Analyzing Hard Braking events of Automated Shuttles from Naturalistic Urban Pilot Sites

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I. INTRODUCTION

The advent of Cooperative, Connected, and Automated Mobility (CCAM) is already underway, yet its safety implications remain under-explored. Hard Braking (HB) events in automated shuttles provide crucial insights into safety performance, particularly when analysed across multiple naturalistic pilot sites. This study employed Negative Binomial (NB) Regression to examine HB event frequency across 10 real-world operational sites within the EU Horizon 2020 SHOW project [1] and also considered site-specific variations.

II. METHODS

Data were collected from 10 European pilot sites: Brno, Carabanchel, Graz, Karlsruhe, Klagenfurt, Les Mureaux, Linköping, Pörtschach, Tampere, and Trikala. These sites provided 1,796 daily observations including 4,820 HB events, with cutoff limits determined by the automated shuttle operators. The statistical modelling included NB regression due to significant overdispersion in the data, with the variance exceeding the mean by a factor of 20.15. The model incorporated average speed, acceleration variance, and pilot site categories as explanatory variables. A random intercept approach was used to account for site-specific variations, with Linköping serving as the reference category. To verify multicollinearity concerns, Variance Inflation Factors (VIF) were calculated, with the highest value being 2.333, ensuring robust model interpretation. Additionally, Marginal Effects to the Mean (MEM) were computed to quantify the impact of predictor variables on HB counts.

III. FINDINGS

Table I presents the results of the NB regression model. Both average speed and acceleration variance were found to significantly increase HB occurrences ($p < 0.001$). A higher average speed led to a proportional rise in HB events, likely due to more abrupt braking requirements in response to traffic interactions or unexpected obstacles. The acceleration variance, which captures fluctuations in driving smoothness, also exhibited a strong correlation with HB events, indicating that higher variations in acceleration contribute to harsher braking events.

Among the pilot sites, Linköping exhibited the lowest HB counts, while Klagenfurt had the highest, followed by Pörtschach, Graz, and Trikala. These findings suggest that site-specific operational factors, such as road design, traffic conditions, pedestrian volumes, or AV control algorithms, influence HB rates significantly. Conversely, Brno, Karlsruhe, Les Mureaux, and Tampere demonstrated relatively lower variations in HB events, indicating more stable shuttle operations in these locations.

TABLE I
NEGATIVE BINOMIAL REGRESSION RESULTS FOR HARD BRAKING EVENTS

Variable	Estimate	Std. Error	z-value	p-value	
Intercept	-4.938	0.232	-21.267	<0.0001	***
Average Speed	0.292	0.024	12.256	<0.0001	***
Average Acceleration Variance	0.052	0.010	5.133	<0.0001	***
Site: Brno [Ref. Cat. Linköping]	1.579	0.302	5.225	<0.0001	***
Site: Carabanchel [Ref. Cat. Linköping]	3.262	0.210	15.500	<0.0001	***
Site: Graz [Ref. Cat. Linköping]	5.962	0.287	20.790	<0.0001	***
Site: Karlsruhe [Ref. Cat. Linköping]	4.098	0.289	14.164	<0.0001	***
Site: Klagenfurt [Ref. Cat. Linköping]	6.179	0.269	22.963	<0.0001	***
Site: Les Mureaux [Ref. Cat. Linköping]	2.738	0.183	14.933	<0.0001	***
Site: Pörtschach [Ref. Cat. Linköping]	6.057	0.210	28.894	<0.0001	***
Site: Tampere [Ref. Cat. Linköping]	1.455	0.330	4.407	<0.0001	***
Site: Trikala [Ref. Cat. Linköping]	5.127	0.268	19.101	<0.0001	***
Dependent variable: Hard Braking Counts per day					
*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*					
Null deviance: 3109.5 on 1795 df. Residual deviance: 1218.4 on 1784 df. AIC: 4843.4					

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Table II provides additional insight into the practical impact of each factor on HB rates. A 1 km/h increase in average speed results in an additional 0.155 daily HB events, reinforcing the observation that faster travel speeds necessitate harsher braking responses. The acceleration variance contributes an estimated 0.863 additional HB events per unit increase (m/s^2), underlining the need for smoother vehicle operation to mitigate HB occurrences.

Higher MEM values for sites like Klagenfurt, Pörtschach, and Graz indicate that these locations have a disproportionate increase in HB events, which could be attributed to unique operational constraints, such as road topology, AV fleet behaviour, pedestrian volumes, or surrounding traffic density. In contrast, the lower MEM values for sites like Brno and Tampere suggest that operational characteristics in these locations lead to relatively more stable braking performance, which may reflect smoother traffic flow or more predictable interactions with other road users.

TABLE II
MARGINAL EFFECTS TO THE MEAN (MEM)

Marginal Effects	**Estimate**	**SE**	**z**	**p**	**lower**	**upper**
Average Speed	0.155	0.036	4.304	0.000	0.084	0.225
Average Acceleration Variance	0.863	0.121	7.133	0.000	0.626	1.101
Site: Brno [Ref. Cat. Linköping]	0.646	0.204	3.170	0.002	0.246	1.045
Site: Carabanchel [Ref. Cat. Linköping]	4.205	0.884	4.755	0.000	2.472	5.938
Site: Graz [Ref. Cat. Linköping]	64.933	22.191	2.926	0.003	21.440	108.426
Site: Karlsruhe [Ref. Cat. Linköping]	9.920	2.931	3.385	0.001	4.176	15.664
Site: Klagenfurt [Ref. Cat. Linköping]	80.705	27.912	2.891	0.004	25.999	135.412
Site: Les Mureaux [Ref. Cat. Linköping]	2.422	0.377	6.419	0.000	1.682	3.161
Site: Pörtschach [Ref. Cat. Linköping]	71.382	20.510	3.480	0.001	31.183	111.581
Site: Tampere [Ref. Cat. Linköping]	0.551	0.137	4.021	0.000	0.282	0.819
Site: Trikala [Ref. Cat. Linköping]	28.065	8.656	3.242	0.001	11.100	45.030

IV. DISCUSSION

This study highlights that both average speed and acceleration variance are strong predictors of HB occurrences, with increased values leading to a higher frequency of events. Sites such as Klagenfurt, Graz, and Pörtschach recorded the highest HB rates, indicating potential infrastructural, traffic, or operational challenges. The substantial disparities in HB rates between sites suggest that local traffic conditions, pedestrian volumes, roadway design, and shuttle operation strategies influence safety outcomes.

The results emphasize the necessity for adaptive and context-aware automation strategies to mitigate HB events. Future research should incorporate additional factors, such as pedestrian interactions, intersection dynamics, and urban layout characteristics, to refine safety models further. The study’s findings provide a foundation for improving AV deployment strategies, guiding regulatory policies, and optimizing automated shuttle operations across diverse European urban environments.

This study presents one of the first evaluations of HB events in automated shuttles using real-world European data. The findings contribute valuable insights for advancing CCAM safety protocols, ensuring improved safety outcomes, and facilitating sustainable automated shuttle integration into public transport systems. Specific actionable approaches include: (i) the enhancement of AV perception and communication systems to proactively address human-driven vehicle behavior, (ii) the adoption of adaptive driving behavior in lieu of conservative speeds as a core strategy to reduce conflicts, as well as (iii) the exploitation of conflict severity modeling and TTC analysis for location-specific AV policy and deployment strategies.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

[1] EU Horizon SHOW project, 2020. More information available: https://show-project.eu/