Passenger-centric analysis of train punctuality:

a case study on Stockholm's commuter rail

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Swedish transport research conference 2025 – Norrköping

2025-10-23

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Agenda

1. Introduction
2. Methodology
3. Results
4. Conclusions

Acknowledgements & credits

- Research conducted by Aurélie Lê (ENTPE) during internship (Apr–Jul 2025)
- This talk presents findings on behalf of the student; any delivery errors are mine!

1. Introduction

a) Motivation
b) Research questions

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1.a) Motivation

- Operational on-time ≠ passenger-experienced reliability
- Time of the day
  - Peaks (AM/PM) align with lower reliability (& higher variability)
- Station context matters
  - Headways, dwell times, and upstream knock-on effects
  - Transfer & multi-track
- Goal:
  - pinpoint when/where delay (variability) is the highest
  - to *prioritize* travel information (TI) & operation management.

1.b) Research questions

- RQ1: How does demand relate to departure delays?
- RQ2: What is the influence of other context factors?
- RQ3: Where is delay variability the highest?

Outcome: Targetet hotspots (in time & space) for more efficient traveler information (& operational actions).

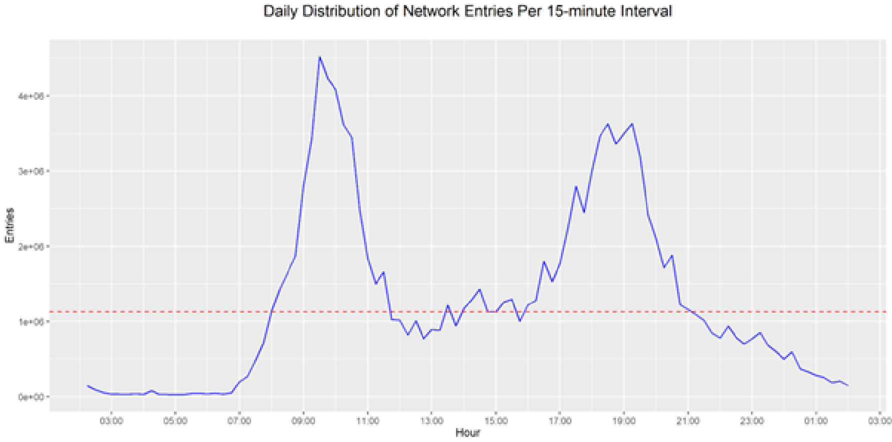
2. Methodology

a) Case & data
b) Variables & indicators
c) Model specification(s)

Frohne et al, 2009

2.a) Case & data

- Corridor:
  - Bålsta ↔ Nynäshamn (≈105 km), 29 stations
- Period:
  - Oct–Nov 2015 (weekdays)
- Timetable and traffic data:
  - scheduled vs. actual times, headways, dwell time
- Context:
  - station type (transfer/hub), # of tracks, distances
- Demand
  - "typical-day" station inflow (15-min bins)



2.b) Variables & indicators

- Outcome (independent variables)
  departure delay; day-to-day variability
- Traffic/timetable
  - Headway, scheduled dwell
  - Upstream delay
- Passengers
  - inflow at station (15-min)
  - Relative inflow (normalized 0–1)
- Other controls
  - Distances, station type, day period

Variable	Description	Unit
Relative inflow	Ratio of the number of entries at a given station, quarter-hour, and direction, to the station's average daily inflow.	Dimensionless
Punctuality at the previous station	Punctuality performance of the previous station during the same time-interval.	Minutes
Type of station	- **Multimodal hub** : Stations allowing several multimodal transfers - **Transfer station** : Stations allowing transfers to other commuter lines - **Simple station** : Other stations (reference category)	Categorical
Number of tracks	The number of tracks a station is equipped with (1, 2 or 4).	Number of tracks
Day period	- **Morning**: 6:00 - 11:59 - **Afternoon**: 12:00 - 18:59 - **Evening**: 19:00 – 22:59 - **Night** : 22:00 – 5:59 (reference category)	Categorical
Scheduled dwell time	The planned duration for which a train is scheduled to stop at a given station, direction, and time interval, to alight and board passengers.	Minutes
Scheduled headway	The planned time interval between two successive train departures from the same station, within a given time period of the day.	Minutes
Distance travelled	The distance covered by the train from its origin up to the station where the departure delay is measured.	km

2.c) Model specification(s)

- Ordinary Least Squares (OLS) regressions are applied:

$$Y_{std} = \alpha + \sum_k \beta_k X_{kstd} + \epsilon_{std}$$

where Y_{std} is the outcome at station s, time t and direction d, and X_{kstd} are the explanatory variables, and ϵ_{std} is the error term.

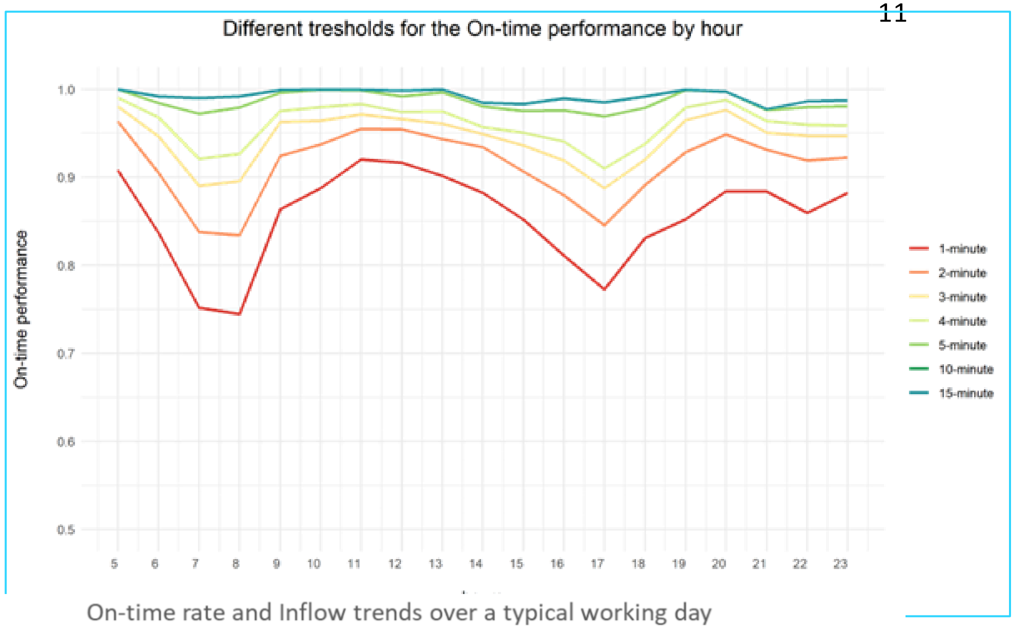
- Key regressors:
  - Demand (inflow), upstream delay, headway, dwell, distance, period of the day
- Generalized Additive Models (GAMs) were also used for potential nonlinear correlations.
- Specification controls:
  - heteroskedasticity checks, skew-reduction transforms

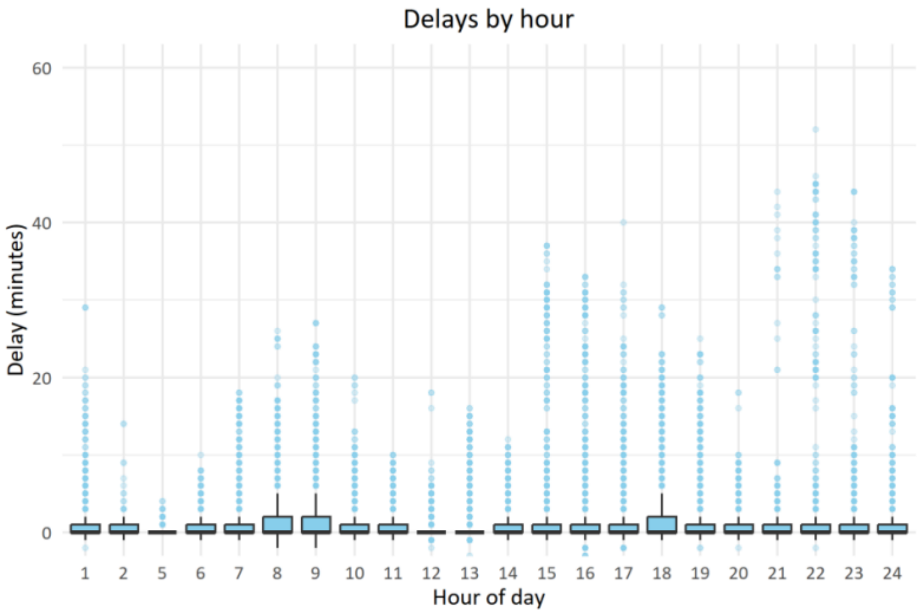
3. Results

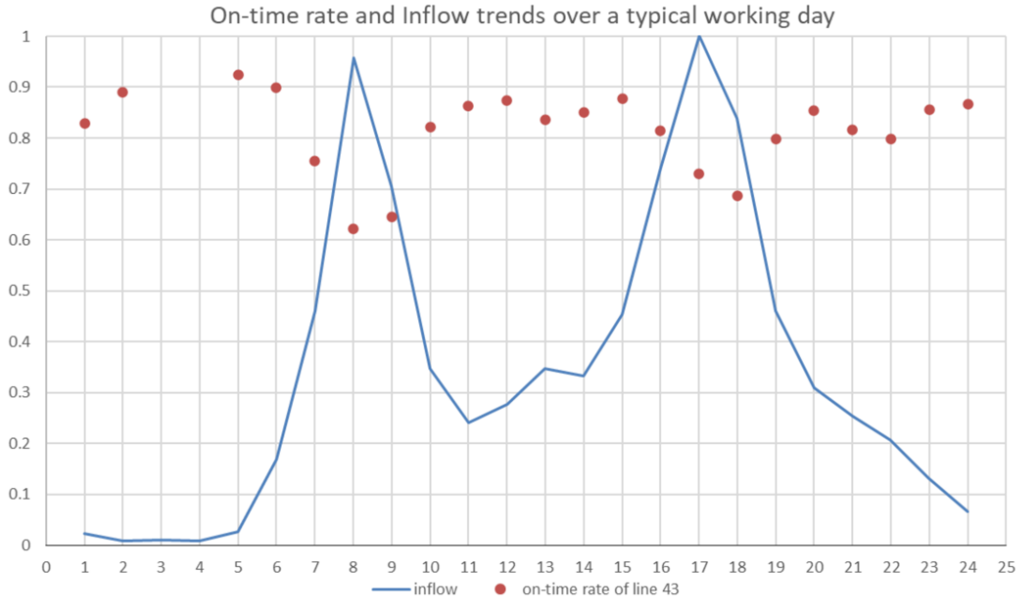
a) Descriptive statistics
b) Empirical results
c) Delay variability (& TI)

3.a) Descriptive statistics

- On-time performance (vs demand)
  - quieter mid-day; outliers late evening
  - two clear peaks (AM & PM);
  - lower OTP when relative inflow is high

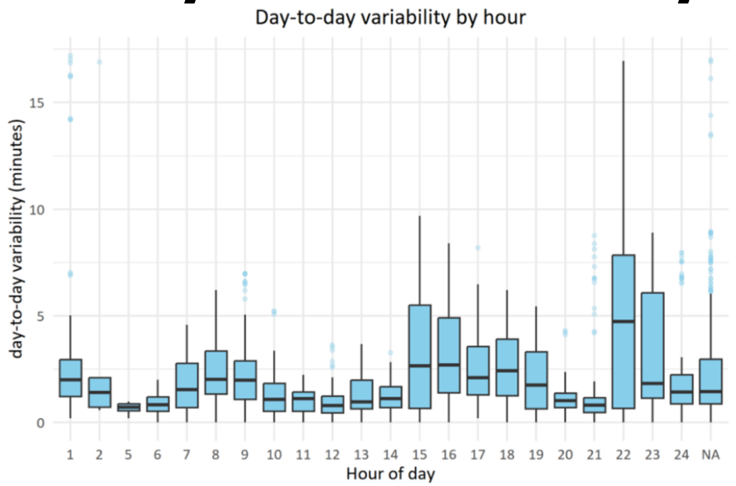


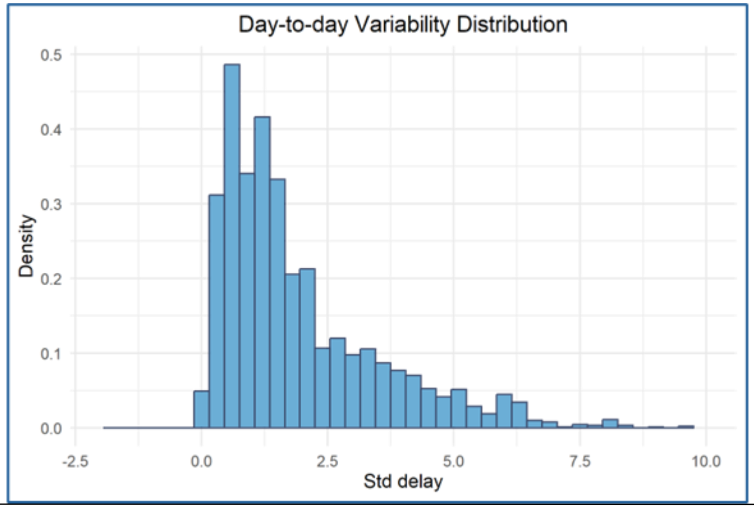


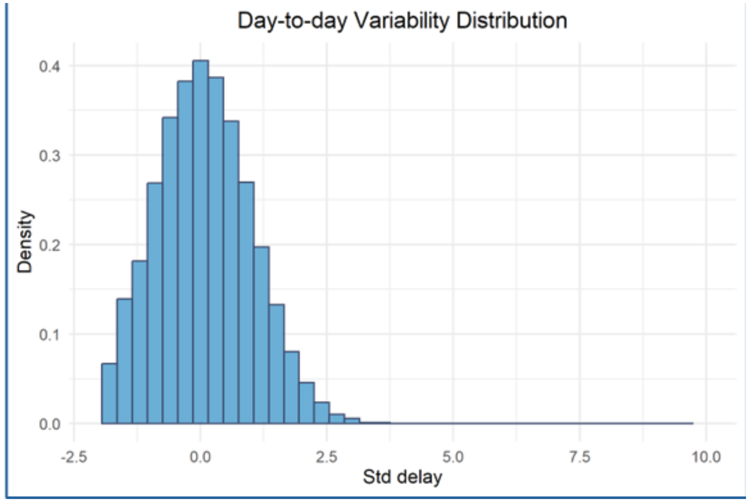


3.a) Descriptive statistics: day-to-day variability

- Day-to-day variability distribution:
  - Lower outside peaks; outliers late evening
  - right-skewed with a long tail (from late services)
- Need for nonlinear transformations







3.b) Results: Departure delay

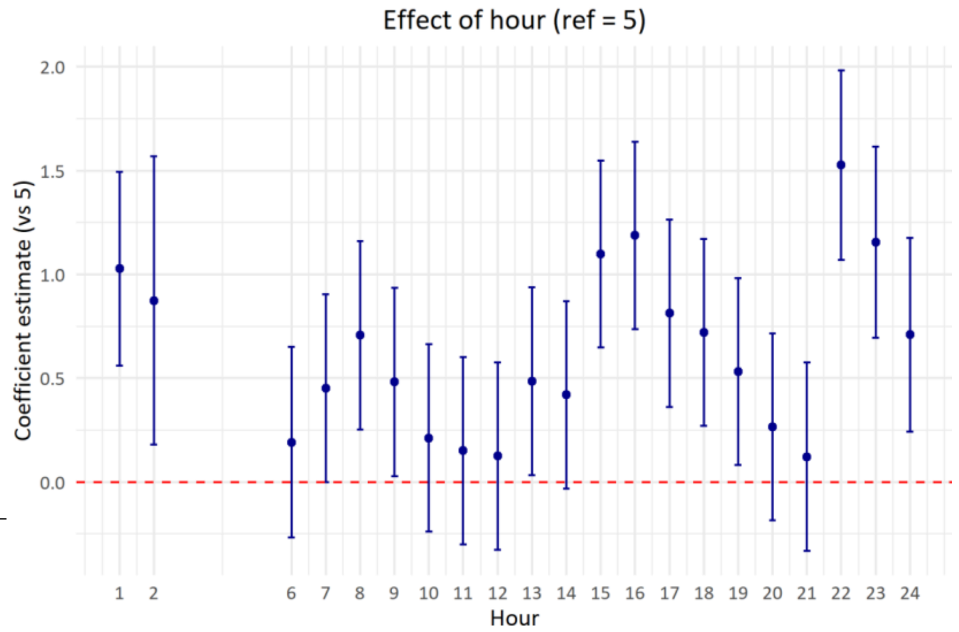
- **Passengers (inflow)**
  - higher relative inflow → higher departure delay
  - Due to longer dwell times (strongest in AM peak)
- **Propagation dominates**
  - larger upstream delay → higher departure delay at current stop
- **Other factors**
  - More tracks and longer scheduled headway and dwell times reduces delay

	Model 1.1
Relative inflow	0.252*** (0.022)
Previous delay	0.608*** (0.003)
Day period - evening	x
Day period - afternoon	x
Day period – morning	x
Number of tracks	-0.020*** (0.003)
Transfer station	0.243***(0.006)
Multimodal hub	-0.156***(0.011)
Distance travelled	0.001*** (0.0001)
Scheduled headway	-0.015***(0.004)
(Scheduled headway)^2	0.002***(0.00005)
Scheduled dwell time	-0.104*** (0.0154)
Relative inflow x scheduled headway	-0.005*** (0.0006)

3.b) Results: Day-to-day variability

- OTP as a proxy for upstream delay
- **Demand**
  - U-shaped relation
    - Low and high inflow → more variability
- **Other factors**
  - Time of the day
  - Higher variability on services with longer distance and longer headways

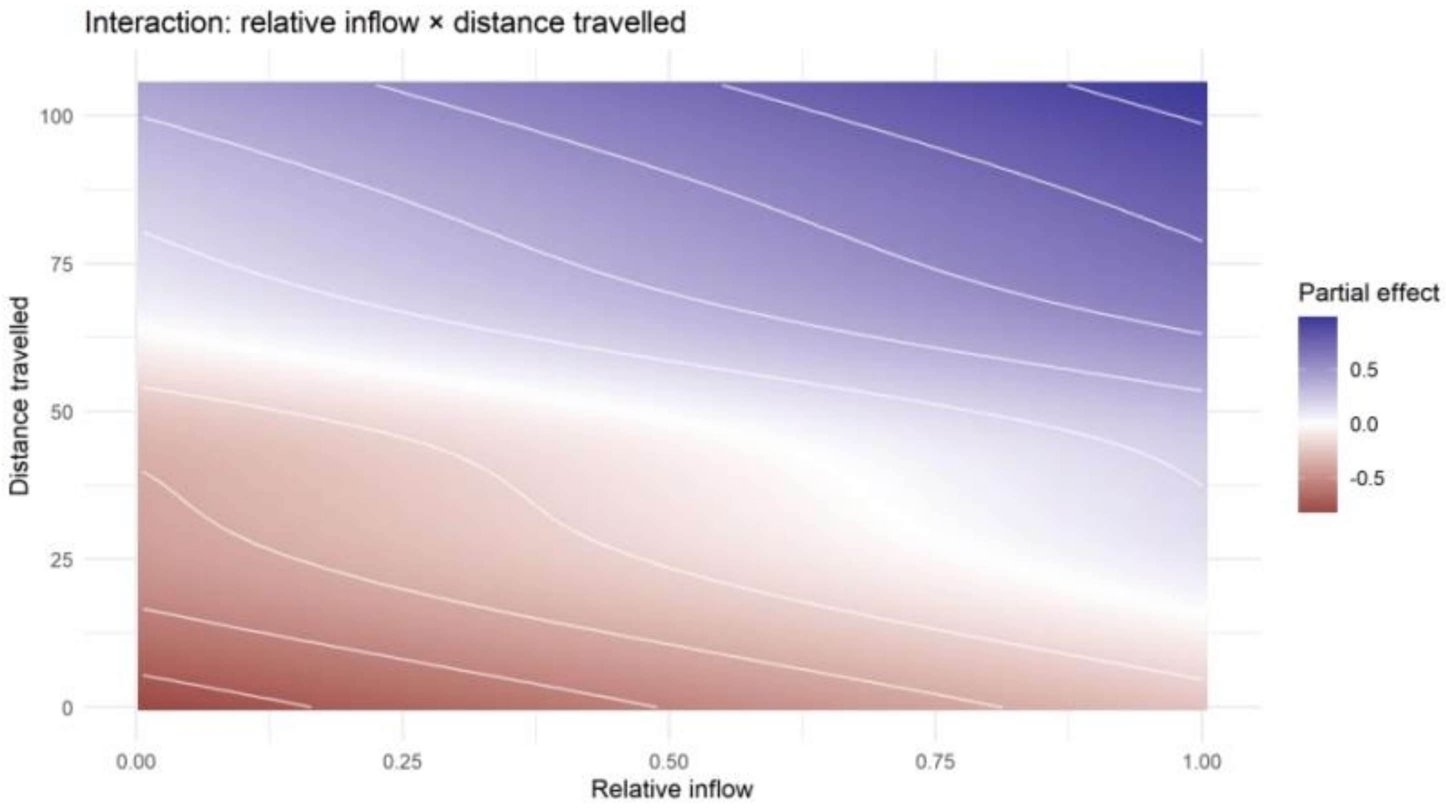
	Model 2.1
(relative inflow)^2	0.470 * (0.024)
OTP	-2.888 *** (0.126)
Number of tracks	0.124 *** (0.037)
Transfer station	0
Multimodal hub	0
Distance travelled	0.011 *** (0.000)
Scheduled headway	0.014 ** (0.001)
Relative inflow x scheduled headway	x
Relative inflow x transfer station	0.291*(0.145)
Relative inflow x multimodal hub	0.593*(0.287)



3.c) Delay variability (& TI)

- After a certain threshold of demand and/or travelled distance
  - High delay variability

- Where/when to prioritized TI



4. Conclusions

a) Highlights

b) Next steps

4.a) Highlights

- Demand amplifies delay, especially with short headways and upstream delay
- **Day-to-day variability**
  - Peaks in PM (14–19) and late evening (21–23)
  - Grows with travelled distance
  - U-shape vs inflow (higher at very low and very high inflow)
- **Summary**
  - if (high inflow ∧ short headway ∧ upstream delay), need for prioritized TI & ops management

4.b) Next step(s)

- **Data**
  - more lines/periods
  - add weather/incidents and
  - More passenger data: Onboard/exits, day-to-day variation.
- Test other **passenger punctuality metrics**
  - e.g., Excess Waiting Time (EWT), travel time reliability buffer
- **Methodology**: explore other specifications, e.g., instrumental variables.
- Other possible **applications**: Headway management (e.g., balancing headway regularity vs. dwell extensions)

Thank you!

Questions?

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Backup slide: regression results

Table 4. Delay per departure coefficient table

	Model 1.1	Model 1.2	Model 1.3	Model 1.4
Relative inflow	0.252*** (0.022)	0.0628*** (0.010)	0.015*** (0.025)	-0.192*(0.094)
Previous delay	0.608*** (0.003)	0.572*** (0.004)	0.606***(0.003)	0.609***(0.003)
Day period - evening	x	x	x	0.040**(0.016)
Day period - afternoon	x	x	x	0.031*(0.015)
Day period – morning	x	x	x	0
Number of tracks	-0.020*** (0.003)	-0.020***(0.003)	-0.024***(0.003)	-0.089***(0.003)
Transfer station	0.243***(0.006)	0.241***(0.006)	0.244***(0.006)	0.255***(0.006)
Multimodal hub	-0.156***(0.011)	-0.154*** (0.011)	-0.157*** (0.011)	-0.139***(0.012)
Distance travelled	0.001*** (0.0001)	0.0007***(0.00009)	0.0008***(0.00009)	x
Scheduled headway	-0.015***(0.004)	-0.016***(0.005)	-0.017***(0.004)	-0.017***(0.004)
(Scheduled headway)^2	0.002***(0.00005)	0.003***(0.00006)	0.002***(0.00005)	0.004***(0.00006)
Scheduled dwell time	-0.104*** (0.0154)	-0.101*** (0.0150)	-0.104*** (0.0153)	-0.103*** (0.0154)
Relative inflow x scheduled headway	-0.005*** (0.0006)	x	x	x
Relative inflow x previous delay	x	0.103*** (0.009x)	x	x
Relative inflow x number of tracks	x	x	0.036***(0.010)	x
Relative inflow x evening	x	x	x	0
Relative inflow x morning	x	x	x	0.296**(0.095)
Relative inflow x afternoon	x	x	x	0.223*(0.094)
Adjusted R-squared	0.443	0.444	0.443	0.445

*** p < 0.001 ; ** p < 0.01 ; * p < 0.05 - standard errors in parentheses

Backup slide: regression results

Table 5. Day-to-day variability coefficient table

	Model 2.1	Model 2.2	Model 2.3
(relative inflow)^2	0.470 * (0.024)	0.584 * (0.071)	0.51 ** (0.014)
OTP	-2.888 *** (0.126)	-2.924 *** (0.125)	-2.896 ***(0.126)
Number of tracks	0.124 *** (0.037)	0.120 **(0.037)	0.118 ***(0.037)
Transfer station	0	0.138 ***(0.040)	0.123 ***(0.040)
Multimodal hub	0	0	0
Distance travelled	0.011 *** (0.000)	0.012***(0.000)	0.011 ***(0.0007)
Scheduled headway	0.014 ** (0.001)	0.016***(0.002)	0
Relative inflow x scheduled headway	x	x	-0.009**(0.004)
Relative inflow x transfer station	0.291*(0.145)	x	x
Relative inflow x multimodal hub	0.593*(0.287)	x	x
Relative inflow x evening	x	x	0
Relative inflow x afternoon	x	x	0.198**(0.089)
Relative inflow x morning	x	x	0.264*(0.095)
Adjusted R-squared	0.459	0.457	0.442

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ - standard errors in parentheses

Backup slide: Transformations

D.1 Yeo-Johnson transformation

$$\varphi(y,\lambda)=\begin{cases}\dfrac{(y+1)^{\lambda}-1}{\lambda} & \lambda\neq 0, y\geq 0\\ \log(y+1) & \lambda=0, y\geq 0\\ -\dfrac{\left[(-y+1)^{2-\lambda}-1\right]}{2-\lambda} & \lambda\neq 2, y<0\\ -\log(-y+1) & \lambda=2, y<0\end{cases}$$

Where λ is a transformation parameter estimated from the data (Datacamp, 2025).

D.2 Ordered Quantile normalization (orderNorm)

$$g(x)=\Phi^{-1}((rank(x)-.5)/(length(x)))$$

Where Φ refers to the standard normal cdf, rank(x) refers to each observation's rank, and length(x) refers to the number of observations (Peterson, 2023).
Appendix E. Regression results additional figures