

# AN EFFICIENT EVALUATION SCHEME FOR KPIs IN REGULATED URBAN TRAIN SYSTEMS

B. ADELIN<sup>1</sup>, P. DERSIN<sup>1</sup>, É. FABRE<sup>2</sup>, L. HÉLOUËT<sup>2</sup> and K. KECIR<sup>1,2</sup>

International Conference  
Reliability, Safety and Security of Railway Systems:  
Modelling, Analysis, Verification and Certification

November 14-16, 2017  
Pistoia, ITALY

<sup>1</sup>ALSTOM, FRANCE

<sup>2</sup>INRIA RENNES – BRETAGNE ATLANTIQUE, FRANCE



## Context

Rail systems are subject to **disturbances**.



(a) Signaling sys. failure



(b) Passenger blocking doors



(c) Bad weather cond.

Bad QoS:

- trains are **delayed** and **more crowded**
- ☺ passengers

QoS requirements:

UITP\* defines

**Key Performance Indicators (KPIs)**

Non-compliance → financial penalties



Figure: Crowded station

\*International association for public transports

## Context (cont.)

Examples of KPIs:



(a) Punctuality



(b) Regularity

$$P = \frac{|\# \text{ trips delayed by } +\text{than } x \text{ t.u.}|}{|\# \text{ trips}|} ; \quad R = \frac{|\# \text{ deps. meeting ref. headways w/ precision of } x \text{ t.u.}|}{|\# \text{ departures}|}$$



Figure: Traffic regulators

# Timetables

A timetable: an **idealized** representation of an execution of the system.

## Timetable:

- departures
- arrivals

## Uses:

- Passenger information
- Regulation
- Logs

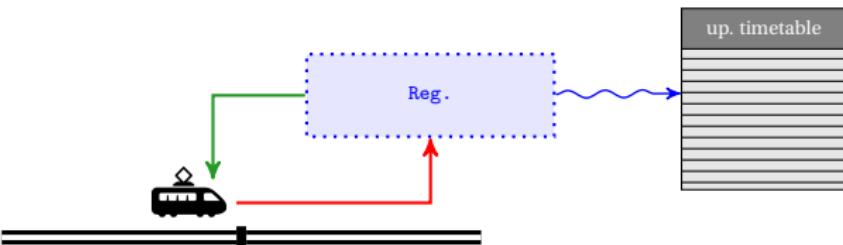
## Objective of regulation:

→ stick to a reference timetable.

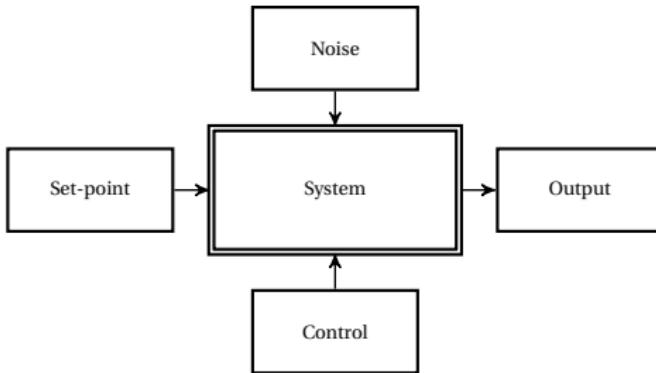
		Monday to Friday			
		ARR	DEP	ARR	DEP
Wheatsheaf Accessible Services		0.00	0.00	12.26	0.47
Mornington Station (Mornington)		0.00	0.00	0.23	0.41
Prairie Creek Station (Mornington)		0.00	0.00	0.23	0.41
Prairie Creek Station (Melbourne City)		0.00	0.00	0.23	0.41
Parliament Station (Melbourne City)		0.00	0.00	0.23	0.41
Hoppers Crossing Station (Hoppers Crossing)		0.00	0.00	0.23	0.41
Princes Street Station (Melbourne City)		0.00	0.00	0.23	0.41
Heidelberg Station (Heidelberg)		0.00	0.00	0.23	0.41
Heidelberg Station (Melbourne City)		0.00	0.00	0.23	0.41
North Melbourne Station (Near Melbourne)		0.00	0.00	0.23	0.41
North Melbourne Station (Melbourne City)		0.00	0.00	0.23	0.41
Yarraville Station (Yarraville)		0.13	0.28	0.28	0.43
Yarraville Station (Melbourne City)		0.13	0.28	0.28	0.43
West Footscray Station (Footscray)		0.14	0.32	0.30	0.47
West Footscray Station (Melbourne City)		0.14	0.32	0.30	0.47
Footscray Station (Footscray)		0.15	0.33	0.30	0.48
Footscray Station (Melbourne City)		0.15	0.33	0.30	0.48
Yarraville Station (St Kilda)		0.16	0.34	0.32	0.49
Yarraville Station (Melbourne City)		0.16	0.34	0.32	0.49
Werribee Station (Werribee)		0.22	0.40	0.38	0.56
Werribee Station (Melbourne City)		0.22	0.40	0.38	0.56
Pennington Station (Pennington)		0.24	0.44	0.40	0.58
Pennington Station (Melbourne City)		0.24	0.44	0.40	0.58
Altona Station (Altona)		0.31	0.40	0.47	0.61
Altona Station (Melbourne City)		0.31	0.40	0.47	0.61
Clayton Station (Clayton)		0.35	0.52	0.51	0.75
Clayton Station (Melbourne City)		0.35	0.52	0.51	0.75
Broadmeadows Station (Broadmeadows)		0.35	0.52	0.51	0.75
Broadmeadows Station (Melbourne City)		0.35	0.52	0.51	0.75
RodHugh Park Station (RodHugh Park)		0.42	0.60	0.58	0.84
RodHugh Park Station (Melbourne City)		0.42	0.60	0.58	0.84
Craigieburn Station (Craigieburn)		0.46	0.64	0.62	0.88

		Monday to Friday			
		ARR	DEP	ARR	DEP
Wheatsheaf Accessible Services		0.00	0.00	12.26	0.47
Mornington Station (Mornington)		0.00	0.00	0.23	0.41
Prairie Creek Station (Mornington)		0.00	0.00	0.23	0.41
Prairie Creek Station (Melbourne City)		0.00	0.00	0.23	0.41
Parliament Station (Melbourne City)		0.00	0.00	0.23	0.41
Hoppers Crossing Station (Hoppers Crossing)		0.00	0.00	0.23	0.41
Princes Street Station (Melbourne City)		0.00	0.00	0.23	0.41
Heidelberg Station (Heidelberg)		0.00	0.00	0.23	0.41
Heidelberg Station (Melbourne City)		0.00	0.00	0.23	0.41
North Melbourne Station (Near Melbourne)		0.00	0.00	0.23	0.41
North Melbourne Station (Melbourne City)		0.00	0.00	0.23	0.41
Yarraville Station (Yarraville)		0.13	0.28	0.28	0.43
Yarraville Station (Melbourne City)		0.13	0.28	0.28	0.43
West Footscray Station (Footscray)		0.14	0.32	0.30	0.47
West Footscray Station (Melbourne City)		0.14	0.32	0.30	0.47
Footscray Station (Footscray)		0.15	0.33	0.30	0.48
Footscray Station (Melbourne City)		0.15	0.33	0.30	0.48
Yarraville Station (St Kilda)		0.16	0.34	0.32	0.49
Yarraville Station (Melbourne City)		0.16	0.34	0.32	0.49
Werribee Station (Werribee)		0.22	0.40	0.38	0.56
Werribee Station (Melbourne City)		0.22	0.40	0.38	0.56
Pennington Station (Pennington)		0.24	0.44	0.40	0.58
Pennington Station (Melbourne City)		0.24	0.44	0.40	0.58
Altona Station (Altona)		0.31	0.40	0.47	0.61
Altona Station (Melbourne City)		0.31	0.40	0.47	0.61
Clayton Station (Clayton)		0.35	0.52	0.51	0.75
Clayton Station (Melbourne City)		0.35	0.52	0.51	0.75
Broadmeadows Station (Broadmeadows)		0.35	0.52	0.51	0.75
Broadmeadows Station (Melbourne City)		0.35	0.52	0.51	0.75
RodHugh Park Station (RodHugh Park)		0.42	0.60	0.58	0.84
RodHugh Park Station (Melbourne City)		0.42	0.60	0.58	0.84
Craigieburn Station (Craigieburn)		0.46	0.64	0.62	0.88

Figure: Example of a timetable



# Objectives



## Goals:

- evaluation of KPIs
- evaluation of regulation algorithms

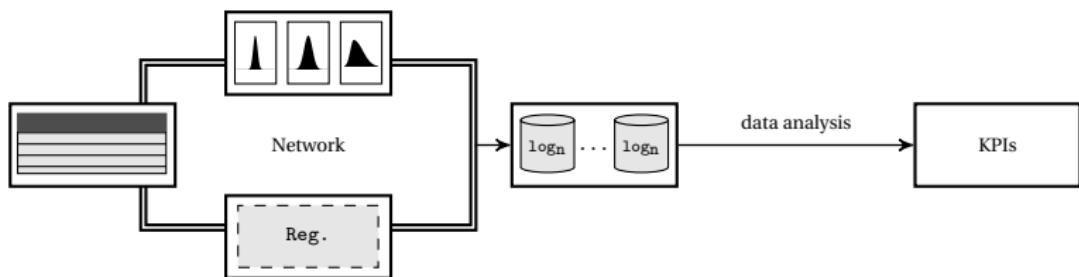
## Needs :

- realistic model with a good level of abstraction:  
→ tracks, trains, time, constraints, stochasticity...
- integration of real traffic control algorithms
- fast simulations → allow for Monte-Carlo

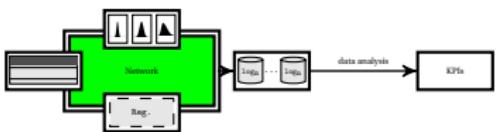
# Outline

- ① a model for simulation of urban rail systems
- ② performed experiences and results
- ③ future work and improvements

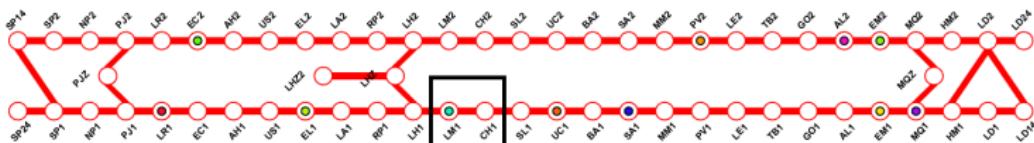
## Approach:



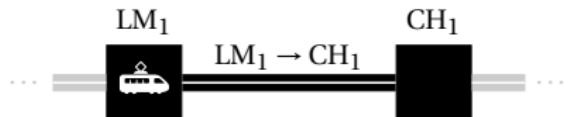
**a framework for evaluation of regulation techniques  
through the measurement of KPIs**



## Real topology:



## Portion of the network:

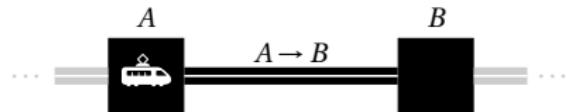


## Assumptions:

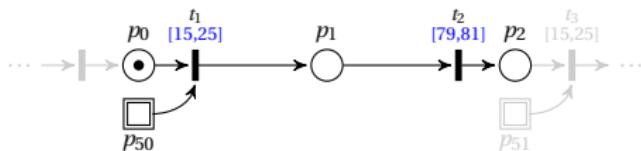
- fixed-block policy
- consider network constraints: min. dwell/run times, interlockings...

## Modeling (cont.)

**Network portion:**

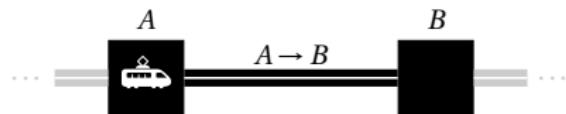


**Model equivalent:**

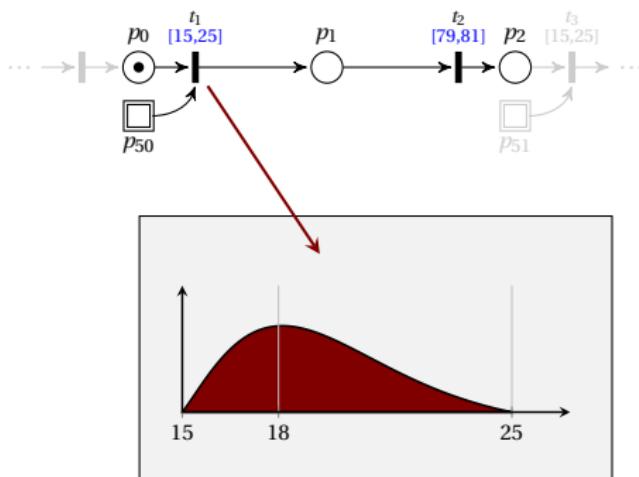


## Modeling (cont.)

**Network portion:**

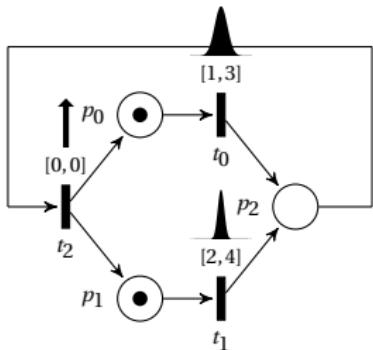


**Model equivalent:**



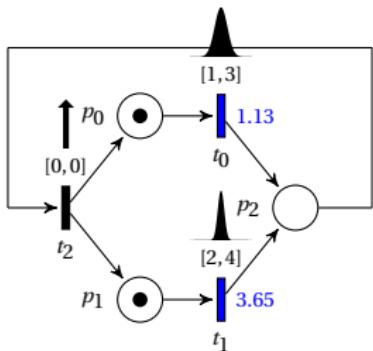
# Semantics

## Semantics of STPNs:



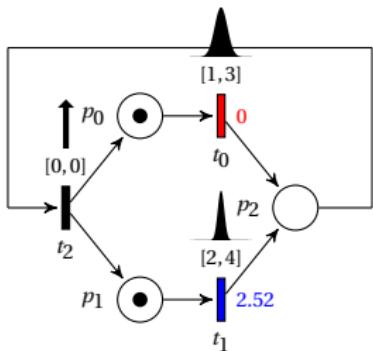
# Semantics

## Semantics of STPNs:



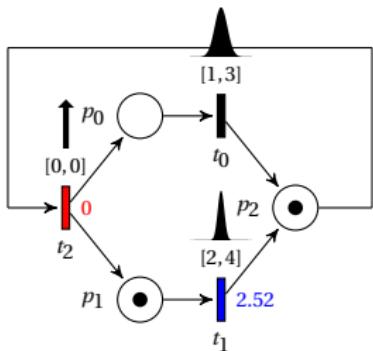
# Semantics

## Semantics of STPNs:



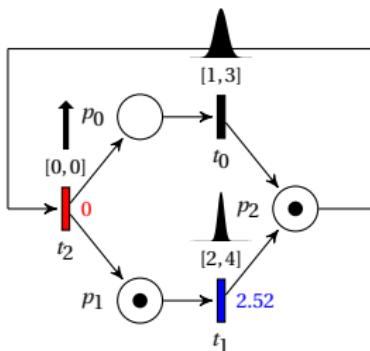
# Semantics

## Semantics of STPNs:

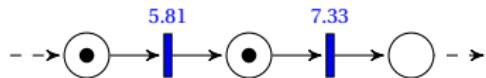


# Semantics

## Semantics of STPNs:

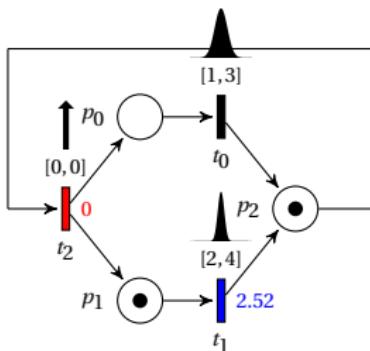


## Block occupation constraints:

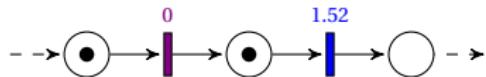


# Semantics

## Semantics of STPNs:

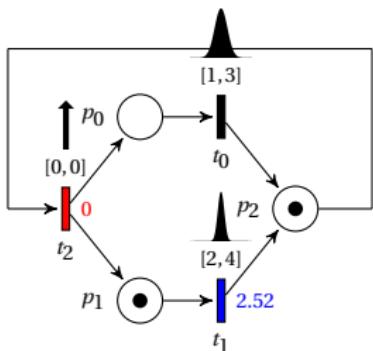


## Block occupation constraints:

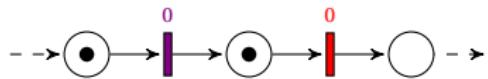


# Semantics

## Semantics of STPNs:

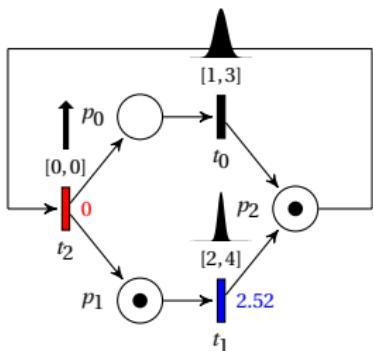


## Block occupation constraints:

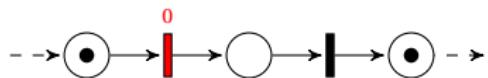


# Semantics

## Semantics of STPNs:

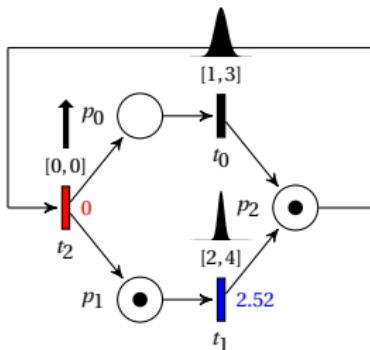


## Block occupation constraints:

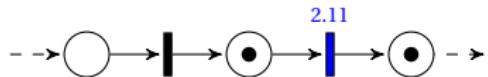


# Semantics

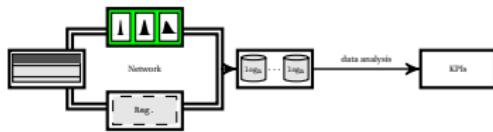
## Semantics of STPNs:



## Block occupation constraints:



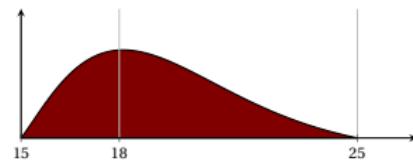
# Distributions



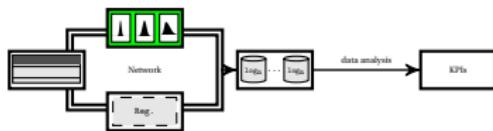
## Construction:

Exponential functions

$$f(x) = \begin{cases} \sum_{k=1}^K c_k \cdot x^{a_k} \cdot e^{-\lambda_k x} & \alpha < x < \beta \\ 0 & \text{otherwise} \end{cases}$$



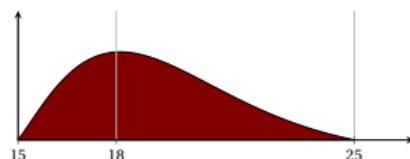
# Distributions



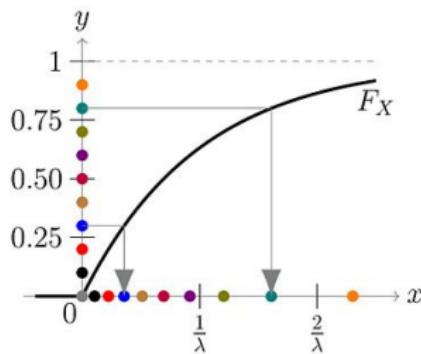
## Construction:

Exponential functions

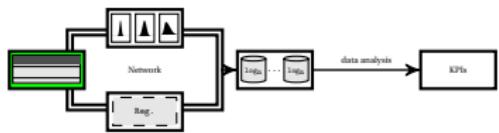
$$f(x) = \begin{cases} \sum_{k=1}^K c_k \cdot x^{a_k} \cdot e^{-\lambda_k x} & \alpha < x < \beta \\ 0 & \text{otherwise} \end{cases}$$



## Inverse transform sampling:

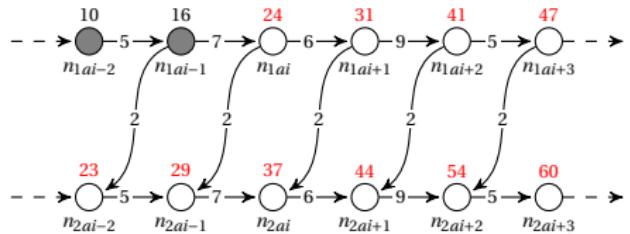


# Timetables

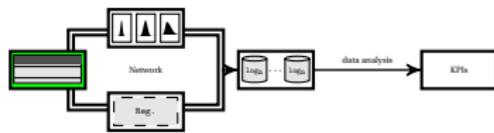


## Several timetables:

- **reference timetable:** target
- **active timetable:** execution + future

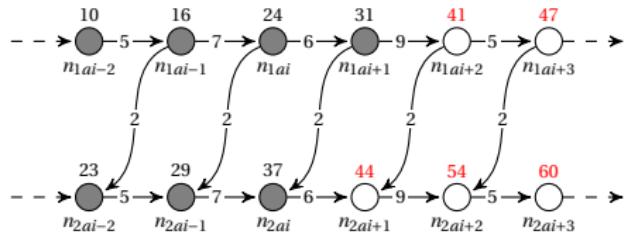


# Timetables

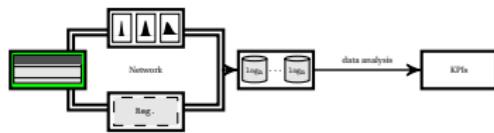


## Several timetables:

- **reference timetable:** target
- **active timetable:** execution + future

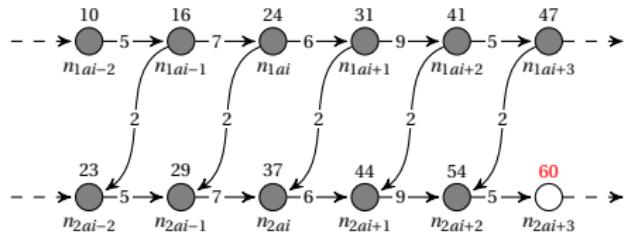


# Timetables

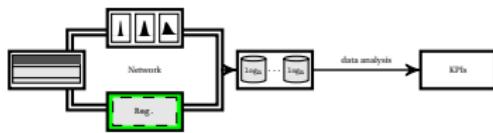


## Several timetables:

- **reference timetable:** target
- **active timetable:** execution + future

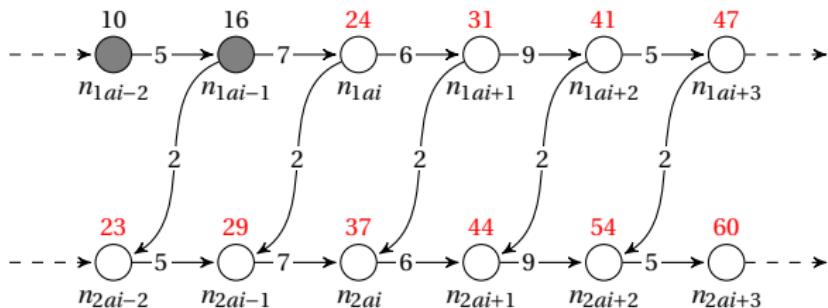


# Regulation module

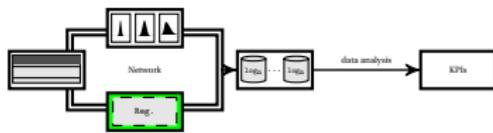


## ■ Regulation mode:

ASAP with change of dwell times

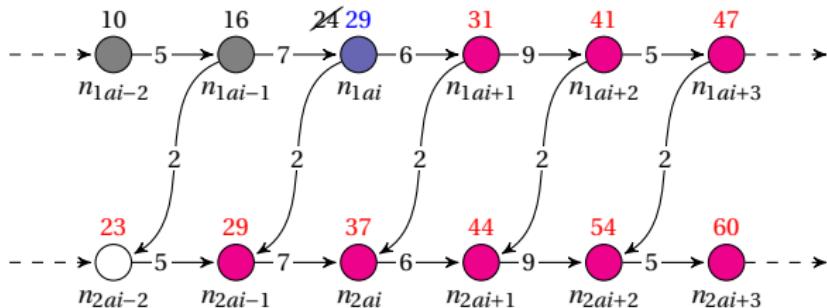


# Regulation module

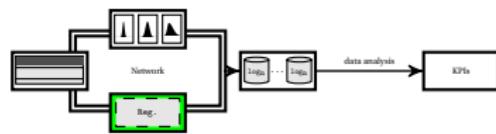


## ■ Regulation mode:

ASAP with change of dwell times

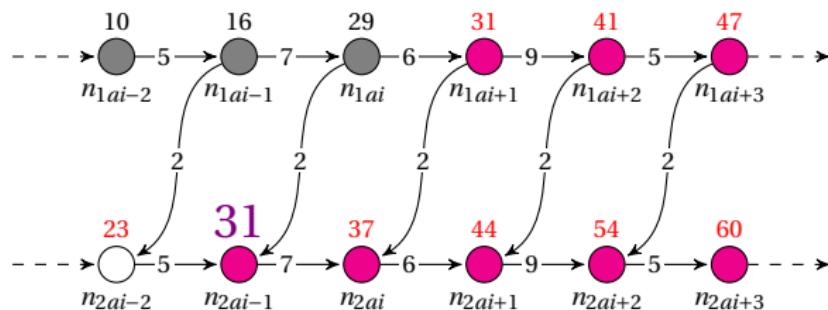


# Regulation module

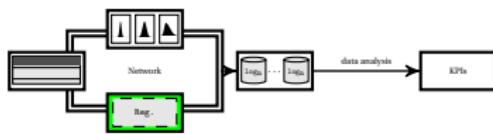


## ■ Regulation mode:

ASAP with change of dwell times

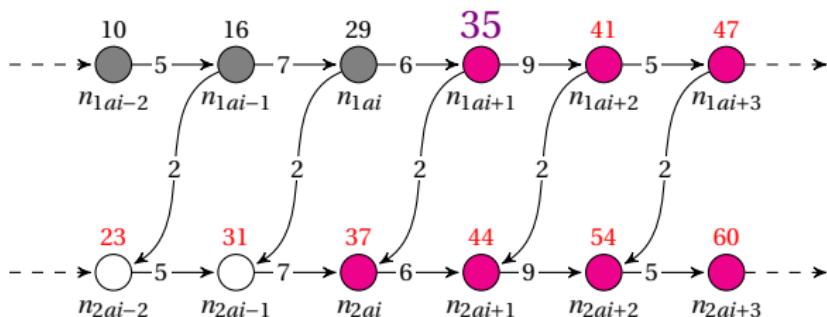


# Regulation module

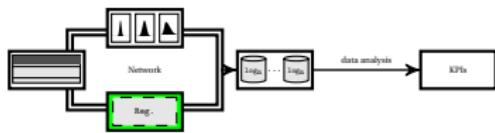


## ■ Regulation mode:

ASAP with change of dwell times

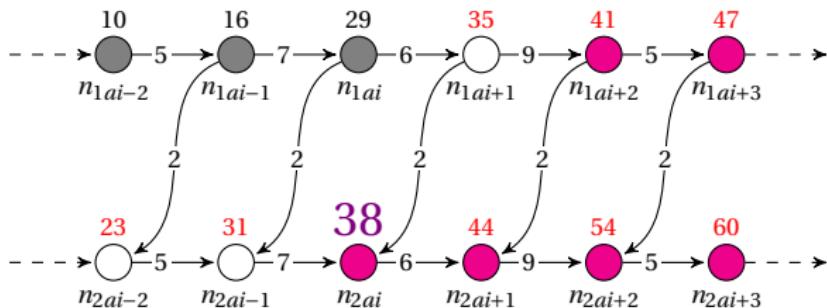


# Regulation module

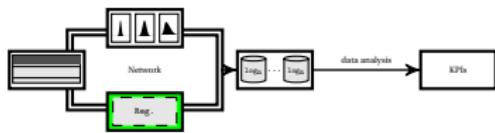


## ■ Regulation mode:

ASAP with change of dwell times

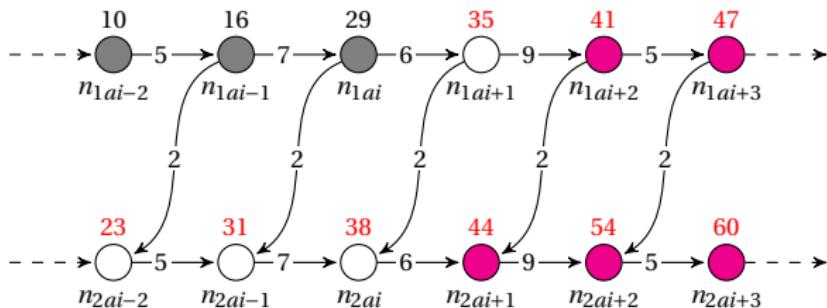


# Regulation module

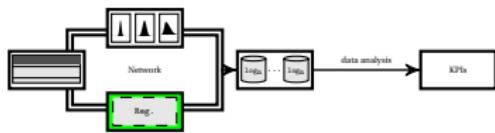


## ■ Regulation mode:

ASAP with change of dwell times

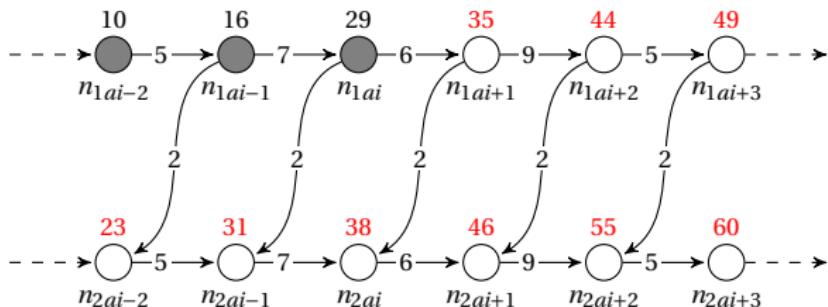


# Regulation module



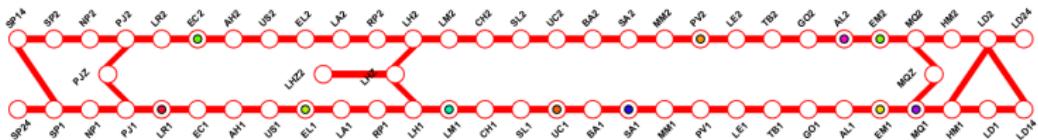
## ■ Regulation mode:

ASAP with change of dwell times



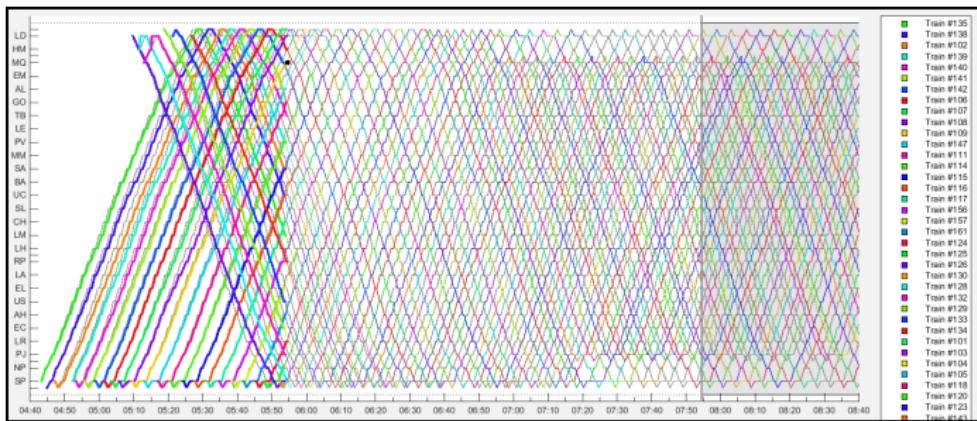
# Simulation

## ■ Real case: Santiago's metro, line 1



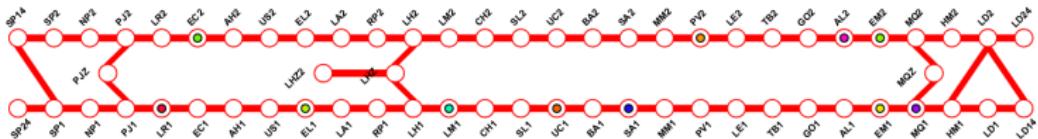
- intertwined loops topology
- 27 stations
- 50 trains

## Time-space graph:



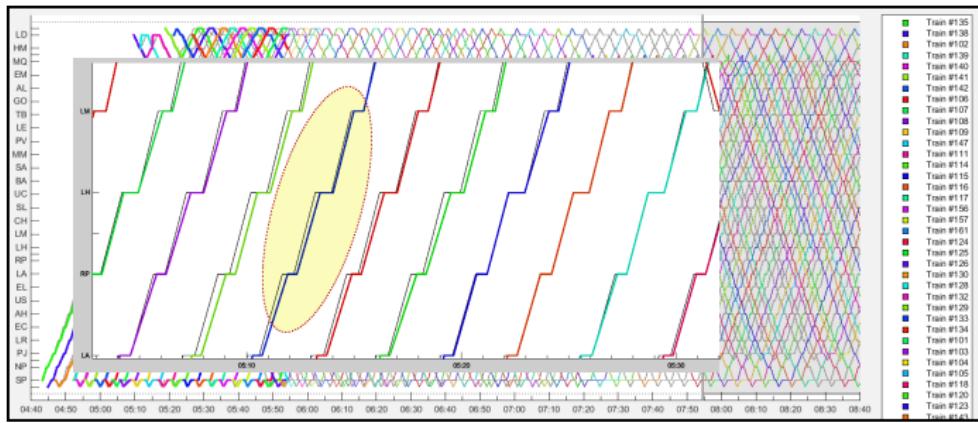
# Simulation

## ■ Real case: Santiago's metro, line 1



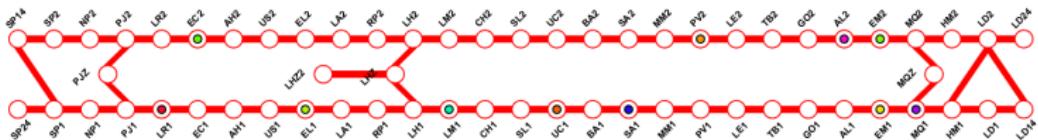
- intertwined loops topology
- 27 stations
- 50 trains

## Time-space graph:



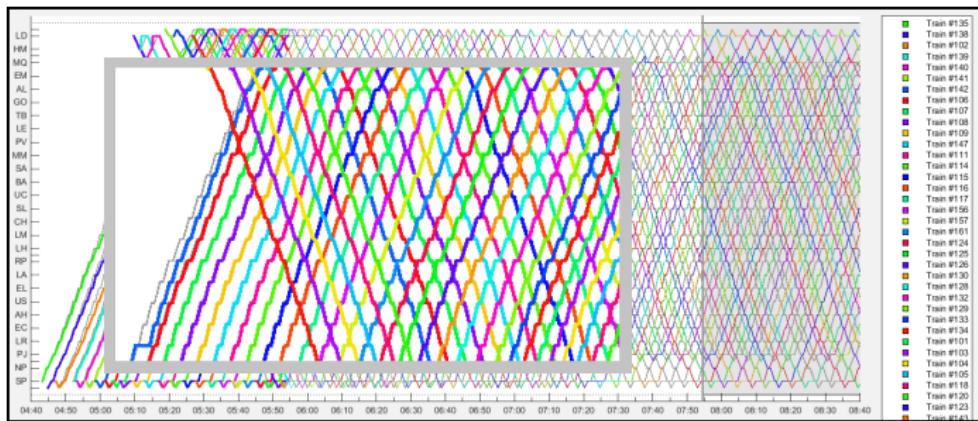
# Simulation

## ■ Real case: Santiago's metro, line 1

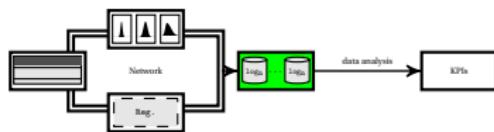


- intertwined loops topology
- 27 stations
- 50 trains

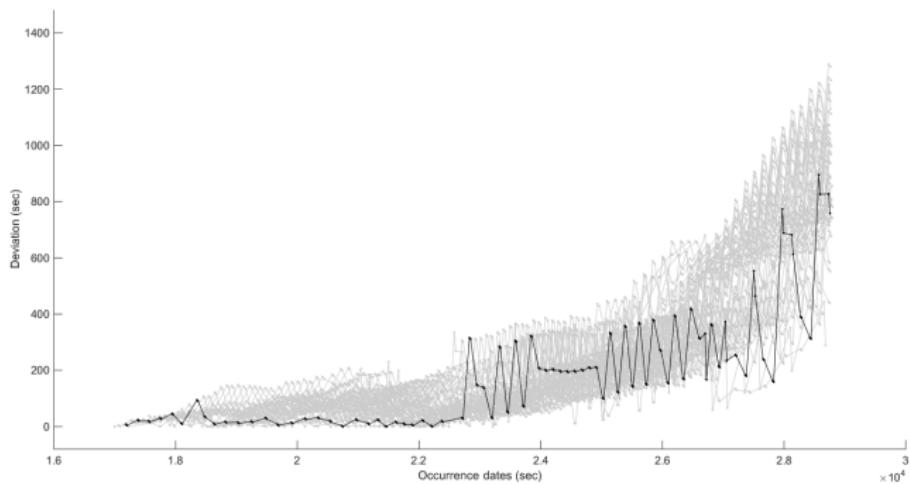
## Time-space graph:



## Simulation (cont.)



**Evolution of deviation (1 simulation - all stations)**



**Simulation speed:** 1 simulation in approx. 35s (w/o display).

# Monte-Carlo method

## Monte-Carlo simulation method:

→ an experimental method to estimate a value.

$X$ : random variable

$f_X(x)$ : probability density function (PDF) of  $X$

$F_X(x) = \mathbb{P}[x \leq X]$ : cumulative distribution function of  $X$

## Central Limit Theorem:

For  $X_1, X_2, \dots, X_n$  experiments when  $n \rightarrow +\infty$ ,

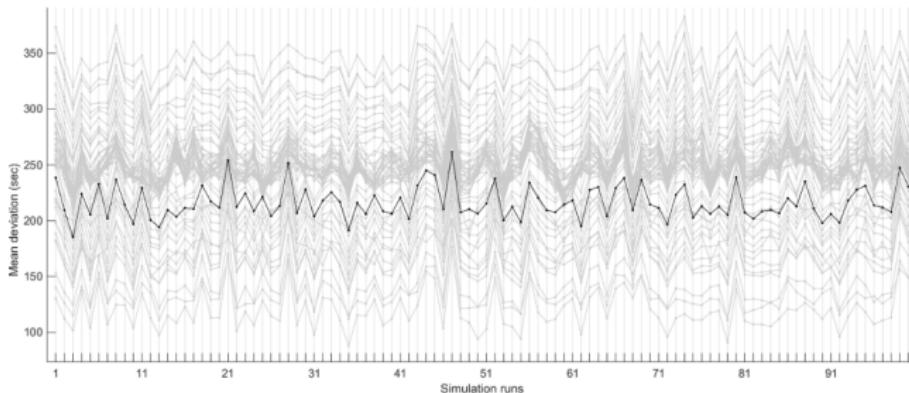
then the empirical mean  $\bar{X}_n = \frac{1}{n} \sum_{i=1}^n X_i$  tends towards  $E[X]$ .

## Can compute:

- a satisfactory empirical mean  $\bar{X}_n$
- a confidence interval  $[\alpha_n, \beta_n]$   
w/  $\alpha_n$  and  $\beta_n$  resp. upper and lower bounds of the interval
- a probability  $\mathbb{P}[E[X] \in [\alpha_n, \beta_n]]$  (precision)

# Simulation campaign

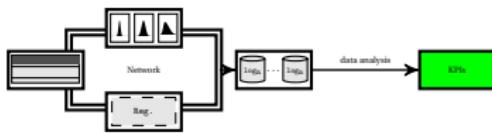
- $n = 100$  stochastic simulation runs:



**mean deviations between reference and observed departure dates  
for all stations**

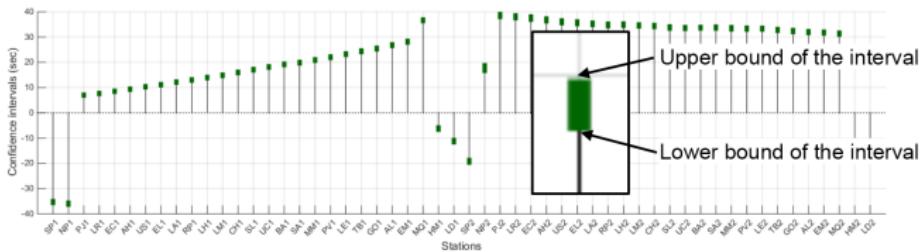
- stochastic simulation → different values
- calculating mean value is not sufficient

# Performance evaluation



## ■ Estimated parameter:

the mean headway deviation, a regularity indicator.



confidence intervals for deviation between  
reference and observed mean headways per station

## ■ Results:

- substantial disturbances → regulation failed to cope with delay
- observation of bunching phenomena

# Future work

## ■ Moving blocks:



# Future work

## ■ Moving blocks:



# Future work

## ■ Moving blocks:



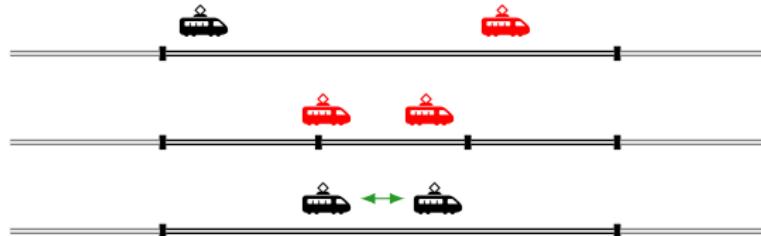
# Future work

## ■ Moving blocks:



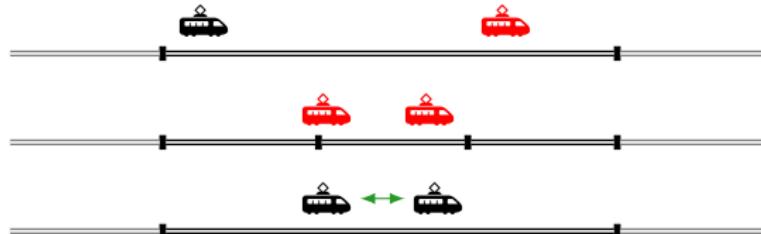
# Future work

## ■ Moving blocks:



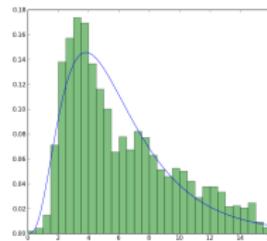
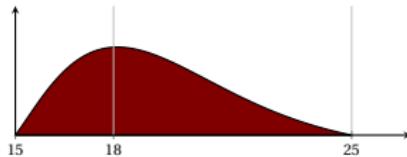
# Future work

## ■ Moving blocks:



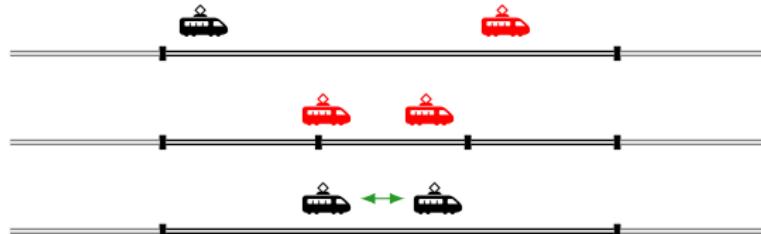
## ■ Distributions:

- learning from real data
- taking into account the non-markovian aspect of delays



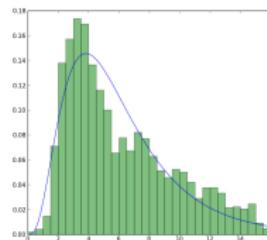
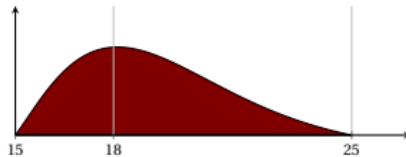
## Future work

### ■ Moving blocks:



### ■ Distributions:

- learning from real data
- taking into account the non-markovian aspect of delays



### ■ Regulation techniques:

- headway equalizing regulation, • mixed regulation (punctuality + regularity)
- progressive delay compensation, • objective regulation, • etc.