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New Signage System For Improving Pedestrian Flow On Single-Exit Metro Stations:Focus On Paris Metro Line 4 Historical Stations

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ABSTRACT; For a number of years now, the use of the Metro is steadily augmenting, making it more and more difficult to ensure traffic regularity (due to a variety of technical problems, increases in exiting/boarding time and passenger accidents), which determines a loss in the system's energy efficiency and the increase of traction current expenses.
In disadvantageous conditions, such as those found in historical stations having only one access to each platform (present notably along the north-south line 4, opened roughly a century ago) and where the movements of passengers can be disorderly, it seems possible to ameliorate the quality of spaces and the overall service through well-focused low-impact improvements.
In this paper, a new signage system with a view to improving flow management and providing better information to passengers is proposed. We focus on a particular moment of the voyage, namely the platform-train exchange, in the case of stations with one single exit that have, still today, a *cul-de-sac* at one end. Without neglecting the architectural aspects and comfort of the passengers, the objective of the proposal is controlling the regularity of traffic and optimising the resulting electricity consumption.
The effectiveness of the signage system is validated via an in-house developed numerical tool allowing to explore the impact of the signage system on the modalities and times of the train-platform exchange.
The analysis and comparison of several variations have upheld the validity of the improvements hypothesis in its entirety.
KEYWORDS: Crowd movement, Design aids, Mathematical modelling, Rail stations, Railway systems, Rehabilitation & renovation

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I. INTRODUCTION

The station is the first architectural spacetravellerssee on entering the metro. When the system was created most stationshad only the one access from the streets above intothe ticket hall area, from where two passages led to a stairway down to the platforms. There was therefore only one means of access to or from either platform.

Metropolitan stations were ofa relatively simple standard designat the time, built to be cost-effective andto comply with basicstandards of safety and comfort.

The first section of metro Line 2 was inaugurated in December 1900.Shortly after the completion of the Line in April 1903 (Porte Dauphine – Nation, like today), a firebroke out in the Couronnes station on 10th August resulting in more than eighty deaths.

The disaster, following a series ofrolling stock breakdowns and minor incidents, has remained the network's worst-ever disaster. It sparked a debate about the safetyof the underground and, indirectly,the design of underground stations.

A municipal enquiry swiftly concluded that the fire had been triggered by a short circuit in the locomotive. The coach was made almost entirely of wood and was poorly insulated. The disaster was made worse by the fact that many passengers refused to evacuate and that the lights went out(Tricoire 1997). The Commission also pointed out thatthe limited number andlocation of the exits further aggravated the situation.

Several measures were adopted to reduce the risk of such an event occurring again. The Chief of Police gave the metro operator, CMP (*Compagnie du chemin de fer métropolitain de Paris*) a 3 phase list of injunctions – some to be carried out urgently, some allowing the company 15 days to submit a report, and some which did not need to come into force until November 1903.

It should be remembered that the metro infrastructures had been provided by the City and that the additional structures, access points, rolling stock and operating regulationshad been checked and approved by the relevant Authorities.

Two injunctions in the list ofissued by the Chief of Policeare of particular interest as they relate to the number of exits and exit signs. The third, for immediate enforcement, required the company to install more (and notably lighted) exit signs. The fifth injunction, with a longer deadline,pushed for the creation of more (and more spacious)exit areas.

The Commission considered that the single access to the Couronnes station was an aggravating factor and partly responsible for the high death toll.The firemen who wereinterviewed called for two separate access points on every platform and for a 60 cm wide passageway per100 exitingpassengers (i.e. a minimum of 3m per 500 passengers), and insisted that under no circumstances should any passageway (e.g. corridor) be less than 1.25 m wide.

Only the last two measures were actually imposed on the Company which conducted a comprehensive study of Lines 1 and2 (already in operation) andLine3 (underconstruction),but their conclusions did not go as far as those of the Commission's enquiry.

The first section of Line 3, running from Villiers toPère-Lachaise,was inaugurated in October 1904, the first to open to the public in the wake of the Couronnes station accident. Apart from steps taken to protect the lighting circuit, its configuration was little different from that of existing Lines. Only the six main stations had openings at both ends of the platforms to facilitate pedestrianflow but it was a long time before this became systematic.

Such minimalist solutions were also used on subsequent metro Lines and onLines A, B and C (opened in 1910 and 1911 and corresponding to today's Lines 12 & 13) which were constructed and operated by*Société du chemin de fer électrique souterrain Nord-Sud de Paris*(the second operator until 1930), resulting in a considerable number of stations where(even today) one end of the platform terminates in a cul-de-sac.

II. PEDESTRIAN FLOW MANAGEMENT, STATION SAFETY & DESIGN

The number, location and width of passages and exits are key safety issues when organising any public space, and are crucial in the particularly complex event of evacuating a metro station and equally important when it comes to directing passenger flows to and from platforms under normal operating conditions(Fig. 1).

The passageways in the (mainly subterranean) Paris metro have been empirically designed to optimise traveller transit. Routes are as direct as possible to prevent congestion and limit panic behaviour. However, expansion of the network has not alwaysmeant the best station location orlayout, with the result that today many stations still only have one exit per platform, the other end of the platform terminating in a cul-de-sac andin some cases very long passage-waysrunning from the platform to the ticket hall.

It should be noted that only a small number of those stations have since seen the addition of additional exits.

Stations featuring a single exit on one or both platforms have cul-de-sacs stretching at least 45m. Stations with two adjacentexitsat one end of the platform orstations on a bend with hard-to-spotexits pose similar problems and may be put in the same category (Fig. 2).

Note that in the case of centrally positionedsingle exits, although the cul-de-sacs are shorter, they are still over 30m long.

The fore-mentionedcases in factbreach fire safety regulations but this is addressed by the adoption ofcompensatory features (e.g. early detection, speedier smoke extraction, improved structural resistance to fire, etc.) designed to comply with safety objectives.

For several years now passengertraffic on the Paris metro and the RER (rapid regional transit system) has been rising, making it harder to ensure a regular service (more frequent technical incidents, longer stops, increased energy consumption, morepassenger casualties, etc.).

To provide an idea of passenger trends, the table 1 below shows the overall annual traffic on the metro over the last 5 years, in million passenger journeys (source:STIF Report 2009/2011).

	2008	2009	2010	2011	2012
Passenger traffic	1 472,5	1 479	1 506	(1 533[1])	(1 555[1])
% change	+ 6,1 %	+ 0,5 %	+ 1,8 %	(+ 1,9)	(+ 1,9)

Table 1.Passenger annual traffic ([1] estimated values).

We feel it is possible to go some way to addressing the shortcomings of the older stations which have one access to platforms(i.e. erratic pedestrian flow) – platform/station areas can be improved and the service can be made more regular via minor changes to the premises or trains (new signage).

III. CASE STUDY – STATIONS ON LINE 4

Paris metro Line 4 started operating in 1908 and was the first to link the left and right banks under the Seine. It runs north-south, between Porte de Clignancourt in the north and Mairie de Montrouge in the south(this extensionwas opened in March 2013).

The Lineruns through the centre of Paris andconnects with all the other metro Lines (except minor Lines 3bis & 7bis) as well as the RER Lines. It has two features of note:

Although Line 4 is the second busiestLine in the network after Line 1, carrying171 million passengers in 2010(there were 135.7 in 1999, 137.9 in 2001and 154.1 in 2004, source:STIF & RATP),it is the oldest Linewith none of its stations overhauled (since 2005 no data has emerged aboutLine traffic or usage as the*Syndicat des transports d'Ile-de-France*and network operators consider such information a trade secret).

Thus, out of a total of 27 stations on this very busy Line, 14 of them have only one exit on at least one platform (including 5in both directions).

If one looks at the annual number of*travellers entering the network* perstation (seehttp://data.ratp.fr/for the latest 2011 data), it emerges that 7 of the 14 stations on Line 4which have at least one single-exit platform are also amongst the hundred busiest metro stations in the system (outof a total of 303).

Travellers entering the network mean people entering from the street or railway network, and joining the RATP transport system through the ticket barrier. This excludes passengers switching metro or RER Lines within the RATP system.

Ranked according to level of usage, these stations are:

PORTE DE CLIGNANCOURT, single exit on platform to P^{te} d'Orléans, Ranked 24(9.000.298)

STRASBOURG-SAINT-DENIS, single exit on both platforms (connections forLines 8 & 9),Ranked 36(7.346.063)

CHATEAU ROUGE, single exit on platform toP^{te} d'Orléans, Ranked 45(6.798.017)

MARCADET-POISSONNIERS, single exit on platform to P^{te} d'Orléans, Ranked 58(6.064.992)

ALESIA, single exit on platform to P^{te} de Clignancourt, Ranked 76(5.317.934)

CHATEAU D'EAU, single exit on both platforms, Ranked 89(4.842.822)

SAINT-GERMAIN DES PRES, single exit on both platforms, Ranked 98(4.548.167)

It should be noted that Paris underground stations are usually vaulted and feature two platforms bordering a doubleline of tracks.

Most platforms are 75mlong but there are exceptions - the stations on Line 4 vary from 90 m to 115 m. They are 4 m wide and tilt slightly towards the tracks. Yellow or grey tactile warning strips run along the platformapprox. 30 cm from the edge for the visually impaired.

The last of theMP 59 rolling stock dating back to the 60's has been taken off Line 4, and since January 2013 only MP 89 CC type state-of-the-art rolling stock is in operation.

IV. OBSERVATIONS, MODELLING &SIMULATION

Given the feedback about passenger movements in the stations onLine 4, we focused on one aspect of thejourney, namely the on/off passenger changeover in the specific cases of single exit stations and platforms with cul-de-sacs, with a view to improving pedestrianflowand providing more information to passengers.

The natural reflex of travellers when alighting from a train is to look left and right in search of the exit- in this instance at only one end of the platform, the distancedepending on the position of the carriage(Fig. 3).

In fact,exit signs are displayed perpendicular to the track / platform (i.e. suspended from the arched ceiling to face passengers as they walk along the platform). They can only be seen once the passengers have stepped out of the train and turned their heads, they cannot be seen as the train enters the station, slows down and comes to a standstill.

Alighting passengers check wherethe exit is, in our case at only one end of the platform,and hesitate briefly before moving away, thus hampering the passage of those wishing to get on. It should be noted that passengers waiting to board gather round the doors in a semi circle (or rather in trapeze formation) to leave room for those getting off.

Passengers leaving the train tend to move rather chaotically, abruptly changing direction, turning back or retracing their steps. Thisdisrupts the on/off passenger dynamics during the short time the train is stopped at the station (approx. 25 secs).

During busy/peak periods, such behaviour increases platform congestion, but it is also an issue when the platform is less crowded or if fewer people leave the train. The mere fact that passengers do not know where the exitis as they step off the train and have to look both ways to check before setting off wastes time, involves retracing theirsteps and causes frustration, even more so if they are in a hurry.

On the basis of this insight we investigated the possibility of introducing signs, which would inform passengers of the exact location of the exits shortly before they leave the train, to determine behaviour changes and any resulting benefits.

There is little doubt that if passengers know where to head for the exit as their train enters the station they will move in a more direct and orderly manner, with less hesitation and less cause to retrace their steps. Their movements will have a knock-on effect on the passengers waiting on the platform, as theyautomatically step aside to let them head towards the exit before boarding.

The sign may simply be anilluminated white (LED) arrow against a blue background (in line with the Operator's colour codes, namely blue-on-white foronward journeys /connections and white-on-blue for end of journey/exits). The sign could be displayed inside the carriage at the side or along the top of the doors, or on the platforms, alongside the sign indicating the name of the station(Fig. 4).

This latter solution is relatively simple to deploy, and seems the moreappropriate and effective.

The sign indicating the direction of a single exit would be automatically activated by a zone entry detector (and remain off the rest of the time). The arrow would light up as the train enters the station and flash for 15 secondsas itmoves down the platform (approx. 75m), slows down and comes to a standstill.

Subsequently, the sign will remaincontinuously lit for 3 seconds, fade for 2 seconds then go off. During this time the carriage doors open and alighting passengers (most now aware of the way to the exit) start to get off the train.

Passengers may see the flashing sign through the windows as the train enters the station, so they know which way the exit is and can set off without more ado.

The train stops for about 25 seconds, then, barring incidents like interference with the closure of the doors or an unscheduled delay, the doors close and the train leaves the station.

Three to seven minutes later, with the arrival of the next train, a new cycle starts up (lasting approximately 20-25 secs).

During peak times the Lines operate at 100% capacity, soa 10 second delay (which is usually not recuperated) is enough to create a considerable increase in the number of passengerswaiting at the next station. The challenge is not tolose time during the stop at the station and to stick stringently to the timetable throughout the journey.

Passengers behave differently if they know where the exit is before leaving the train, and this in turnchanges the crowd formation on the platform, makes for smootheron/off passenger flow and far fewer delays or incidents preventing a promptdeparture.

Apart from the traffic control advantages of this solution, the additional information provided by these new signsincreases passenger comfort.

On-site findings and observations (photos, video recordings & timekeeping) led to lengthy research into train/platform passenger dynamics with the help of a modelling tool simulating pedestrian behaviour in architectural spaces.

A mathematical model reproducing the movements of a group of active particles helped recreate our specific conditions, to compare and qualitatively predict the type and duration of passenger movements between platform and train,with the aid of the new signage and under different circumstances.

The model was originally designed for the study of granular materials, based on a discrete non-smooth approach (Frémond 1995, 2001, Dimnet 2002). The approach was then enhanced to represent pedestrians with a will to movein an evolution space ('active' circular particles) towards a specific destination (exit or place inside a carriage) (Pécol 2010).

The model deployed,shortly presented hereafter, can simulate crowd dynamics or pedestrian flows under different conditions like counter-flow, unhinderedflow or emergency evacuation. It can, notably,depict interaction between pedestrians and their environment, and also determine or check local interactions (inter-pedestrian or pedestrian vs. obstacles),shedding light on global pedestrian dynamics in specific situations.

V. A PARTICLE COLLISION MODEL

Over the last decades, many studies have been developed to describe the behaviour of walking pedestrians and crowd movements (Hankin 1958, Helbing 2002). A first classification of these approaches is suggested by the mode of representation of the crowd: (a) macroscopic models, where the crowd is represented as a continuum, e.g. (Hoogendoor 2001, Hughes 2002), or (b) microscopic models, e.g. (Reynolds 1987, Moreau 1994, Helbing1995) where the behaviour and decisions of each crowd component are treated individually.

In this paper, the latter approach is retained, i.e. a microscopic model is used. In this class, perfectly rigid particles (Discrete Elements) are usually retained for describing the evolution of the whole granular system as well as the multiple simultaneous collisions. The discrete model is then extended and adapted for describing the movements of the subway passengers. To be considered as a pedestrian, each particle must have a "willingness" to move toward a given target, which might be time varying.

Within the DE class, the instant of the collision is crucial. In the literature, two approaches are usually developed to take into account the contact: the "smooth" approaches, e.g. (Cundall1971), and the "non-smooth" approaches, e.g.(Moreau 1994, Frémond1995, 2002, Jean 1999).

Regular approaches were first introduced by (Cundall 1971). Contacts are handled by means of a repulsion force and the contact forces are determined by an explicit calculation as the forces' amplitude depends on the distance between particles. A "slight" interpenetration between particles is allowed to compute the repulsion force and small time steps are required to ensure the time integration scheme stability. The Distinct Element Method (DEM) (Cundall 1971) has been later extended to the case of a human crowd (Helbing 2002).

In non-smooth approaches, contact forces are determined from the solution of local nonlinear equations. The non-regularity is retrieved in three nonlinear aspects: (1) spatial non-linearity, due to the geometric condition of non-interpenetration (use of inequalities instead of equalities); (2) time non-linearity, due to shocks between particles (velocity discontinuities); and (3) the (eventually) non-linear contact law. Non-regular laws are used to link forces and describe the unilateral contact. The most known non-smooth approach in granular media simulations is the Non-Smooth Contact Dynamics approach, proposed by Moreau and co-workers, e.g. (Moreau 1994, Saussine 2006). It is based on the use of the "coefficient of restitution" representing the changes in the relative velocity of a rigid particle before and after collision. Frémond and co-workers, e.g. (Frémond 1995, Dimnet 2002, Dal Pont 2006),developed a similar approach. In this work, the contact force between two colliding particles is determined with a constraint on the relative deformation velocity between particles, as in Moreau's approach. The particles' system is considered deformable, and the motion equations result from the virtual work principle, while constitutive laws are given by a pseudo-potential of dissipation. In Frémond's approach, the rebound is characterized through a "coefficient of dissipation": (Frémond 2007) showed that the use of a restitution coefficient may be inconsistent in describing the collision of more than two particles. This latter approach, fully detailed in (Frémond 1995) and developed in a rigorous thermodynamic frame, has been retained in what follows. The numerical aspects were later developed by (Dal Pont 2006).

5.1. Theoretical aspects

It is assumed that the system is subjected to two actions – forces and percussions. Forces are smooth quantities and a function of time, whereas percussions are concentrated into a (Dirac) instant and are therefore non-smooth quantities. Internal forces (forces & percussions) are defined on the basis of their work. Let us consider the set of *N* particles as a deformable system composed of *N* rigid solids. Collisions among particles can be inelastic or elastic. The relative deformation velocity between the $i^{th}$and j^{th}particles of velocity u is introduced: $\underline{\Delta}_{ij}\left(u(t)\right) = \underline{u}_i - \underline{u}_j$. The equation of motion of the system can be writtenas:

$$\underline{\underline{M}}\dot{\underline{u}}(t) = -\underline{f}_{int} + \underline{f}_{ext}\, Almosteverywhere \quad (1)$$

$$\underline{\underline{M}}(\underline{u}^{+}(t) - \underline{u}^{-}(t)) = -\underline{p}_{int} + \underline{p}_{ext}\, everywhere \quad (2)$$

where $f^{\ ext}$ and $f^{\ int}$ is the exterior and interior forces vector of dimension *2N* applied to the deformable system,$\underline{\underline{M}}$ is the mass matrix and the exponents + and –indicate the quantity after and before the collision. The existence of a solution of the system given by Eqs. (1) and (2) is proven, e.g. in (Cholet 1999).

Equation (1) (which uses a Lebesgue measure) describes the smooth evolution of the multi- particle system, whereas (2) (which uses a Dirac measure) describes its non-smooth evolution during a collision. Consequently, Eq. (1) applies almost everywhere, except at the instant of the collision, where it is replaced by Eq. (2). When a contact is detected, velocities of colliding particles are discontinuous, and so in Eq. (2), the percussions p^{int} and p^{ext}(interior and exterior to the system respectively) are introduced. By definition, percussions have the dimension of a force multiplied by a time. The p^{int} percussions are unknown; they take into account the dissipative interactions between the colliding particles (dissipative percussions) and the reaction forces that permit the avoidance of overlapping among particles (reactive percussions).

(Frémond 1995) defined the velocity of deformation at the moment of the impact $\frac{\underline{\Delta}(\underline{u}^{+})+\underline{\Delta}(\underline{u}^{-})}{2}$ and showed that $p^{int}$is defined in duality with $\frac{\underline{\Delta}(\underline{u}^{+})+\underline{\Delta}(\underline{u}^{-})}{2}$according to the work of internal forces. As in classical mechanics, a pseudopotential of dissipation Φ is then introduced, allowing to definep^{int}as:

$$\underline{p}^{int} \in \partial\Phi\left(\frac{\underline{\Delta}(\underline{u}^{+})+\underline{\Delta}(\underline{u}^{-})}{2}\right) \quad (3)$$

where the operator ∂ is the subdifferential that generalizes the derivative for convex functions (Frémond 2007). The convex function Φ (Moreau 1970) is defined as the sum of two pseudopotentials: $\Phi = \Phi^{d} + \Phi^{r}$; where Φ^{d} and Φ^{r} characterize the dissipative and the reactive interior percussions. For the sake of simplicity, the pseudopotential Φ^{d} is chosen to be quadratic: this choice allows one to find the classical results when the coefficient of restitution is used. Reactive percussion p_{reac} is the reaction assuring the non-interpenetration of particles.Non-interpenetration occurs if the normal velocity after collision is directed outward and is expressed as$u_{N}^{-} \geq 0$ (with $u_{N}^{-} = u_{N}^{+}N$). Such percussion is equal to 0 if $\mathrm{u}_{\mathrm{N}}^{-} \geq 0$, is not null if $\mathrm{u}_{\mathrm{N}}^{-} = 0$ and ensures that the condition $\mathrm{u}_{\mathrm{N}}^{-} < 0$(i.e. the interpenetration) does not hold. Such properties may be described using an indicator function. The indicator function is also a pseudo-potential of dissipation (Frémond 1995, Pfeiffer 2001). Therefore, the whole interior percussion may be expressed as a function of a single pseudo-potential as previously stated.

In Eq. (2), the problem is to find the velocity $\underline{u}^{+}$ after particles' collision. After some manipulations, it can be proven that the solution of the whole system is given by the following constrained minimization problem:

$$\underline{X} = \underset{\underline{Y} \in \boldsymbol{R}^{2N}}{\arg min}\left[\ {}^{t}\underline{Y}\underline{\underline{M}}\underline{Y} + \Phi\left(\underline{\Delta}(\underline{Y})\right) - {}^{t}\left(2\underline{u}^{-} + \underline{\underline{M}}^{-1}\underline{p}^{ext}\right)\underline{\underline{M}}\underline{Y}\right] \quad (4)$$

where the solution $X = \frac{\underline{u}^{+}+\underline{u}^{-}}{2}$.

In this approach, the velocity of a particle after a contact ($\underline{u}^{+}$) has a clear physical meaning. Proof of the existence and uniqueness of this velocity after the simultaneous collisions of several rigid solids, as well as the dissipativity of the collisions, is presented in (Dal Pont 2006).

5.2. Numerical method

The numerical solution of such a differential problem requires a time discretization. J.J. Moreau and M. Jean proposed the so-called time-stepping method (Moreau 1994, Jean 1995), where the time step is not event-driven and the contact forces in the system are iteratively determined.
This approach is retained and the *A-CD²* method (Atomized Contact Dynamics respecting Clausius-Duhem inequality) is used (Dal Pont 2006). All smooth forces are treated as a succession of percussions in order to define the work within the system as percussions. The consequence of atomizing forces is that system changes are shown as a succession of discontinuous velocities. The simulation time *[0, T]* is split into *n* intervals $[t_n, t_{n+1}]$. In each interval, the smooth forces (forces & moments) are atomized, i.e. replaced by percussions applied at instant $\vartheta_n = t_n + \frac{1}{2}t_{n+1}$.
These aspects are highlighted in Fig. 5. More details are given in (Dal Pont 2006).

5.3. Resolution algorithm

Initial positions $q^0=q(0)$ and velocities $u^0=u(0)$ are given as well as q^n and u^n (i.e. $\underline{u}^{-}$) at time t^n at each step *n*. A resolution algorithm is required to determine q^{n+1} and u^{n+1} (i.e. $\underline{u}^{+}$ at time t^{n+1}).

The discrete equation governing discontinuity becomes, for $[t^n, t^{n+1}]$:

$$\underline{u}^{n+1}(\vartheta_n) - \underline{u}^{n}(\vartheta_n) = \underline{\underline{M}}^{-1}\left[-\underline{p}^{int}\left(\frac{\underline{\Delta}\left(\underline{u}^{n+1}(\vartheta_n)\right)+\underline{\Delta}\left(\underline{u}^{n}(\vartheta_n)\right)}{2}\right) + p^{ext}(\vartheta_n)\right] \quad (5)$$

As $X_{n+1} = \frac{u^{n+1}(\vartheta_n)+u^{n}(\vartheta_n)}{2}$, the equation to be solved becomes equivalent to the constrained minimisation stated below. More details are given in (Dal Pont 2006):

$$\underline{X}^{n+1} = \underset{\underline{Y}^{n+1} \in \boldsymbol{R}^{2N}}{\arg min}\left[\underline{{}^{t}Y^{n+1}}\underline{\underline{M}}\underline{Y}^{n+1} + \Phi\left(\underline{\Delta}\left(\underline{Y}^{n+1}\right)\right) - {}^{t}\left(2\underline{u}^{n}(\vartheta_n) + \underline{\underline{M}}^{-1}\underline{p}^{ext}(\vartheta_n)\right)\underline{\underline{M}}\underline{Y}^{n+1}\right]$$

(6)

with$\underline{Y}^{n+1} = \frac{\underline{u}^{n+1}(\vartheta_n)+\underline{u}^{n}(\vartheta_n)}{2}$
As previously stated, for the sake of simplicity, a linear constitutive law is used, i.e. a quadratic pseudopotential Φ^d is retained. Concerning the non-interpenetration condition, the following inequality has to be verified when a contact between two (circular) particles *i* and *j* is detected:

$$ {}^t\underline{\Delta}_{ij}\left(\underline{Y}^{n+1}\right)\underline{e}_{ji} + {}^t\underline{\Delta}_{ij}\left(\frac{\underline{u}^{n}(\vartheta_n)}{2}\right)\underline{e}_{ji} \leq 0 \qquad (7)$$

where $\underline{e}_{ji}$ corresponds to the normal at the contact point. Eq. 7 gives a pseudo-potential of reaction that reads:

$$\Phi^r = \sum_{1\leq i<j\leq N} \mu_{ij}^{n+1}\left({}^t\underline{\Delta}_{ij}\left(\underline{Y}^{n+1}\right)\underline{e}_{ji} + {}^t\underline{\Delta}_{ij}\left(\frac{\underline{u}^{n}(\vartheta_n)}{2}\right)\underline{e}_{ji}\right) \leq 0 \qquad (8)$$

where μ_{ij}^{n+1} corresponds to the Lagrange multiplier, i.e. a percussion that develops in the instant of the contact. In can be proved that the classical Kuhn-Tucker conditions are respected (Dal Pont 2006).

The constrained minimisation problem (6) can be resolved with the help of Uzawa's algorithm (Ciarlet 1989).

VI. APPLICATION TO PEDESTRIAN DYNAMICS

The*A-CD*^{2}model can easily be adapted to describe the behaviour of pedestrians as they walk through a structureor interact with others. The approach has been used to describe the specific moment when passengers board and alight at single exit stations with cul-de-sac platforms.
Pedestrians may be treated as circular particles with a 'will' (i.e. wishing to walk in a certain direction, towards aplatform exit or empty seat in a carriage) at speeds which may vary with time and space.
Below we shall ignore the rotational velocity component and focus on circular particles.

To address the moment passengers alight and board once the carriage doorsare open, a shortest path strategy is adopted, allowing us to use the so-called *Fast Marching* method (Kimmel1996). The direction $e_{d,j}$ will thus depend on the pedestrian's environment (i.e. the presence of obstacles, other travellers, the location of exits, etc.), the interval considered and pedestrian profile (age, gender,attitude/intention, etc.).
The direction becomes$e_{d,i}(t) = \frac{u_{d,i}(t)}{|u_{d,i}|}$,where$u_{d,i}$ is the desired speed of the *[ith]*passenger. The amplitude $|u_{d,i}|$ represents the speed with which the pedestrianwishes to move through the area (without taking into account other pedestrians),and it is integrated as a random parameter with normal distribution (average*1.34* ms^{-1}, standard deviation*0.26* ms^{-1} (Henderson 1971)).

The desired walking speed derived from the*Fast Marching* method is then introduced into the *A-CD*^{2} Model as an external accelerating force defined as$f^{ext}(t) = f_a^{ext}(t)$, theforce$f_a^{ext}(t)$allowing individual pedestrians to achieve the direction and speed they desire(Helbing 1995).

Each component$f_{a,i}^{ext}(t)$ of the force vector of size*2N* is linked to each*i* pedestrian (i.e. pedestrians with individual strategies), which may be expressed as follows:

$$f_{a,i}^{ext} = m_i \frac{\|u_{d,i}\| e_{d,i}(t) - u_i(t)}{\tau_i} \qquad (9)$$

where u_i is the actual speed andτ_i is the reactivity time (giving pedestrians time to regain their desired speed in the wake of contact). The lower the value of$\tau_i$is, the quicker is the response rate (changes in direction), the typical value being τ=0.5 s (Pécol 2010). This value may be statistically distributed but the mean will be lower if, for example, the pedestrian knows in advance which direction to take.
A pedestrian's behaviour, driven by his individualstrategy, canbe made to reflect the effect of other forcesas applied to particles. These are called 'social' forces (Helbing 1995) because they affect a person's attitude to other people, and make the behaviour of the particles more like that of real pedestrians.Examples are the repulsive forcecausing a slight deviation in the paths of two pedestrians walking towards each other (a socio-psychological parameter), or the force which keeps pedestrians at a certain distance from each other (a cultural parameter).

The mathematical model presented here has been validated on emergency evacuations situations and crowd flow management (Pécol 2010, 2012). The scope of the numerical simulations is then to compare the effectiveness of the signage and compare the situations with and without the signage. For the sake of simplicity, some specific assumptions have been made, i.e. counterflows effects as well as the shear force exerted between the pedestrian and the ground are not considered. These two phenomena are critical in some situations (Schadschneider 2010, Pécol 2010) but in our case of Paris metro, pedestrians evolution is limited within a range of a few meters, crushing/slippery accidentsare very rare (i.e. these accidents are out-of-the-scope of this paper) and boarding takes place only after passengers complete alighting. Moreover, due to the lack of experimental data, the role of the numerical tool is to qualitative evaluate the effectiveness of the signage.

VII.NUMERICAL RESULTS AND DISCUSSION

The average number of passengers on Line 4 on a working day is 458148; 374 501 on Saturdays and 241 681 on Sundays. On weekdays an average station has two busy times - between 8 and 9 a.m. (peaking after 8.30)and then between 5 and 6.30 p.m.

The on/off passenger changeover between the opening and closing of the train doors was timed at the Strasbourg-Saint-Denis station on Line 4(which has single exit platforms on both sides) between 8.10 and 9.10 a.m. and between 5.30 and 6.30 p.m. (Line 4's busiest times). Data was collected Monday through Friday on the 3rd week of June 2012, the 3rd week in September 2012 and the third week in December 2012, i.e. 150 times per week, making a total of 450 (approx. 15 measures taken per hour, twice a day). This number of measurements allows to obtain at least a qualitative overview of the passengers' flow in the current station configuration and permits a first feeding of the numerical model.

As the probability density of the times measured follows a low-dispersion normal law, probability is high ifthe actual waiting time is close to the average time (i.e. 16-17 secs).As for the geometric aspects of the model, particle interactionsimulated passenger/passenger and passenger/environment dynamics, on a plane comprising the inside of the carriage (MP 59 type, Fig. 6) and the adjacent platform edge.A response time, i.e. the time required for a passenger to start moving after the doors opening is also used.

Thecollected data was used to calibrate the model selected for train/platform passenger changeovers(Fig. 7), thus providing satisfactory results in terms of the numerical simulations. The main parameters used in the analysis are given in table 2 (without signage). This set of parameters allowed to obtain an average evacuation time consistent with the in-situ observations. As explained in what follows, a probabilistic approach is required.

	withoutsignage	withsignage
Velocity [ms^{-1}]	[1.2-1.5]	[1.2-1.5]
Response time[s]	[0.3-0.5]	[0.1-0.5]
Reactivity time[s]	[0.4-0.5]	[0.1-0.5]

Table 2.Pedestrians' parameters range for the illustrated simulation.

The presence of the signage was then taken into account by modifying some parameters as follows.

The particles (assumed 'active') areadapted to include a passenger's desire to walk through an area towards a particular destination(exit or carriage), but it was not possible to predict the number of passengers who knew the direction of the exit before alighting from the train.

Generally speaking, there are at least 5 categories of travellers, although the percentagesat a particular moment or particular station vary according to the day and the time. Tourists and groups of visitors fall into the category of those who do not know where the exit is as they get off the train, but such users tend to only frequent the stations serving tourist destinations. On the other hand, residents, regular travellers, workers and commuters who take the same route every day know the layout of the station they get off at.

Because of the host of random elements in such contexts, a computational tool can only provide qualitative feedback about passenger behaviour and the time it takes to clear the platform. From in situ observations, the key parameters in passenger flow seem to be how full the train is and the reactivity time$[\tau_i]$, which reflects passenger responsiveness and ability to move swiftly in the right direction. The automatic signal(illuminated arrow) has a bearing on the latter as it increases the number of 'informed' passengers and reduces the time needed to head towards the right exit. The reactivity time (as well as the response time) may be then reduced. Quantitative information about these new quantities are unavailable but the numerical tool allows at least to perform a sensitivity analysis.

A discrete-elementsmethodallows to track each particle(i.e. passenger) and to personalize its individual characteristics (average speed, BMI, responsiveness, etc.). This feature of the model allows to affect individual properties to each passenger (or group) accordingly to a statistical properties distribution. Although some parameters can be considered as deterministic(e.g. mass or average pedestrian speed), other parameters are affected by familiarity with station layout and, notably, passenger reaction capability.

Given the probabilistic aspects of the model, numerous simulations are required to determine an average validity of the results. Different configurations in terms of the number of boarding/alighting passengers are also considered to validate the signage effectiveness.

Fig.7 is a typical result of a numerical simulation (with and without the arrow sign). In this example, the parameters affected by the signage are presented in table 2.The presence of the sign statistically increases the percentage of ‘informed’ users,thus reducing the average time it takes to clear the platform. The illuminated arrow informs even the occasional traveller ofthe position of the exit and makes them better prepared. The arrow alone is not enough to inform all travellers (e.g. absent-minded passengers, those far from the windows or ill-placed will not be able to see the sign), i.e. the statistical distribution of the reactivity time takes into account also this possible lack of information (upper bound of the parameters’ distribution).

It is worth noting that the hypothesis and simplifications in the model may lead to an overestimation of the evacuation time, e.g.the ‘go with the flow’ effect is not implemented into the model. However, numerical simulations consistently proved the role of the signage reducing the time it takes to clear the platform edge, using different parameters’ ranges and different passengers’ configurations.

VIII. CONCLUSIONS

Without ignoring station architecture and passenger comfort, the initial objectives of our research were to assess traffic regularity and (in line with the transport system’s current energy efficiency policies) any resulting power savings.

Taking the global context of the modelling of pedestriandynamics and the improvementsto station signagedescribed above, the highlights of our avenue of research are the following:

a,Improved traffic management& traffic flows, keeping to train timetables
- shorter stops at station, less time required foralighting and boarding
- encouragement of behaviour producing smoother pedestrian flows.

b, Better information for travellers &greater user comfort
- Clearer station layout for passengers increases user-friendliness
- More information is provided via easily-understood interactive systems.

c, Safety, security, reliability, design & project support
- Improved travel safety via signage at stations or on board trains
- Reduced risk of incidents via digital modelling of passenger behaviour, reflections on operating methods and insights into the human factors.

The model enabled simulations to be conducted in a range of specific configurations. Analysis and comparison of several case studies helped confirm the validity of the pedestriandynamics model and the improvements offered by the new station signs.

Figures

Fig. 1 ***Dans le métropolitain… on court pour une place*** **- The rush for a seat in the Paris metro (c. 1900).**

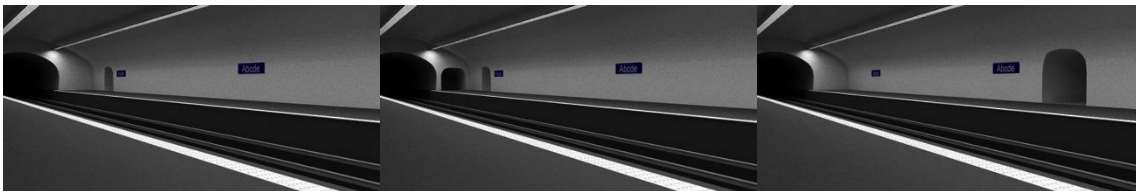

Fig. 2 a, Interior view of metro station featuring a single exit on one platform; b, Station with two adjacent exits at one end of the platform; c, Station with centrally positioned single exit.

Fig. 3 Video photograms of passengers alighting from the train…

Fig. 4 New signs and displays indicating the name of the station.

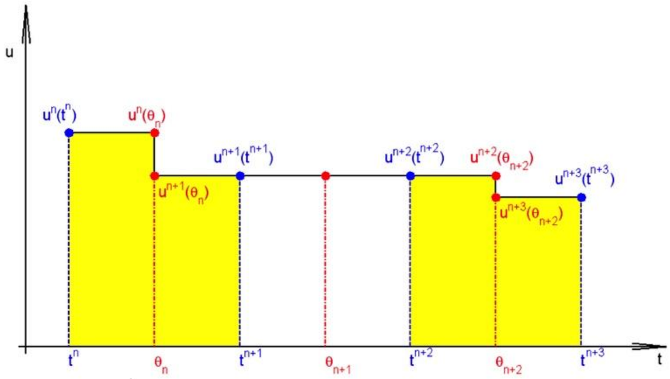

Fig. 5 Diagram of temporal discretization.

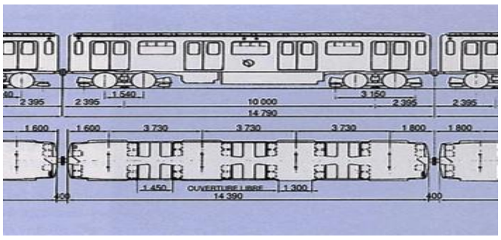

Fig. 6 MP 59-type coach.

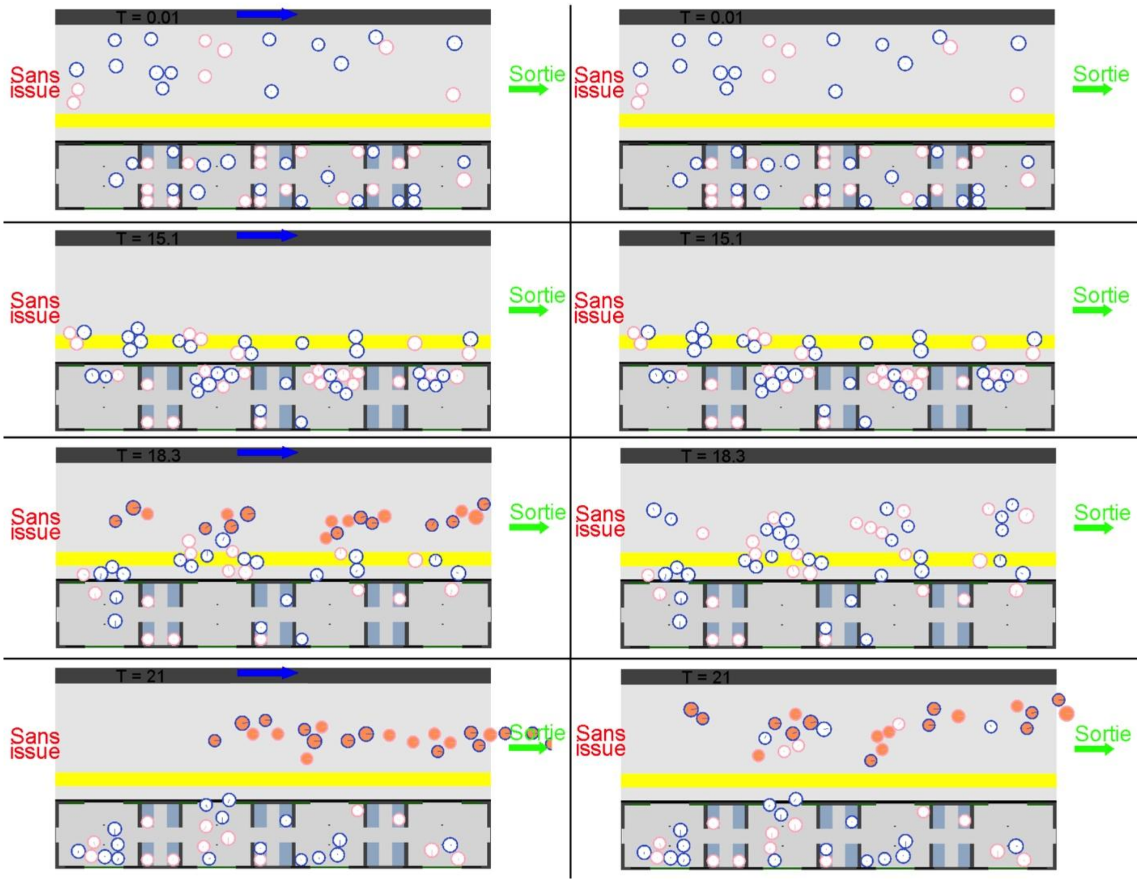

Fig. 7 Photograms of one typical simulation of the platform/train passenger interchange with (on the left) and without (on the right) arrow sign (time stations t=0.01s, 15.1s, 18.3s, 21s).

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