



TRANSPORT
RESEARCH
ARENA
BUDAPEST

18-21/05/26

Exploring the Complex Influences on Sustainable Driving

A Structural Equation
Modeling Approach with
Multisource Data

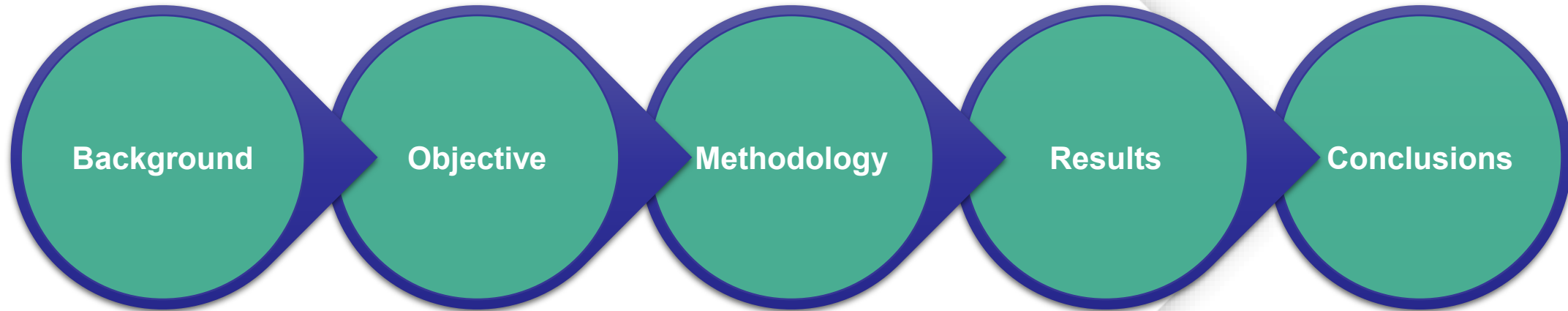


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20/05/2026

Outline



Background

Problem Statement

Rapid urbanization, with urban populations rising from 55% today to a projected 68% by 2050, is increasing reliance on road transportation while generating significant challenges for sustainable mobility



Road crashes

- major public health issue
- leading cause of death for 29 years
- 1.19 million road fatalities per year globally



Emissions

- transport sector is responsible for about a quarter of the EU's total CO₂ emissions
- 72% of which come from road transport

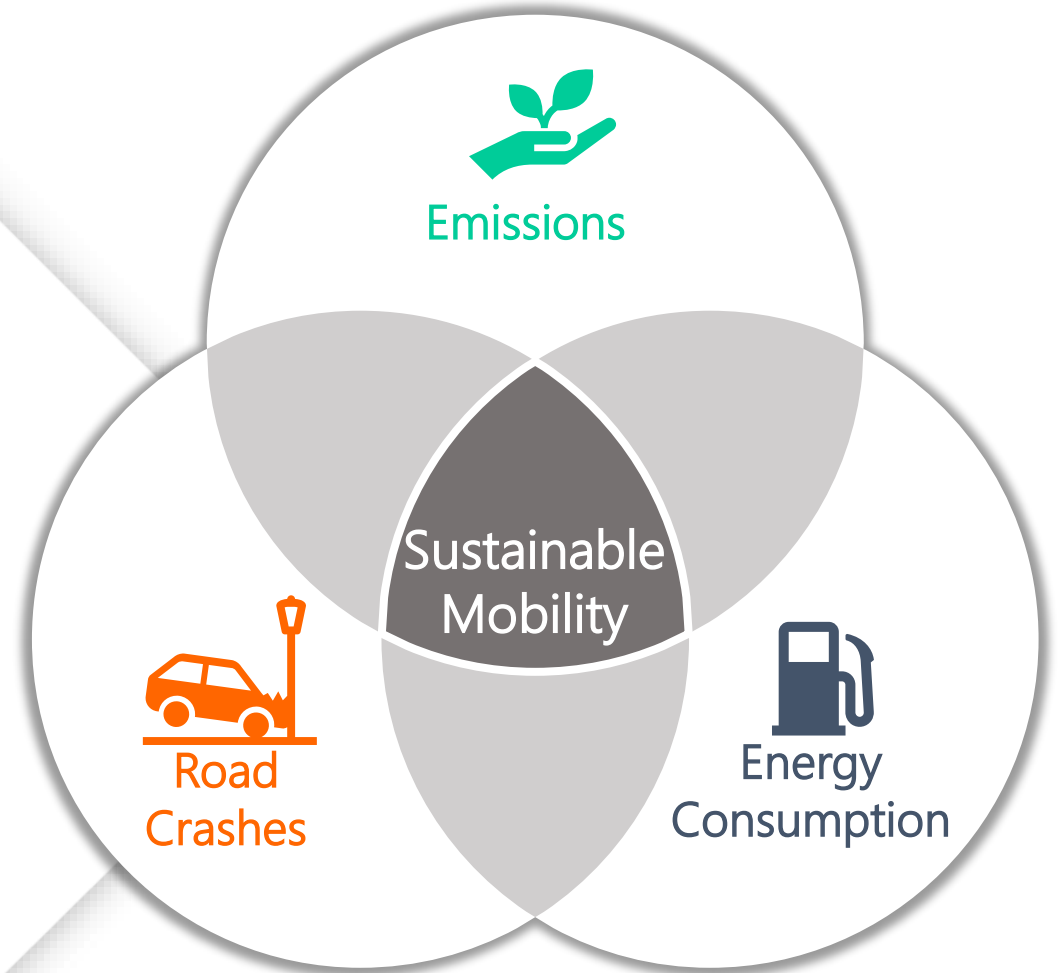


Energy consumption

- transport sector is responsible for 31% of the EU's total energy consumption
- 74% of which comes from road transport

Research Gap

- **Sustainable mobility** is grounded in the broader definition of sustainable development introduced by the World Commission on Environment and Development in 1987, identifying three interrelated dimensions:
 1. **economic sustainability**
 2. **environmental sustainability**
 3. **social sustainability**
- **Both the UN and EC** define sustainable transport as mobility with minimal greenhouse gas emissions and environmental impacts, safety, affordability, and equal access for all users
- Most existing methodologies have attempted to address these mobility dimensions **individually**
- This lack of co-consideration underscores the **need for analytical frameworks that holistically capture those dimensions**



Objective & Methodology

Objective

This study aims to investigate the factors and their complex interrelationships that influence key indicators of **driving sustainability at trip level**, with a focus on both road safety and fuel efficiency

Research Questions

- How can unobserved latent factors influencing both risky and inefficient driving behavior be measured within a unified framework?
- What is the relationship between risky and inefficient driving behavior at the trip level?
- How can multiple datasets encompassing driving behavior, road environment, temporal, and weather data be integrated to investigate sustainable driving behavior?



Methodology

Multi-Source Data Collection

Driving behavior [32,815 trips, Athens, Mar–May 2024]

- Smartphone sensors: speed, acceleration
- SSMs: harsh braking/acceleration, speeding, mobile use

Fuel consumption

- Estimated via Virginia Tech Comprehensive Power-Based Fuel Consumption Model
- It estimates instantaneous fuel consumption rates by calculating instantaneous power

Road infrastructure

- Map-matching trip trajectories to OSM road segments
- Extracted: road type, geometry, intersections
- Road grade from elevation data (NASA/Mapzen)

Weather data

- Temperature, humidity, wind, snowfall, daylight



Naturalistic
Driving Data
OSeven Telematics



Road Network Data
Open Street Map (OSM)



Weather Data
Open-Meteo

Methodology

Modeling Approach

- **Structural Equation Modeling (SEM)** capturing direct & indirect relationships
- Analysis performed at the trip level (~33,000 trips)
- Latent Constructs
 - Driving Volatility** → instability in driving behavior
 - Route Characteristics** → roadway & geometric features
 - Weather** → environmental conditions
 - Aggressive Driving** → harsh events
- Data Processing: Selected variables scaled to reduce variance and improve model stability
- Modeled Outcomes
 - Fuel consumption
 - Safety indicators: Speeding, Phone use, Aggressive driving
- Model Evaluation
 - CFI, TLI, RMSEA, SRMR

Latent	Variable	Description
Driving Volatility	stop_count_per_km	Stop frequency per trip kilometer
	pos_jerk_Q90	90 th percentile of positive jerk
	acc_SD	Standard deviation of longitudinal acceleration during the trip
Route Characteristics	perc_motorway	Proportion of trip distance driven on motorways (speed limit > 80 km/h)
	perc_residential	Proportion of trip distance driven on residential roads (speed limit < 50 km/h)
	inzone	1 if trip occurs within one municipality, 0 if it crosses more
	unique_u_count_perkm_sc	Number of intersections per kilometer (scaled by /10)
	std_grade	Standard deviation of road grade during a trip
	perc_grade_flat_sc	Proportion of flat road sections (scaled by /100)
Weather	is_day	Daytime indicator (1=day, 0=night)
	temperature_sc	Temperature scaled by /10 (°C)
	humidity_pct_sc	Relative humidity scaled by /100 (%)
Aggressive Driving	harsh_brk_per_10km	Harsh braking events per 10 km
	harsh_acc_per_10km	Harsh acceleration events per 10 km
-	speeding_per_100m	Number of speeding events per 100 m
-	mobile_use_per_100m	Mobile phone interactions per 100 m
-	FC_100	Fuel consumption in liters per 100 km of trip

Results

Key SEM Results

Model Performance

Good overall model fit across all indicators

Comparative Fit Index (CFI)	0.962
Tucker-Lewis Index (TLI)	0.947
Root Mean Square Error of Approximation (RMSEA)	0.055
Standardized Root Mean Square Residual (SRMR)	0.035

Statistically Significant Regression Relationships

↑ **Driving Volatility** ↑ fuel consumption
 ↓ speeding
 ↑ distraction

↑ **Route Complexity** ↑ fuel consumption
 ↑ aggressive driving
 ↓ speeding
 ↑ distraction

↑ **Favorable Weather** ↓ speeding
 ↑ distraction

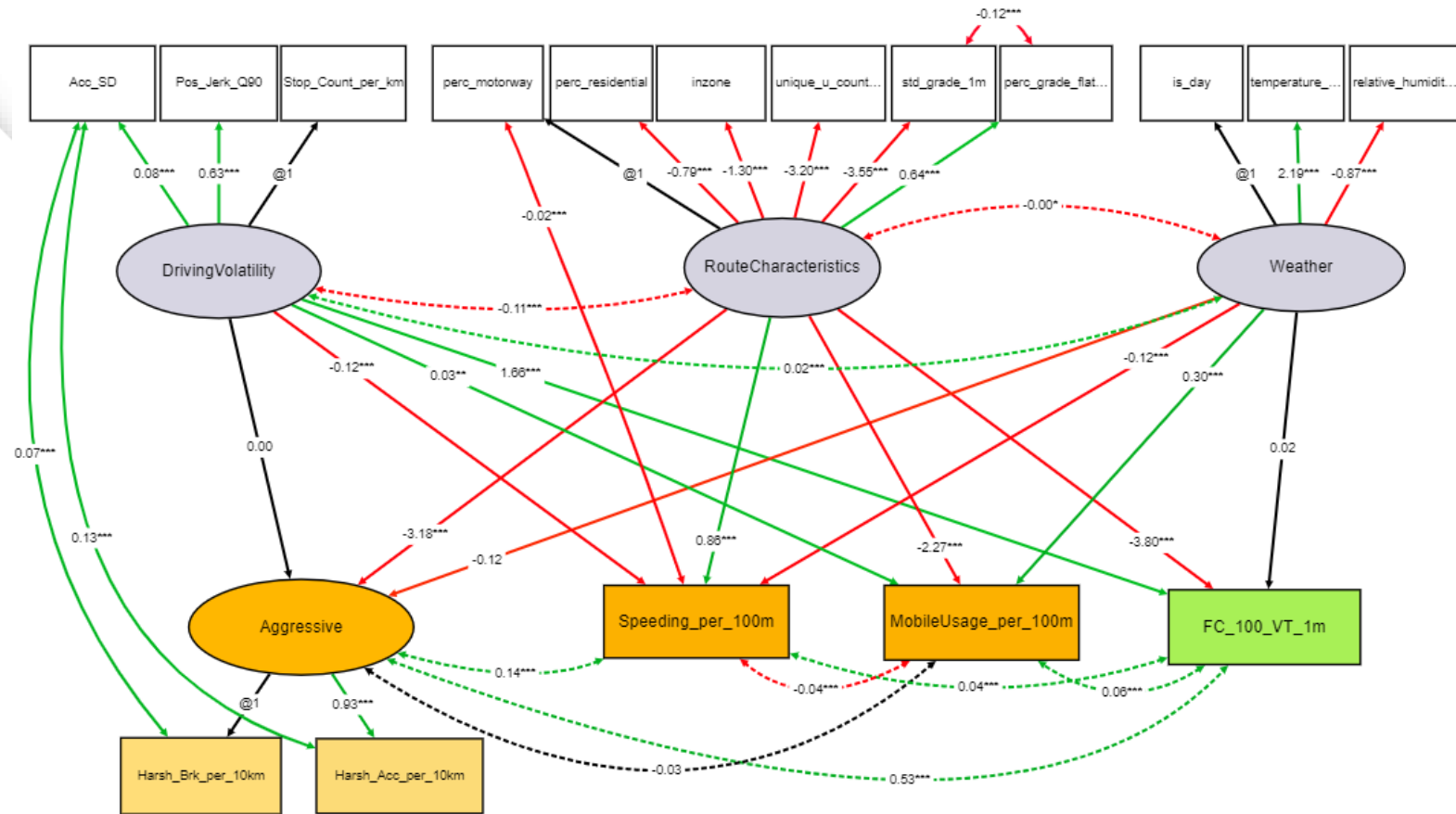
Significant Covariances (Efficiency ↔ Safety)

↑ Aggressive Driving ↔ Fuel Consumption
 ↑ Speeding ↔ Fuel Consumption
 ↑ Mobile Phone Use ↔ Fuel Consumption
 ↓ Speeding ↔ Mobile Phone Use

SEM Components	Parameters	Estimate	Std.Err	P(> z)		
Latents:	DrivingVolatility	stop_count_per_km	1	-	-	
		pos_jerk_Q90	0.634	0.002	0.000	
		acc_SD	0.081	0	0.000	
	RouteCharacteristics	perc_motorway	1	-	-	
		perc_residential	-0.788	0.01	0.000	
		inzone	-1.301	0.02	0.000	
		unique_u_count_perkm_sc	-3.199	0.029	0.000	
		std_grade	-3.553	0.053	0.000	
	Weather	perc_grade_flat_sc	0.639	0.008	0.000	
		is_day	1	-	-	
		temperature_sc	2.19	0.028	0.000	
	AggressiveDriving	humidity_pct_sc	-0.867	0.011	0.000	
		harsh_brk_per_10km	1	-	-	
	Regressions:	FC_100	harsh_acc_per_10km	0.931	0.028	0.000
			DrivingVolatility	1.663	0.01	0.000
RouteCharacteristics			-3.801	0.103	0.000	
AggressiveDriving		Weather	0.015	0.048	0.747	
		DrivingVolatility	0.001	0.013	0.964	
		RouteCharacteristics	-3.182	0.147	0.000	
speeding_per_100m		Weather	-0.12	0.068	0.076	
		DrivingVolatility	-0.12	0.003	0.000	
		RouteCharacteristics	0.856	0.04	0.000	
mobile_use_per_100m		Weather	-0.122	0.018	0.000	
		DrivingVolatility	0.032	0.011	0.004	
		RouteCharacteristics	-2.266	0.122	0.000	
Covariances:		perc_motorway	Weather	0.3	0.06	0.000
			speeding_per_100m	-0.023	0.001	0.000
			std_grade	-0.117	0.001	0.000
	acc_SD	perc_grade_flat_sc	0.126	0.002	0.000	
		harsh_acc_per_10km	0.07	0.002	0.000	
		harsh_brk_per_10km	0.07	0.002	0.000	
	DrivingVolatility	RouteCharacteristics	-0.112	0.002	0.000	
		Weather	0.019	0.002	0.000	
	RouteCharacteristics	Weather	0	0	0.016	
	AggressiveDriving	FC_100	0.53	0.02	0.000	
		speeding_per_100m	0.139	0.007	0.000	
		mobile_use_per_100m	-0.034	0.023	0.139	
	FC_100	speeding_per_100m	0.042	0.005	0.000	
		mobile_use_per_100m	0.06	0.016	0.000	
	speeding_per_100m	mobile_use_per_100m	-0.036	0.006	0.000	

Interpretation & Insights

- **Higher driving volatility** is associated with increased fuel consumption and higher distraction, while reducing speeding, reflecting congested stop-and-go conditions that raise energy demand, limit speed, and encourage secondary task engagement
- **Higher route complexity** is associated with increased fuel consumption, more aggressive driving, higher distraction, while reducing speeding, reflecting the impact of complex urban environments that constrain speed while increasing driver workload
- **Weather conditions** have no significant effect on fuel consumption or aggressive driving, but are associated with lower speeding and higher distraction, suggesting that more favorable conditions reduce speed-related risk while increasing secondary task engagement
- **Fuel consumption was positively correlated with aggressive driving and with speeding and mobile phone use**, although less so



Conclusions

Conclusions

- Analysis shows that **fuel inefficiency and unsafe driving are not independent**, and they share behavioral and contextual roots, shaped by the combined effects of driving behavior, roadway environment, and external conditions at the trip level
- **Driving behavior**, rather than external conditions alone, is the dominant driver of both fuel consumption and safety outcomes
- **Driving sustainability involves trade-offs**, as conditions that improve one aspect of safety or efficiency may worsen others
- Covariance results show that fuel consumption is positively associated with multiple unsafe behaviors, including speeding, indicating that **different driving patterns can both lead to inefficient and unsafe trips**
- The proposed SEM framework effectively captures direct and indirect relationships, **enabling integrated analysis of safety and efficiency at the trip level**
- These findings underscores the **need for integrated approaches** that simultaneously target eco-driving and road safety objectives, instead of addressing them in isolation

Limitations & Future Directions

- **The dataset is context-specific** (Athens, limited time period); extending the framework to different locations, conditions, and longer periods would improve generalizability
- **Fuel consumption** is estimated using a generic vehicle profile and a black-box model (VT-CPFM); future work could integrate vehicle-specific data and refine energy modeling
- **The model excludes driver- and vehicle-specific characteristics** and focuses on trip-level analysis; future research could include these factors and explore segment-level or predictive applications
- The analysis is conducted at the trip level; **future research could explore segment-level** analysis and predictive models (e.g., machine learning) for real-time applications



Thank you!

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