An Energy-absorbing Countermeasure Concept for Subway-to-Pedestrian Collisions Using Numerical and Analytical Modelling Techniques

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I. INTRODUCTION

The number of cities with operational subway systems has increased from 50 in the 1970s to over 219 in 2019, alongside a global subway track length in excess of 15,000 km [1]. The high number of road deaths worldwide is a well-documented issue, with extensive research on the topic to improve vehicle safety for pedestrian protection [2-4]. However, the subway crashworthiness research found in the literature focuses on subway occupant protection and does not account for or protect against subway-to-pedestrian contact. Thus, although this is a substantial problem in several jurisdictions [5-6], there is a lack of published literature regarding this topic. Subway-specific pedestrian incidents involve both accidental and suicidal cases and can often be severe due to the difficulty in accessing the injured and the high risk of amputations. A recent study of New York City (NYC) incident reports has highlighted standing, lying and jumping as important pre-impact configurations [7]. This short communication presents an energy-absorbing countermeasure (EAC) concept developed using a numerical and analytical model. The method works by determining the required stiffness and crush depth of an EAC to reduce the primary impact head acceleration to a survivable level.

II. METHODS

Using the (NYC) subway system as a reference, 185 NYC subway-to-pedestrian collisions from 2019 were analysed [7]. This analysis highlighted that a typical collision event involves a 35–45-year-old male contacting the front face of an R160 model subway train at 25–30 mph (40–48 km/hr). A multibody model of an R160 was created using the software package MADYMO (MAthematical DYnamic Models, TASS International), which was used in combination with the MADYMO 50th percentile male model to simulate a baseline impact at an initial velocity of 30 km/hr.

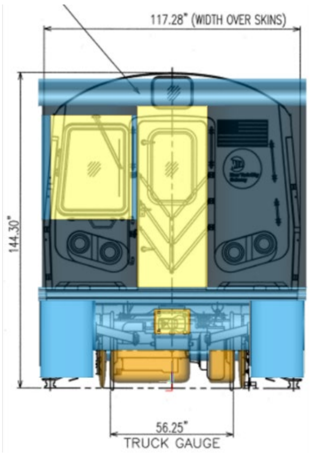

Fig. 1. Multibody model surface representation of subway front-end.

During the countermeasure design stage, an analytical model of a head impact was created using Matlab. Using a spring mass model to represent the pedestrian mass and pedestrian-to-train contact stiffness, and support motion to represent the train displacement during contact, a set of equations was derived to analytically describe the motion of a struck pedestrian:

$$x(t) = -\frac{\dot{x}(o)}{\omega n} sin(\omega nt) + \dot{x}(0)t \qquad \dot{x}(t) = -\dot{x}(o)\cos(\omega nt) + \dot{x}(0) \qquad \ddot{x}(t) = (-\dot{x}(o)\omega n)(sin(\omega nt))$$

Given a known mass, contact stiffness and impact velocity, this model provides fast estimates of crush depth for EACs. These EACs are then added to the multibody baseline model to show the change in peak linear head and sternum acceleration due to the EAC.

III. RESULTS

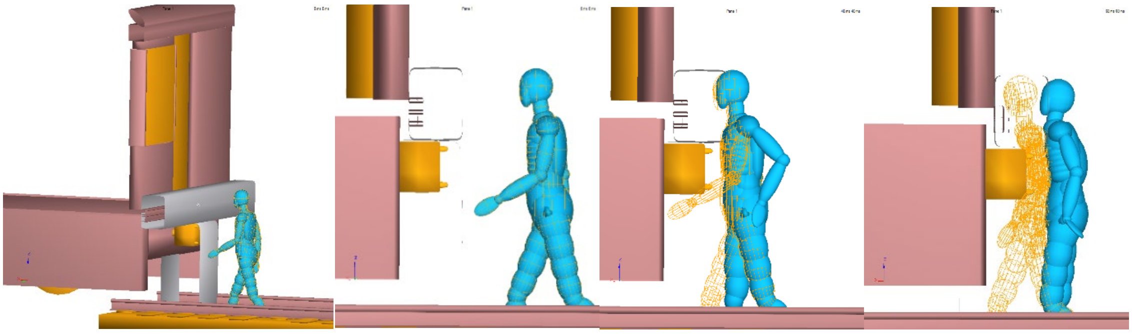

Fig. 1. MADYMO model of baseline (orange) and EAC (blue) pedestrian impacts.

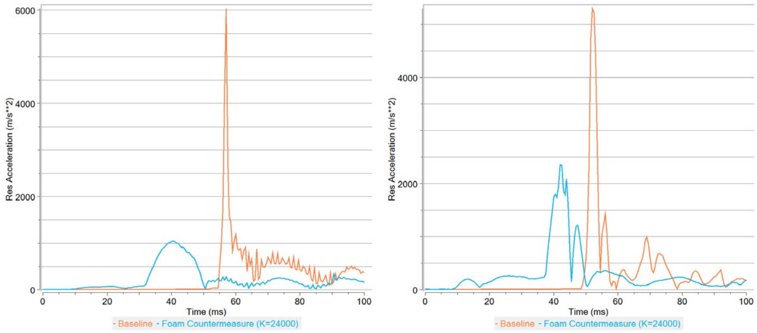

Fig. 2. Linear acceleration of baseline (orange) and EAC (blue) pedestrian impacts.

The analytical model showed that a material of equivalent stiffness 24,000 Nm^{-1} would require 0.12 m of crushable material to significantly reduce the peak head acceleration to below 100 g. This stiffness and geometry were implemented into the MADYMO baseline model covering the anticlimber and coupler, which act as the contact points between the train and pedestrian for this scenario. The resulting kinematics and linear acceleration of the baseline model overlayed with the EAC for both the head and sternum are presented Fig. 2 and Fig. 3.

IV. DISCUSSION

The effect of an EAC that produces a contact stiffness of 24000 Nm^{-1} is a significant decrease in both peak head and sternum acceleration. These head accelerations can be used to calculate the Head Injury Criterion (HIC) score and to determine the associated head injury risk using the Abbreviated Injury Scale (AIS). Table I shows the reduction in injury risk due to the concept EAC. The results presented are preliminary results as part of a larger study. More research is required to investigate injury risk reduction for different pedestrian positions and impact velocities. The operational feasibility of adding EAC to key areas, such as the coupler, must be considered for real-world application. Secondary contact and wheel rollover risks should also be considered. While the resulting injury risk remains high, the results show a significant improvement in safety.

TABLE I
AIS INJURY RISK OF BASELINE AND EAC BASED ON HIC

AIS	1	2	3	4	5	6
Baseline (%)	100.05	99.77	99.45	96.96	92.02	78.83
Foam (%)	98.72	84.82	45.97	13.57	1.96	0.51
Reduction (%)	1	15	54	86	98	99

V. REFERENCES

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