analyses the relationship between various causal factors and causes. It provides the examine the entire sociotechnical system design to identify the weaknesses in the existing safety control structure (Leveson 2011a). STAMP provides a more comprehensive perspective than RAIB investigation to ensure the safety of a system.

With the same objective of improving safety by using feedback, Zhang et al. (2016) created a database called: Metro Operation Incident Database (MOID). It brings together three types of incidents in the Shanghai subway: serious accidents, non-serious accidents and near misses (Table 9). With MOID in the Shanghai subway, 24 accident precursors were identified. The authors concluded that MOID analysis could help the subway company and the government to manage and improve operation safety.

4 Conclusion and perspectives

The subway is a risky environment, especially at the interface between the platform, train and tracks (PT²I). Some results emerge from the literature. Accidents occur more during rush hour or very off-peak hours, such as at night. In other words, accidents occur when the metro network is overcrowded or almost deserted. Moreover, accidents seem to occur more during the boarding and alighting of passengers. The people involved in accidents are predominantly middle-aged men, in an altered state of consciousness (alcohol and drugs detected). In the majority of cases, accidents are considered to be directly related to user risk-taking behavior, whether due to a lack of knowledge or deliberate flouting of the regulations, either to maximize personal comfort or out of a desire to transgress.

Our review has shown that this subject has been insufficiently studied and that existing studies do not allow us to conclude on the factors involved in the occurrence of accidents and the efficient associated preventive measures. Various phenomena make it difficult to cross-reference the existing literature on the subject. First, there is no international consensus: the categories of incidents and their definitions vary from one country to another. Second, most existing studies consider both accidental events and suicides. Third, studies focusing on user behaviour and risk perception are very sparse; by the way, they are mostly located in Asia. Fourth, each network studied has its own characteristics, both physical and in terms of passenger flows, which makes it difficult to make reliable comparisons. Finally, too few studies validate the effectiveness of preventive measures, which are most often only mentioned in passing. In addition, some of these evaluations or propositions are dated, changes have occurred in the subway environment that have rendered certain measures obsolete (e.g. speed limit, airbag on train, etc.). The majority of studies do not mention the potential impact of the proposed or evaluated measures on the subway operation (e.g. frequency reduction, structural adaptations, etc.).

To address these weaknesses, we argue that more research is needed and that it is necessary to draw on what is proposed in systemic approaches, i.e. to look at the problem as a result of the interaction of all the system's components, considering the whole as the unit of analysis, not just individual's behaviour. Indeed, several levels of explanatory factors could be involved in incident and accident development from a system-oriented approach (Hollnagel 2016; Leveson 2011b; Read et al. 2012; Stefanova et al. 2015 ; Wilson 2014). For example, Stefanova et al. (2015) analysed in particular the following levels: individual, socio-cultural environment, the equipment and surroundings, and lastly the organisational level. The organisational level includes all the factors related to the management of the systems (e.g. urban planning, station design, procedures and policy, human resources, collaboration between organisations, public safety awareness campaigns, etc.). The equipment and surroundings level encompasses contributing factors related to the characteristics of the environment (e.g. type of tracks, presence of controls, etc.), the size of the urban area, the temporal characteristics of the moment (e.g. time of day, weather). The social environment refers to the visible presence of other actors (including both other passengers - our case -, staff, police patrols, etc.) in the immediate context and the way they behave. Finally, the individual level includes various dimensions strictly related to the characteristics of the persons. While the few existing research explores almost exclusively the later level, very few theoretical considerations have been adduced to explain behaviours (only the attitudes are considered). Furthermore, the prevention of unsafe passenger behaviour and the apprehension of associated risk factors require taking intentionality into account, i.e. distinguishing between errors and violations (Stefanova et al. 2015; Reason et al. 1990). While errors result from failures on different levels of information processing (skill, rules, knowledge-based levels of performance) and are thus associated with cognitive precursors, violations highlight the role of social context in decision-making (e.g. social norms, rules, operating procedures) and are therefore associated with motivational factors which lead the person to intentionally deviate from the prescribed rules (Reason et al. 1990). This distinction will inevitably have an impact on the modes of prevention to be considered. Errors are more likely to be minimised through "retraining, redesign of the human-machine interface, memory aids, and better information", whereas violations are more likely to be reduced by the modification of attitudes, norms, beliefs or the overall safety culture (Parker et al. 1995, p.1036).

Existing technological, physical, educational and organisational preventive measures act at different levels of prevention (primary, secondary or tertiary). Concerning technological measures, PSD, suicide pits, CCTV, detection with infrared beams and the appropriate (re)design of the front train material are solutions that were identified long ago. Sliding steps, alarms, lighting, and barriers associated with a good ticketing system appeared more recently. Educational and communicational measures include educational and communication campaigns, media guidelines to avoid copycat behaviour, and staff training. A wide range of organisational measures have been identified: trying to change passengers' habits by using ticketing policies or by the presence of surveillance units, adapting the train speed to facilitate the mitigation of critical situations, and fostering organisational learning by using incidents feedback. Most of the identified measures have not yet been evaluated however. In fact, the available evidence is meagre, and concerns a very small set of measures such as Platform Screen Doors, or Suicide pits. Other preventive measures used in the railway context could be relevant for subway networks. In their review, Havârneanu et al. (2015) showed the effectiveness of communication and educational programs, and reinforcement to avoid trespassing. PSDs are sufficiently well documented to stand out as the most effective measure in terms of accident prevention and mitigation of feelings of insecurity. Unfortunately, this installation is very expensive, especially for already built subways (Law and Yip 2011). We found in our literature review other, less costly preventive measures such as reducing the speed limit. One opportunity to decrease the accident rate is to change users' behaviour using implicit techniques (station design, promotional tariffs) or targeted communication programs.

Subsequently, suggestions for future research and for public authorities include the study of the actual behaviour of subway users through systematic observations taking into account its various determinants within a system-oriented framework. At the moment, we have too little information on the characteristics of a situation that may lead users to adopt or not certain behaviours. This information would make it possible to propose preventive measures acting on the precursors of behaviours. Research should also screen the effectiveness of different preventive methods depending on where they are implemented and the specificities of the place. The physical and socio-economic environment of the station must be taken into account. Some measures can only be effective in specific contexts and cannot be extended to all stations. The evaluation of preventive measures requires more information about passengers' habits and perceptions. Preventive measures do not have the same effect depending on the habits and experience of users and this must be measured and this consideration of passengers' perceptions would improve the acceptability of certain measures and improve their effectiveness.This information could make it possible to propose new, cheaper interventions to reduce risky behaviours or to increase passengers' knowledge. Finally, international standards in the definition of accidents and their categorisation would significantly improve future research, together with the development of databases for systematically recording detailed information about the conditions of the accident and the characteristics of the victim. Indeed this would provide a strong support for the comparisons and monitoring of accidents at both national and international levels, as well as a useful framework for the development of research on precursors and prevention of individual accidents in subway systems.

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