A numerical model to assess the risk of fall in public transportation – application to the influence of the Jerk in emergency braking

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I. INTRODUCTION

Non-crash events (e.g. emergency brakings) are a prevalent cause of injuries for public transportation (PT) passengers [1]. In particular, fall of standing passengers induced by the vehicle dynamics can have dramatic consequences, notably for fragile passengers, such as the elderly. One solution to mitigate this risk is to limit the aggressiveness of the interior design, which goes through the evaluation of the injury risks induced by secondary collisions [2]. Another solution is to limit the occurrences of unbalance by identifying, and possibly adjusting, the sources of loss of balance in the vehicle's dynamics. Perturbations characteristics that induce a fall or a loss of balance have been assessed experimentally. However, the perturbations considered are extremely rarely relevant to those encountered in PT. In addition, apart from [3], no quantitative information exists on critical parameters, such as the Jerk of the emergency profiles. Finally, experimental results are very specific and difficult to generalise. There is, therefore, a need for a numerical tool that can evaluate the risk of fall of standing persons submitted to transient perturbations representative of PT. One of the difficulties is that, contrary to the passive human models classically used in injury biomechanics, it must include the reactions of passengers trying to restore their balance. To our best knowledge, such a tool does not yet exist. This study aims to fill this gap. It proposes a first evaluation of the model's performance and uses it to evaluate the influence of an emergency braking's Jerk on the risk of fall.

II. METHODS

Hypotheses

We consider the idealised situation of a free-standing passenger facing the front of a vehicle that brakes suddenly. The deceleration profile consists of a ramp followed by a plateau. The loss of balance that may occur at the end of the deceleration, due to the transition from the plateau to a null acceleration, is not considered in this study.

Mechanical model and human reactions modelling

The human body is represented as an Inverted Pendulum (IP) mounted on a massless, foot-like Base of Support (BoS), with a concentered mass at the Center of Mass (CoM) and with a flywheel (FW) centered at the CoM. It is installed on a moving cart, reproducing the PT vehicle's dynamic. For a given perturbation, we can estimate this system's evolution, considering the maximal recovery reactions. The two first reactions, related to the "ankle" and "hip" strategies, are triggered after an initial delay (the reaction time, RT). They consist of an instantaneous displacement of the Center of Pressure (CoP) toward the edge of the BoS and an acceleration/deceleration of the FW following a bang-bang type of profile, respectively. Further, a recovery step can be taken after an additional Step Preparation Time (SPT). It can be seen as an extension of the BoS, which is bounded at each instant after the SPT by a 5^{th} order polynomial expression linked to maximal acceleration of swing foot and, if reached, by the maximal step length. All feasible step length/duration are tested.

Evaluation of the risk of fall

Evaluation of the risk of fall is based on the XCoM criteria [4]. XCoM computation was adapted to take into account the presence of a constant perturbation, such as the acceleration plateau (Equation (1)). For each feasible step length/duration combination tested, the XCoM was estimated at the first instant, that is both after the end of the hip and step reactions and on the acceleration plateau. If, at this instant, the XCoM lies within the BoS, we considered the applied perturbation recoverable for the considered step (Fig. 1). It resulted in two types of information: 1. The possibility to avoid a fall for the applied perturbation (binary answer), if any feasible step led to a possible recovery; 2. An approximation of the difficulty to avoid the fall for the applied perturbation, given by the percentage of feasible steps that do not lead to a recovery, noted $FS_{\%}$.

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$$XCoM(t)=x_{proj}(t)+\frac{\dot{x}_{proj}(t)}{\omega_0}-\frac{\ddot{x}_{platform}(t)}{\omega_0^2}, \qquad \omega_0=\sqrt{\frac{g}{z}} \tag{1}$$

Model evaluation

This model was already used successfully for simple and instantaneous perturbations [5]. Here, its performances are assessed against data representing PT decelerations [3]. Note that this unique set of data does not consider the possibility to step or to use the upper body inertia. We also use this model to evaluate if an adjustment of the emergency braking parameters could limit the risk of fall without increasing the stopping distance. This evaluation was performed using the characteristics of tramways emergency brakings type FU2 from the comfort performances provided in the EN13452 and considering an initial velocity of 30 km/h.

III. INITIAL FINDINGS

The maximal acceleration plateau sustainable, without stepping and using upper body inertia, is about 1 m/s², which is slightly above but within the order of magnitude of the mean value from [3]. Our model also predicts the sustainable Jerk for about 50% of the volunteers tested (Table I). Influence of the Jerk was also demonstrated on emergency braking profiles, in particular the possibility to limit the risk of fall while keeping a constant stopping distance (Table II).

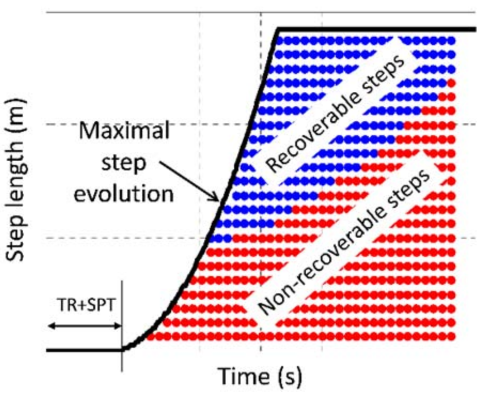

Fig. 1. Example of all feasible steps: blue steps can lead to a recover, whereas red steps cannot.

TABLE I

EXPERIMENTAL RESULTS ABOUT THE JERK EFFECT ON 0-STEP THRESHOLD FROM [3] AGAINST RESULTS FROM THE IP MODEL WITHOUT FW (1 = RECOVERABLE, 0 = NON-RECOVERABLE SITUATION)

Jerk	1	2	5	10
% of recover from [3]	65	47.5	12.5	2.5
Model results (binary)	1	1	0	0

TABLE II

RISK OF FALL ESTIMATION FOR A REFERENCE CASE FROM EN13452 AND FOR TWO OTHER CASES EQUAL IN TERMS OF STOPPING DISTANCE WITH A HIGHER AND LOWER JERK, RESPECTIVELY

Tram velocity = 30 km/h	Jerk (m/s^3)	Acceleration (m/s^2)	Stopping Distance (m)	$FS_{\%}$ (%)
Lower	2	3.8	16.4	0
Reference	4	2.5	16.4	38
Higher	8	2.3	16.4	77

IV. DISCUSSION

This model still lacks experimental validation, especially for population with reduced mobility, and it remains limited to free-standing postures and transient perturbations in the AP direction. Nonetheless, this unique model shows promising results in terms of identification of the situations at risk. It could also be used to optimise the vehicles' dynamics, typically the characteristics of the braking/acceleration profile, in order to limit the risk of fall. As such, it has an interesting potential to increase the comfort and safety of PT vehicles.

V. REFERENCES

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