

## Introduction

Cooperative, Connected and Automated Mobility (CCAM) is advancing from controlled pilots to real-world operations. As **automated shuttles enter public transport networks, rigorous safety evaluation becomes critical.**

Most evidence to date derives from closed-course trials or single-site studies, which rarely capture the variability of mixed urban traffic. **Hard Braking (HB) events serve as Surrogate Safety Measures (SSM),** offering a proactive crash-risk proxy without requiring collision records.

This study, conducted within the **EU Horizon 2020 SHOW project,** analyses HB events across **ten European pilot sites** using a Negative Binomial regression framework to identify key safety determinants.

### Three contributions:

- Cross-European real-world safety assessment using naturalistic operational data.
- Quantification of speed and acceleration variance effects on HB frequency.
- Site-specific evidence for context-dependent safety calibration.

## Data Collection

The analysis draws on operational data from the Horizon 2020 SHOW project, which **deployed automated shuttles across multiple European cities** to evaluate their safety, efficiency, and integration into public transport.

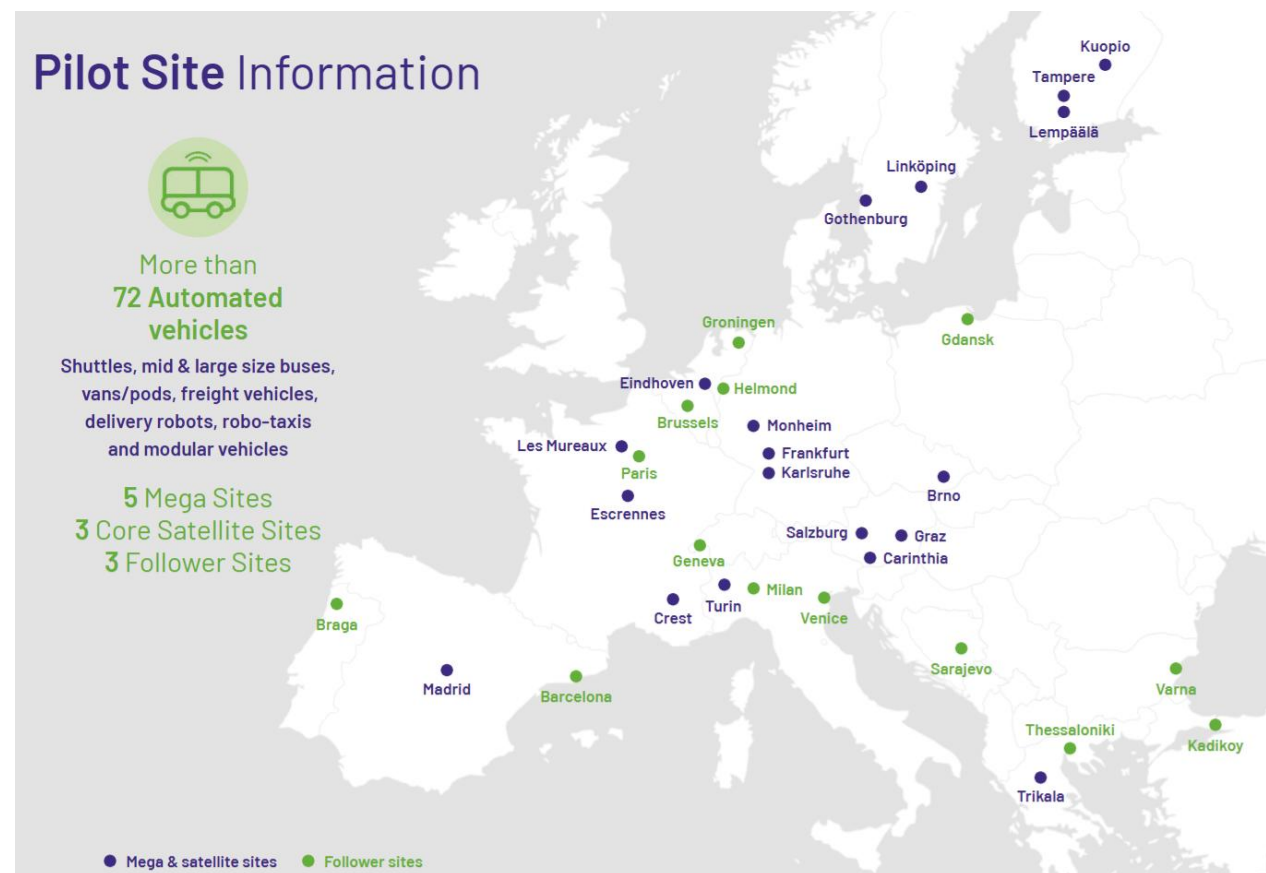


Figure 1 Distribution of SHOW project pilot sites across Europe and examples of the automated shuttle fleet

Operational data from the SHOW project, deploying automated shuttles across multiple European cities under real mixed-traffic conditions.

### Key figures:

- **10 pilot sites** across Europe
- **1,796 site-days** of operation
- **4,820 Hard Braking events** recorded

HB was defined consistently via a **longitudinal deceleration threshold of  $-3 \text{ m/s}^2$ ,** applied uniformly across all sites.

### Variables:

- **Average speed** (km/h): mean daily operating speed.
- **Acceleration variance** ( $\text{m/s}^2$ ): variation in longitudinal acceleration.
- **Pilot site** (categorical): 10 sites, Linköping as reference.

Table 1 Extracted HB road safety-related KPI values

Site	Total Hard braking events	Daily Hard braking events
Brno, Czech Republic	37	0.563
Graz, Austria	496	13.053
Les Mureaux, France	726	1.941
Linköping, Sweden	46	0.058
Carabanchel, Madrid	237	1.896
Tampere, Finland	520	5.2
Karlsruhe, Germany	120	3.333
Trikala, Greece	277	6.295
Klagenfurt, Carinthia, Austria	829	15.351
Pörschach, Carinthia, Austria	1533	9.581

## Statistical Modelling

HB events modelled using a **Negative Binomial (NB) regression,** appropriate for overdispersed count data. Site effects tested as random intercepts but yielded no additional power; **fixed-effects specification retained.**

### Diagnostics:

- Max VIF = 2.333 (no multicollinearity)
- Marginal Effects to the Mean (MEMs) computed for interpretation

## Results

Scatterplots revealed only a **weak linear relationship between speed and HB counts,** while **acceleration variance showed upward-sloping trends,** suggesting unstable speed control contributes to HB frequency.

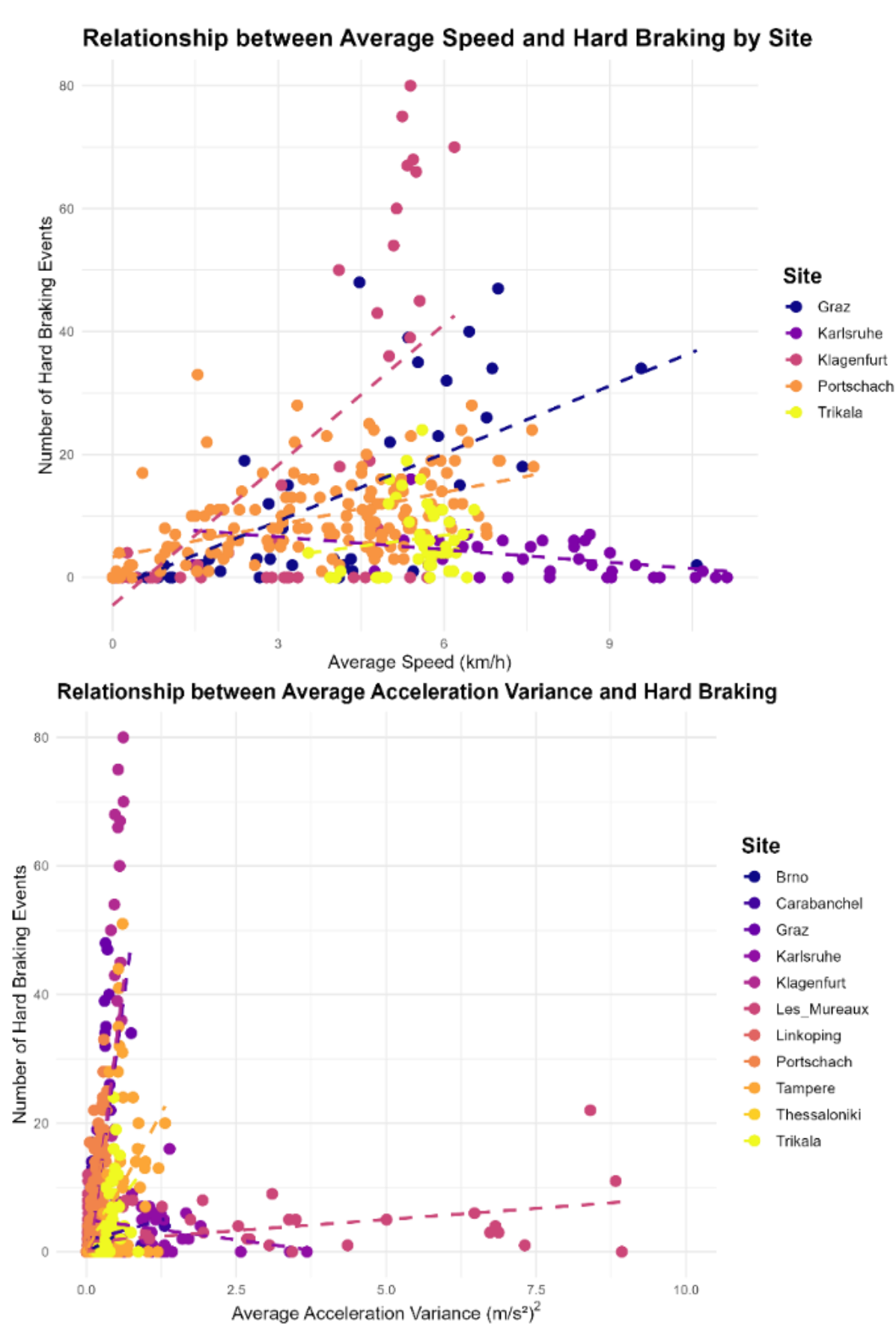


Figure 2 (a) Hard brakings vs. average speed (b) Hard brakings vs. acceleration variance

Table 2 details the Negative Binomial regression results, confirming that both average speed and acceleration variance are **highly significant predictors ( $p < 0.0001$ ).** Positive estimates demonstrate that faster operations and unstable longitudinal control directly elevate the likelihood of abrupt braking.

Table 2 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: Pörschach [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

Figure 3 visualizes the model's IRRs, highlighting **substantial site-to-site heterogeneity** across the European pilots. Clearly displays Klagenfurt, Pörschach, Graz, and Trikala as major outliers, exhibiting much higher hard braking rates compared to the Linköping baseline.

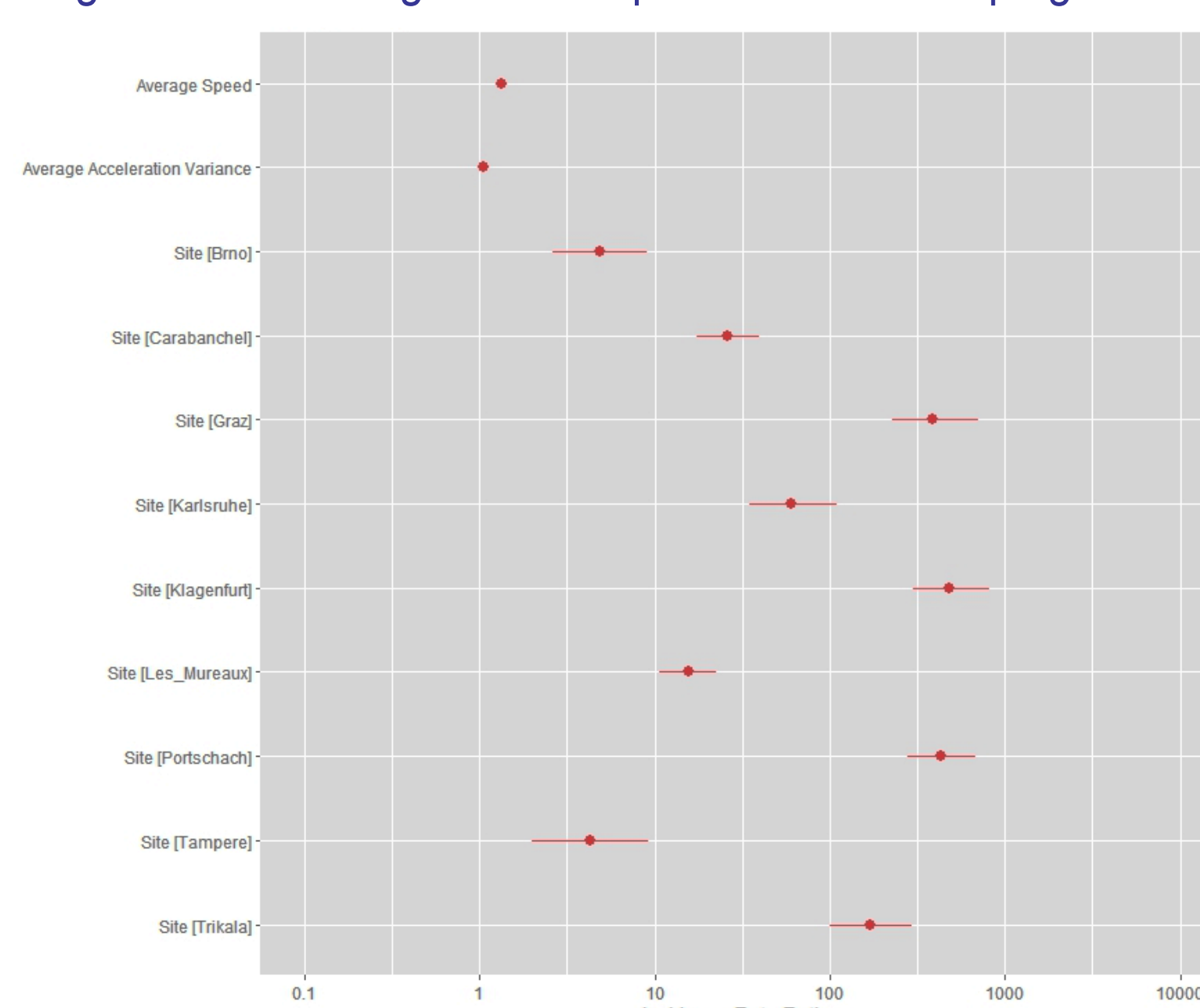


Figure 3 Incidence Rate Ratios for HB counts from NB regression on SHOW site data

## Discussion

### Impact of Vehicle Dynamics

- Both speed and the stability of acceleration control are significant determinants of hard braking.
- **+1 km/h speed translates to a 34% increase** in the expected HB rate (IRR = 1.34), or roughly  $\sim 0.16$  additional daily events.
- **+1 unit of acceleration variance raises the HB rate by 5.3%** (IRR = 1.05), adding  $\sim 0.86$  daily events.
- Even marginal increases in speed and instability substantially elevate HB risk, indicating that smoother longitudinal control must be prioritized in shuttle programming.

### The Role of Local Context

- **Substantial site-to-site differences** persist even after controlling for vehicle dynamics, meaning safety outcomes are strongly shaped by local environments.
- Site-specific Marginal Effects to the Mean (MEMs) show massive variations: Klagenfurt (+80.7) and Pörschach (+71.4) recorded the highest additional daily HB events relative to Linköping.
- **Automation share alone does not dictate safety performance,** it is heavily influenced by urban density and interaction patterns.

### Operational & Safety Recommendations

- Integrating HB thresholds into automated control logic could enable operators to proactively adjust maximum speeds or reprogram acceleration profiles in VRU-heavy areas.
- Safety models are not easily transferable across pilots, a model calibrated in Klagenfurt would likely overestimate risks in calmer sites like Brno.
- Deployments require context-aware AI modules or dynamic geofencing that adapts control strategies based on local operating conditions, rather than a "one-size-fits-all" approach.

## Conclusions & Future Work

### Three main insights:

1. **Speed and acceleration stability are significant HB determinants,** even small speed increases substantially raise HB frequency.
2. **HB events are effective SSM** for automated shuttle safety evaluation without crash records.
3. **Strong site-specific effects** indicate safety performance is context-dependent meaning one-size-fits-all speed limits are insufficient.

### Future research proposals:

- Expand to near-crash metrics and conflict severity scoring.
- Incorporate route geometry, traffic density, weather.
- Longitudinal before-after comparisons.
- Larger-scale deployments for generalizability.

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