Traffic Flow Reconstruction

Corso di: Big Data Architectures

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Overview

Goal

- Obtain a **traffic reconstruction** in every road in **real-time**, at **low-cost**, using a general and self-adaptive model

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How

- Exploit a **fluid-dynamic model** adapted for the road network
- **Road graph** and possible **restriction** obtained from KM4City Knowledge Base, using Open Street Map data
- Traffic measurements from **IoT sensors** scattered over the municipality

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- **Open**: methods and software are made available under open licenses

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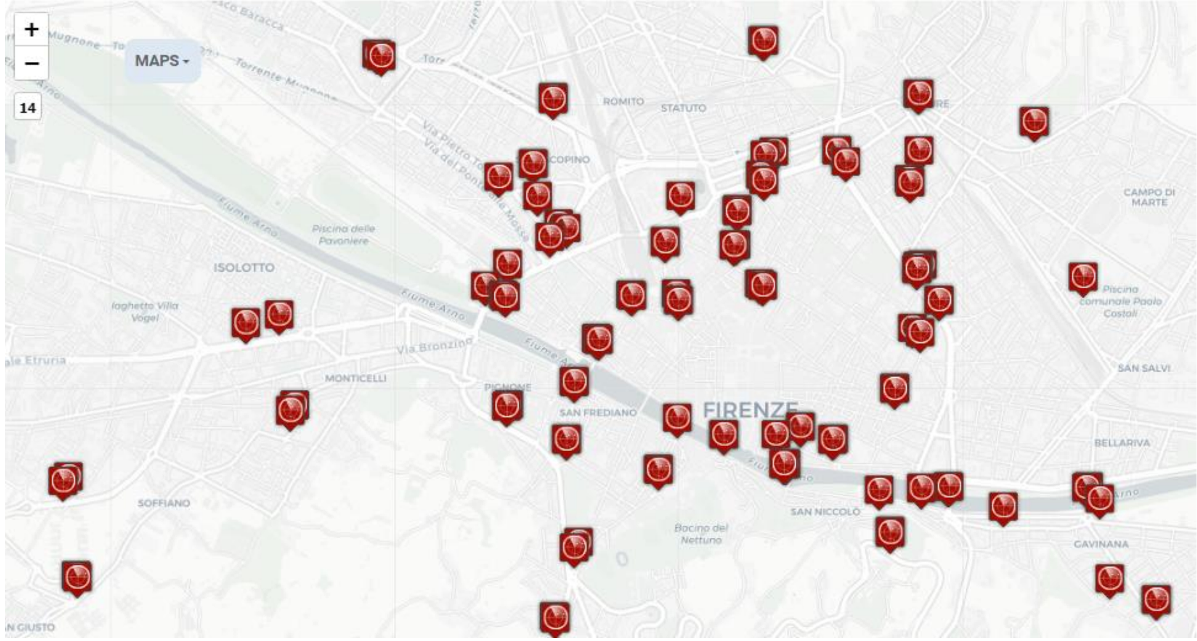
- Starting from fixed traffic sensors scattered in the city, our scope is the prediction/reconstruction of the real-time vehicular traffic density in the whole urban network.



https://www.snap4city.org/dashboardSmartCity/view/Gea.php?iddasboard=MzQ4OA==#

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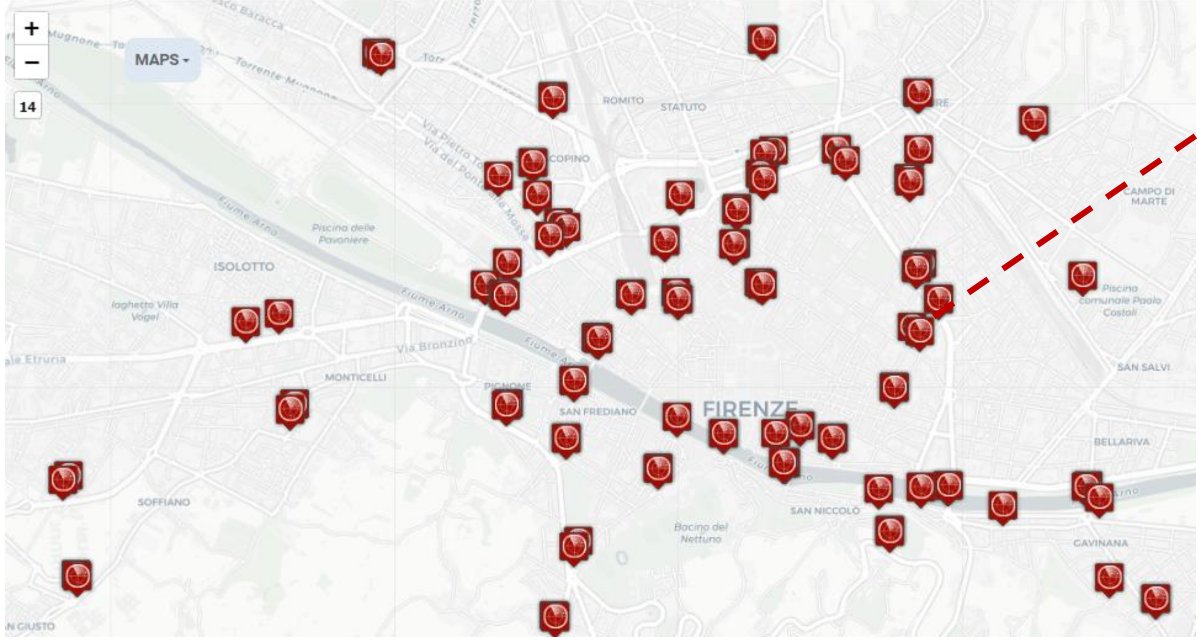

METRO20

VALUE NAME: METRO20

DETAILS | DESCRIPTION | RT DATA

Last update: 2023-11-05 11:40:00.000+01:00

Description	Value	Buttons						
anomalyLevel	0.57837826	Last	4h	24h	7d	30d	6m	1y
averageSpeed	29.225376	Last	4h	24h	7d	30d	6m	1y
avgTime	12.305	Last	4h	24h	7d	30d	6m	1y
concentration	8.514098	Last	4h	24h	7d	30d	6m	1y
congestionLevel	115.00001	Last	4h	24h	7d	30d	6m	1y
dateObserved	2023-11-05T10:40:00.000Z	Last	4h	24h	7d	30d	6m	1y
vehicleFlow	248.82773	Last	4h	24h	7d	30d	6m	1y

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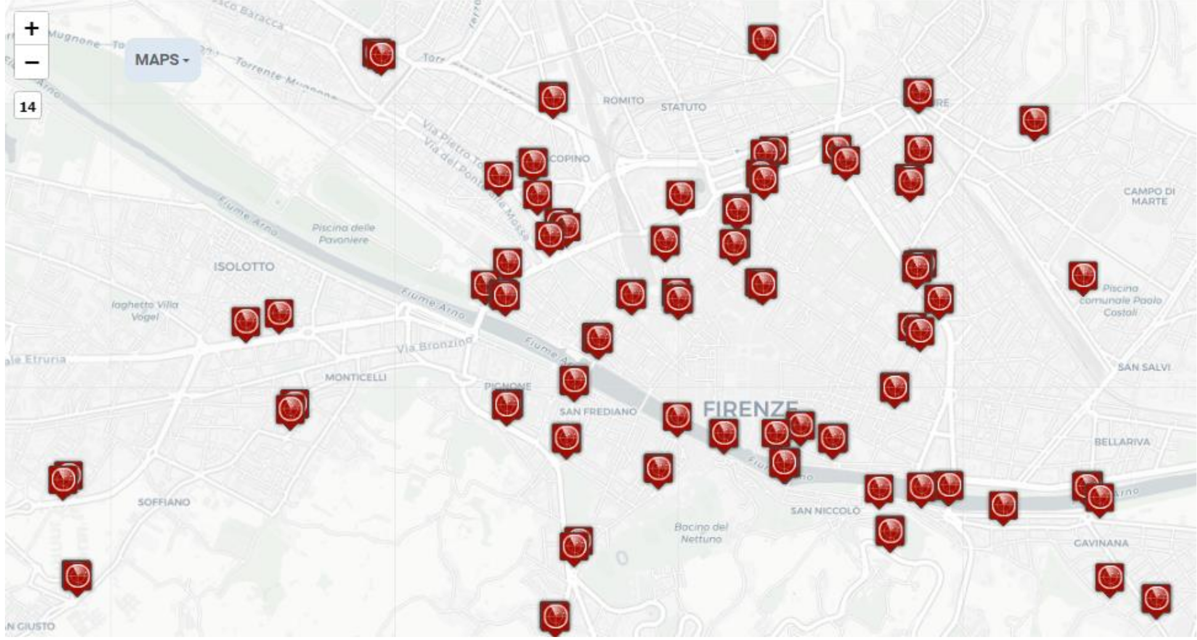

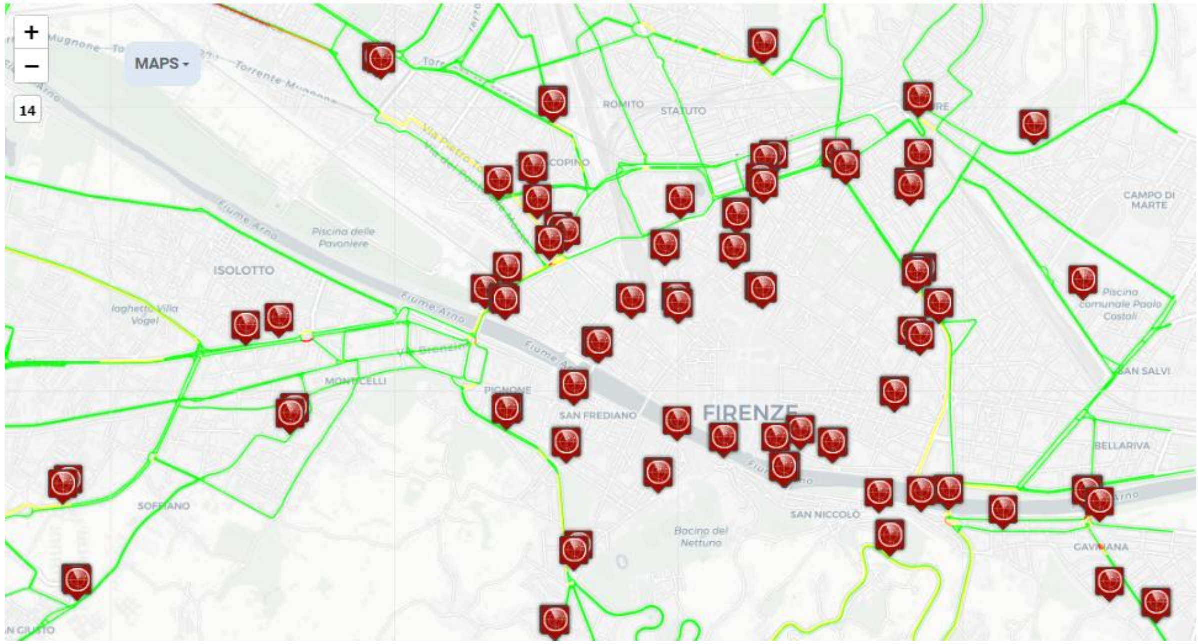

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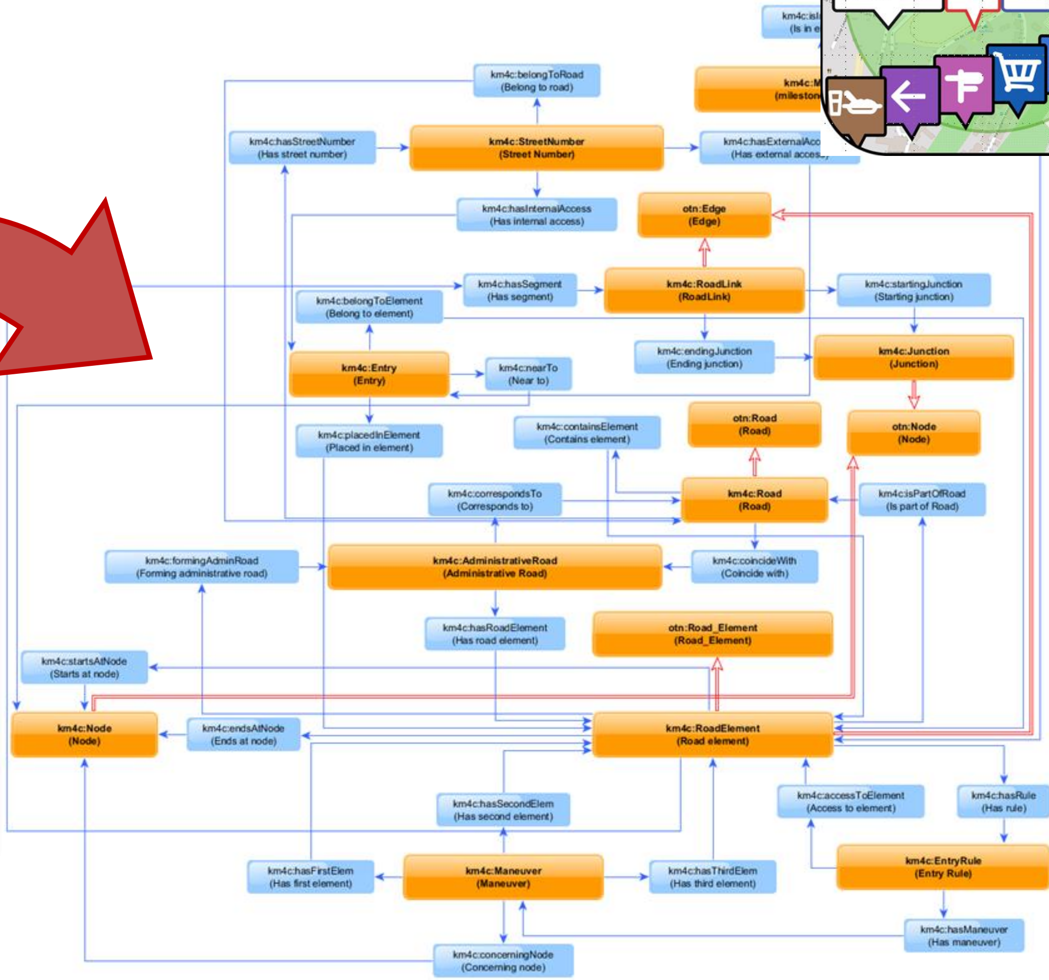
OSM to KM4City



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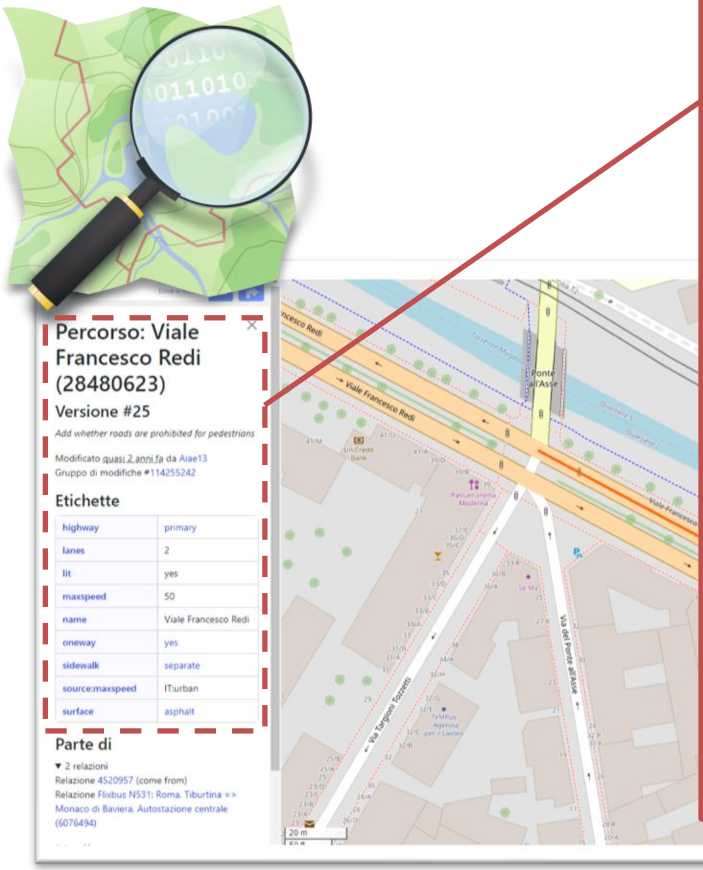


Percorso: Viale Francesco Redi (28480623)

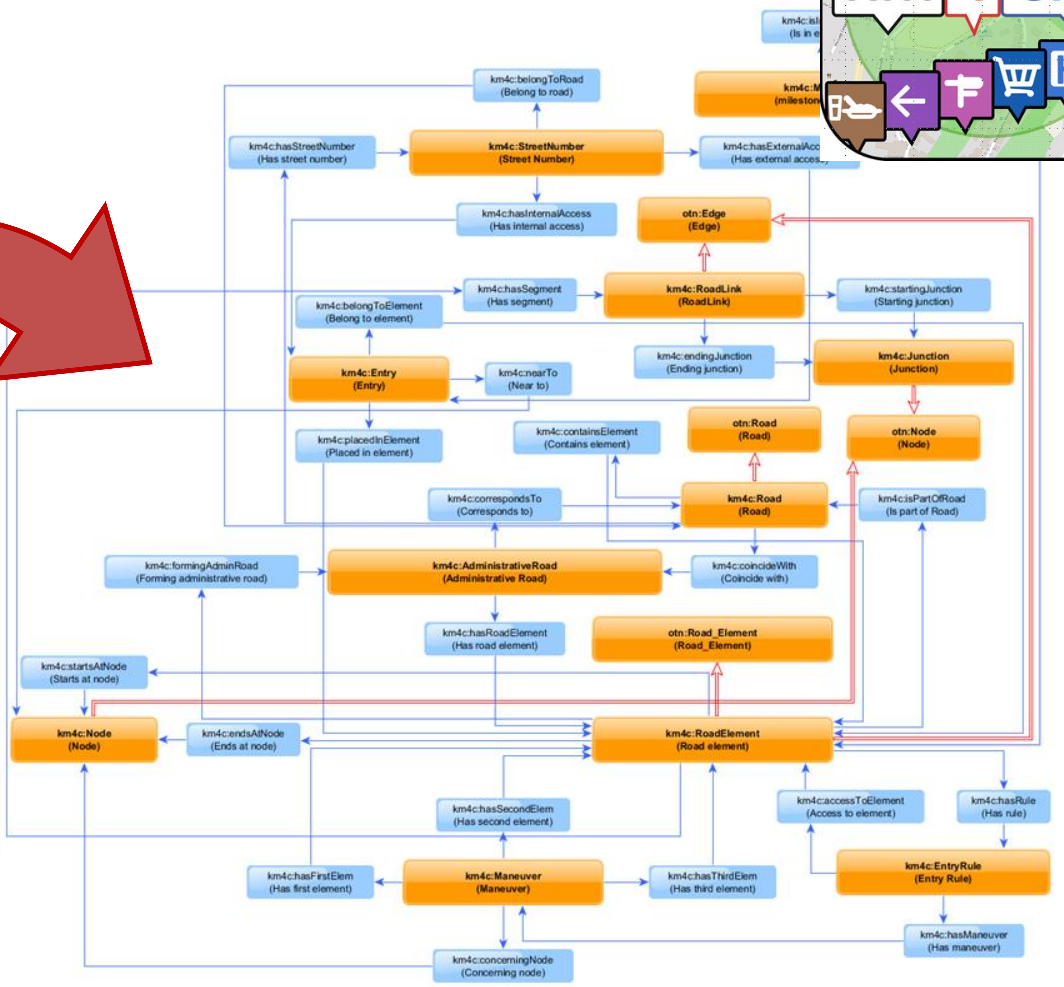
Versione #25

Add whether roads are prohibited for pedestrians

Modificato quasi 2 anni fa da Aiae13
Gruppo di modifiche #114255242

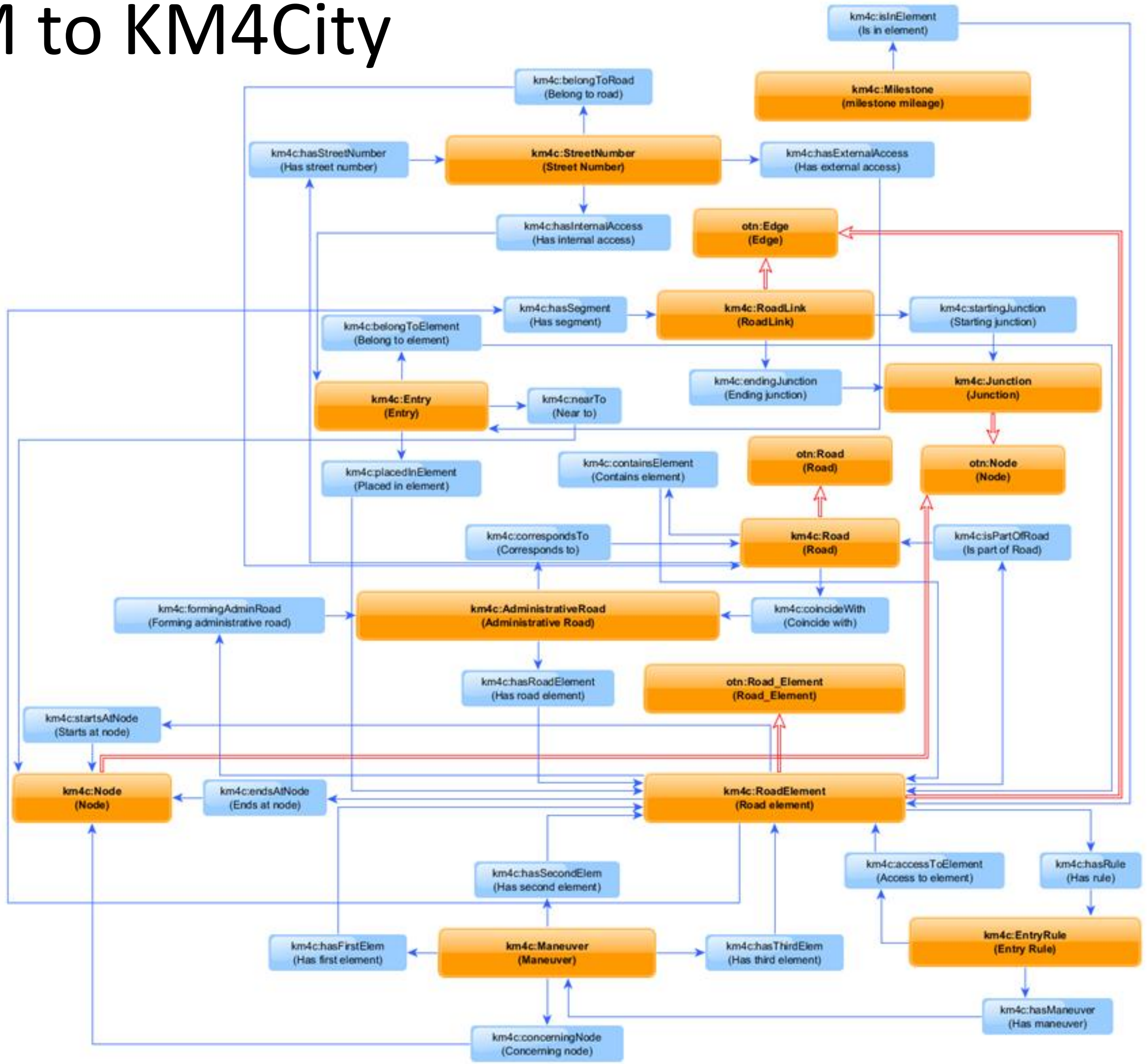
Etichette

highway	primary
lanes	2
lit	yes
maxspeed	50
name	Viale Francesco Redi
oneway	yes
sidewalk	separate
source:maxspeed	IT:urban
surface	asphalt



OSM to KM4City

- Road
- AdministrativeRoad
- RoadElement
- Node
- StreetNumber
- Entry
- Lanes/Lane
- Restriction
- …



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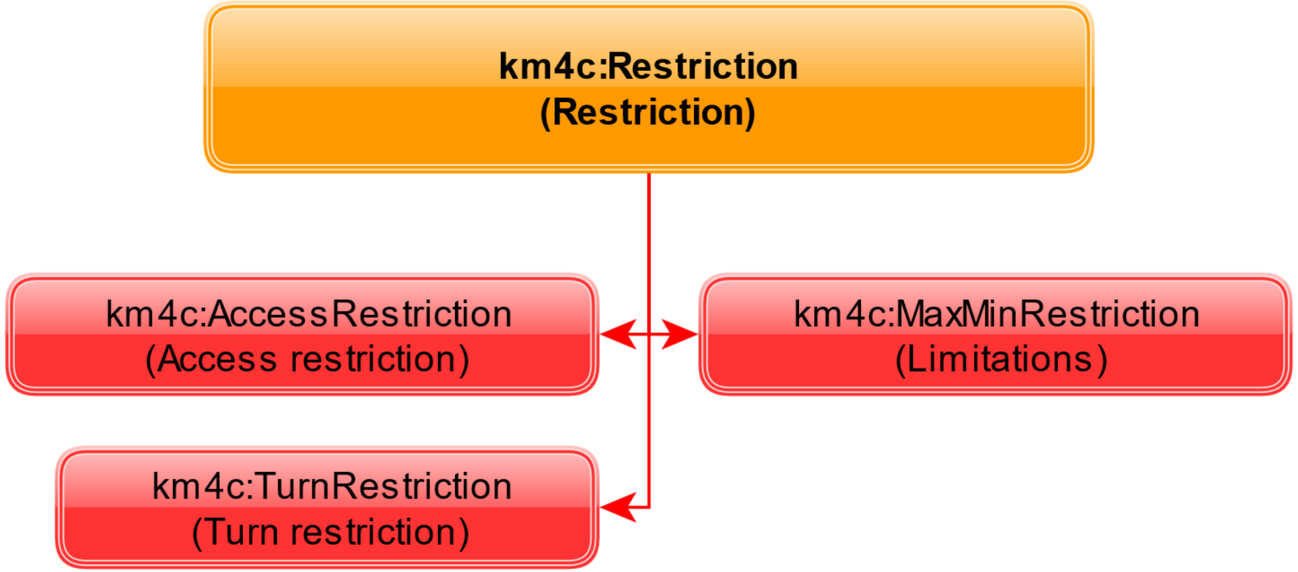

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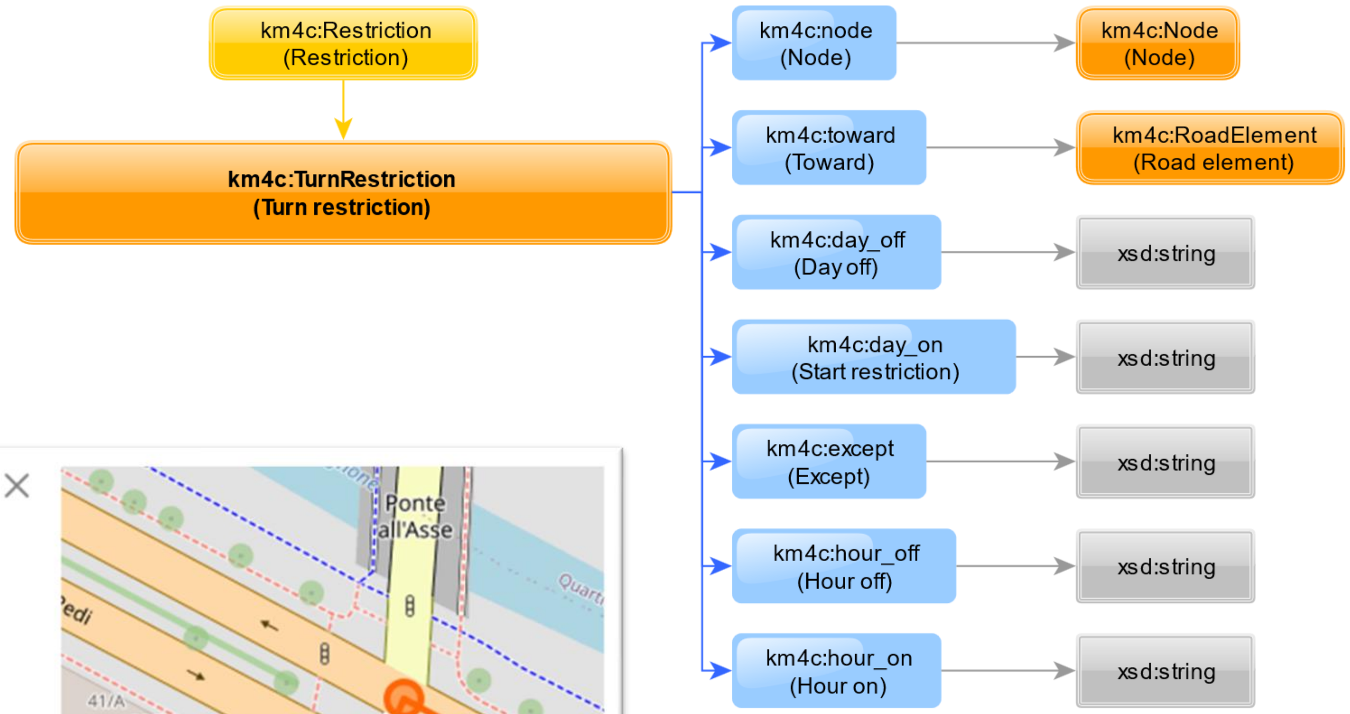
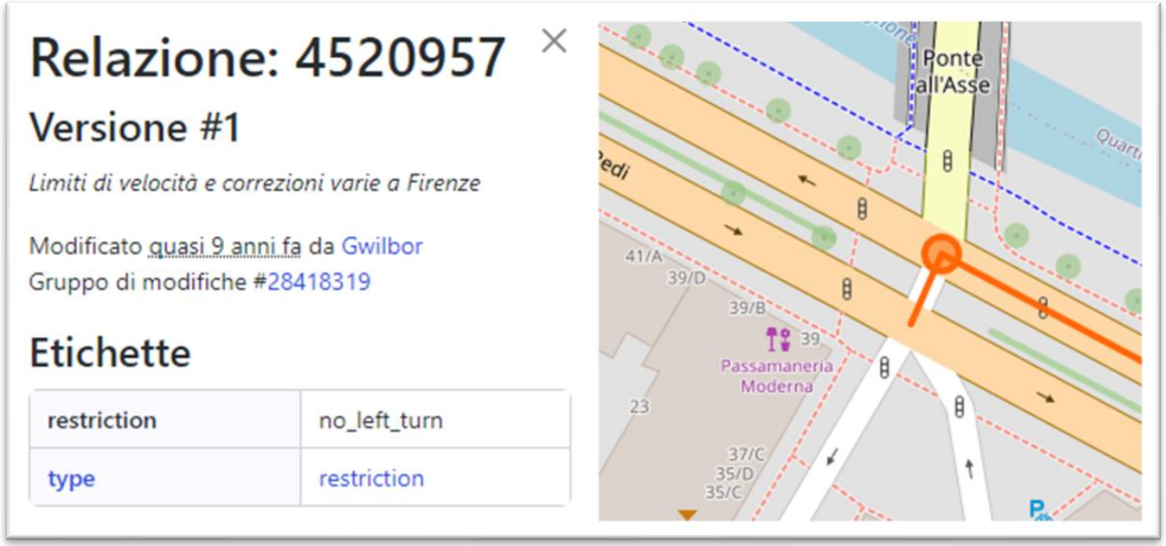




SPARQL Query

- The road graph can be queried from KM4City KB using SPARQL

```
PREFIX km4c: <http://www.disit.org/km4city/schema#>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX rdfsn: <http://www.w3.org/2003/01/geo/wgs84_pos#>
PREFIX dct: <http://purl.org/dc/terms/>
SELECT ?strada ?nomeStrada ?elementostradale ?highwaytype ?startlat ?startlong ?endlat ?endlong
?compositiontipo ?operatingstatus ?latrafficDir ?lalunghezza WHERE {
  ?strada a km4c:Road.
  ?strada km4c:extendName ?nomeStrada.
  ?strada km4c:inMunicipalityOf ?municip.
  ?municip foaf:name "Firenze".
  ?strada km4c:containsElement ?elementostradale.
  ?elementostradale km4c:startsAtNode ?startnode.
  ?elementostradale km4c:highwayType ?highwaytype.
  ?elementostradale km4c:composition ?compositiontipo.
  ?elementostradale km4c:operatingStatus ?operatingstatus.
  ?elementostradale km4c:trafficDir ?latrafficDir.
  ?elementostradale km4c:length ?lalunghezza.
  ?startnode rdfsn:lat ?startlat.
  ?startnode rdfsn:long ?startlong.
  ?elementostradale km4c:endsAtNode
  ?endnode. ?endnode rdfsn:lat ?endlat.
  ?endnode rdfsn:long ?endlong.
}
```

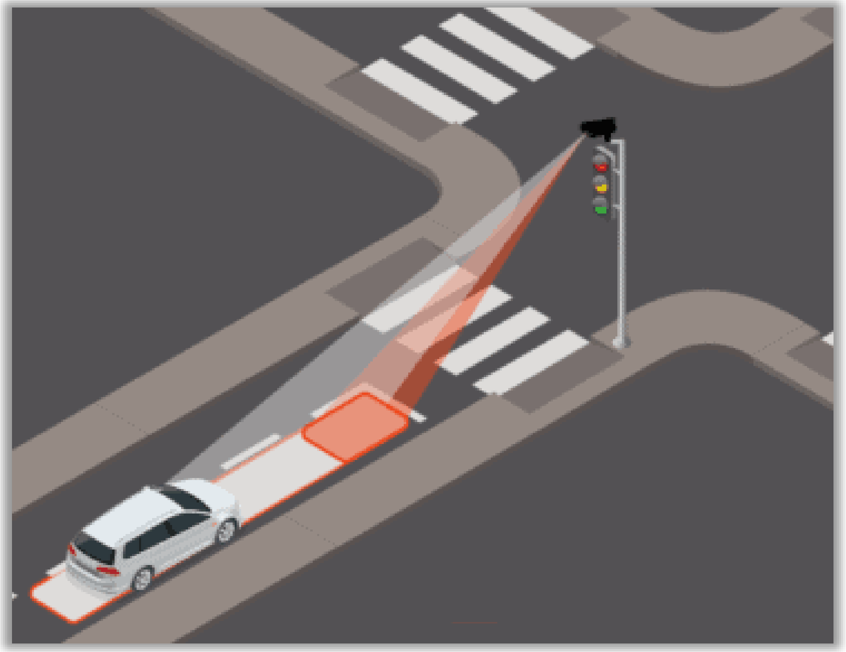
Query Results

Visual Results Mode

#	strada	nomeStrada	elementostradale	highwaytype	startlat	startlong	endlat	endlong	compositiontipo	operatingstatus	latrafficDir	lalunghezza
1	http://www.disit.org/km4city/resource/OS00509333832SR	Via Lambertesca	http://www.disit.org/km4city/resource/OS00509333832RE/0	pedestrian	43.7685	11.2555	43.7685	11.2555	carreggiata unica	in esercizio	tratto stradale aperto in entrambe le direzioni (default)	1.0e0
2	http://www.disit.org/km4city/resource/OS00509333834SR	Piazzale degli Uffizi	http://www.disit.org/km4city/resource/OS00509333834RE/0	pedestrian	43.7679	11.2553	43.7679	11.2553	carreggiata unica	in esercizio	tratto stradale aperto in entrambe le direzioni (default)	1.0e0
3	http://www.disit.org/km4city/resource/OS00524781006SR	Via del Fiordaliso	http://www.disit.org/km4city/resource/OS00524781006RE/0	pedestrian	43.7699	11.2526	43.7699	11.2526	carreggiata unica	in esercizio	tratto stradale aperto in entrambe le direzioni (default)	1.0e0
4	http://www.disit.org/km4city/resource/OS00507103663SR	Viale Alessandro Guidoni	http://www.disit.org/km4city/resource/OS00507103663RE/4	unclassified	43.7976	11.2182	43.7976	11.2183	carreggiata unica	in esercizio	tratto stradale aperto nella direzione positiva (da giunzione NOD_INI a giunzione NOD_FIN)	10.0e0

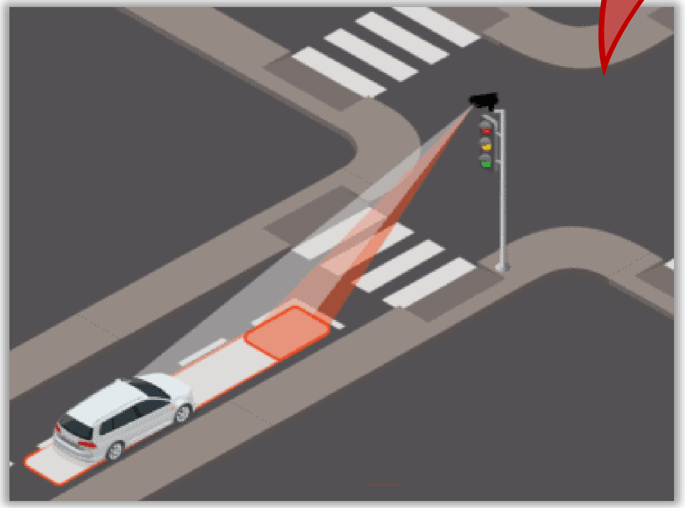
Sensors and detections

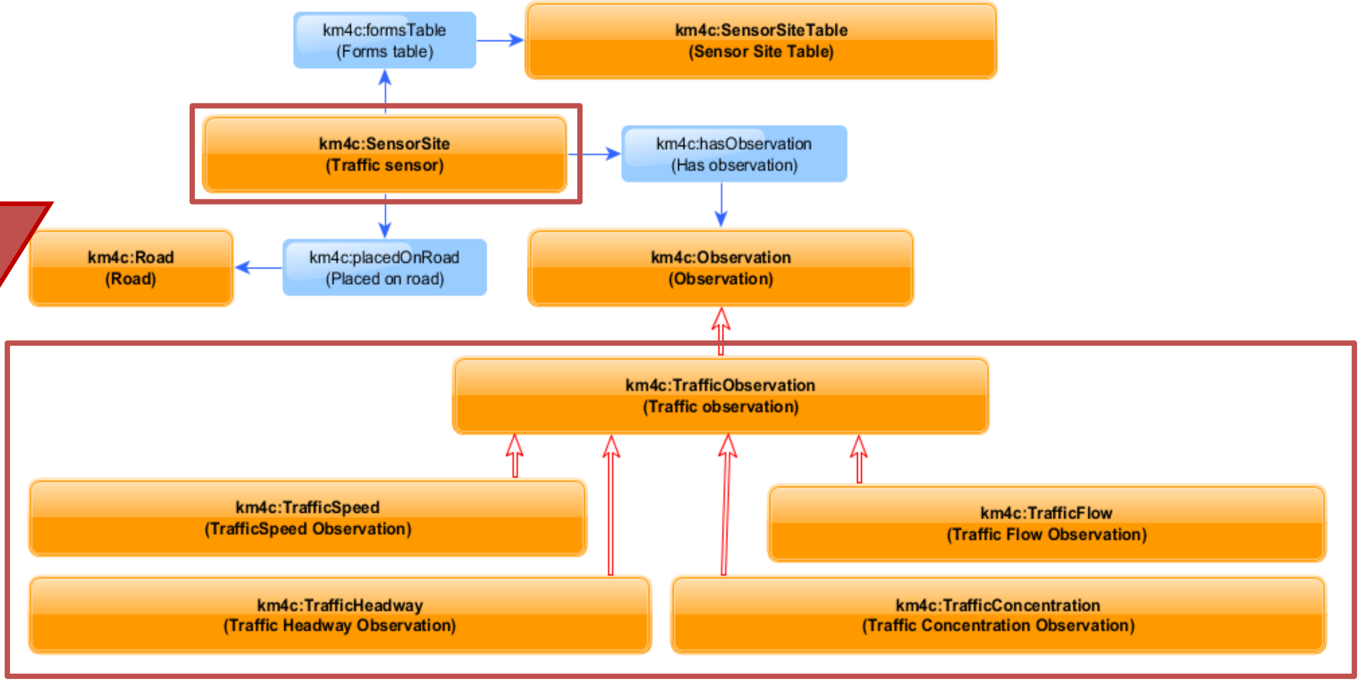
- The traffic sensors in a municipality (e.g., spire road sensors and cameras) give the state of the traffic **counting the number of vehicles** which pass through the supervised area
- Traffic Sensors come from Open Data and have
  - Static information
    - identifier,
    - geolocation,
    - street address,
    - technical specifications
    - …
  - Real-time traffic flow detections
    - timestamp,
    - detected traffic flow,
    - estimated speed
    - …



Sensors to KM4City

- SensorSite
- TrafficObservation
  - TrafficSpeed
  - TrafficFlow
  - TrafficHeadway
  - TrafficConcentration





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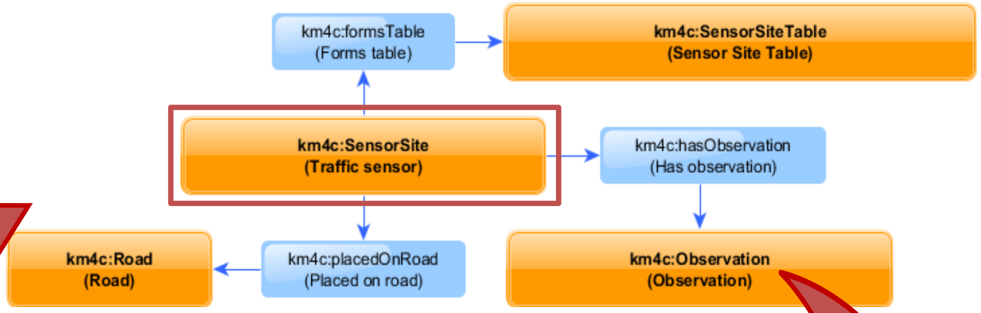
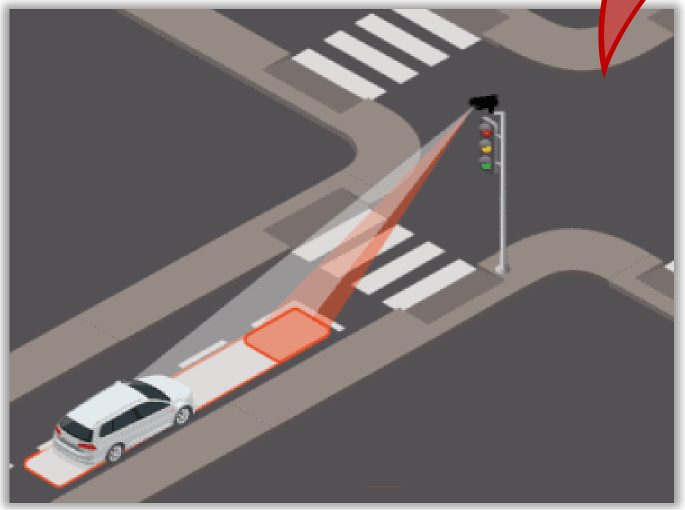
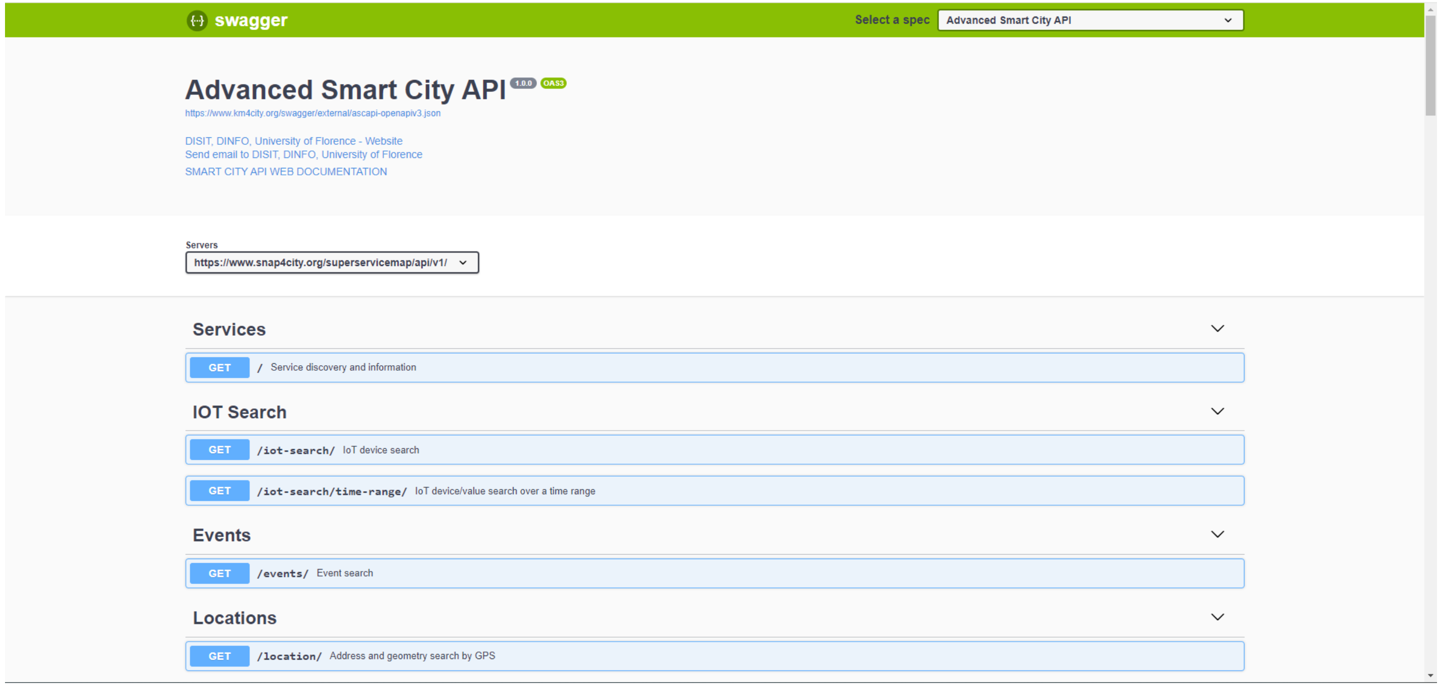




OpenSearch

Smart City API

- The traffic reconstruction model implementation accesses traffic data through **dedicated APIs**
- Traffic flows are read every **10 minutes**, the refresh frequency of the traffic sensors.



https://www.snap4city.org/drupal/node/20

Mathematical model

- The traffic sensor detections are interpreted as **sources of traffic** leading into the outcoming roads of the nodes where sensors are located.

- We consider a mathematical model for **fluid dynamic flows** on networks which is based on conservation laws.

- Road network is studied as a **directed graph** composed by arcs that meet at some nodes, corresponding to junctions.

Mathematical model

- Roads are modelled as if they were water pipelines.
- Crossroads are modelled as if they were pipeline junctions.
- The flow of the vehicles is modelled as if it was a water flow.
- The **law of conservation of the flow (of the vehicles)** applies:

$$\frac{\partial \rho(t,x)}{\partial t} + \frac{\partial f\big(\rho(t,x)\big)}{\partial x} = 0$$

where
– $\rho(t,x)$ is the vehicular density,
– $f(\rho(t,x)) = \rho(t,x)v(t,x)$ is the vehicular flux, and
– $v(t,x)$ is the local speed of the vehicles.

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Partial derivative of product of the **density** and the **velocity** w.r.t. the **space**

$$\rho(t,a) = \rho_a(t) \text{ and } \rho(t,b) = \rho_b(t)$$

$$\rho(0,x) = \rho_0(x).$$

Mathematical model

- $\rho(t, x)$ denotes the car density which admits values from 0 to ρ_{max}, where $\rho_{max} > 0$ is the **maximal vehicular density** on the road.

- The function $f(\rho(t, x))$ is the **vehicular flux** which is defined as the product $\rho(t, x)v(t, x)$, where $v(t, x)$ is the **local speed** of the cars.

- If we assume that $v(t, x)$ is a decreasing function, only depending on the density, then the corresponding **flux is a concave function**

Fundamental diagram

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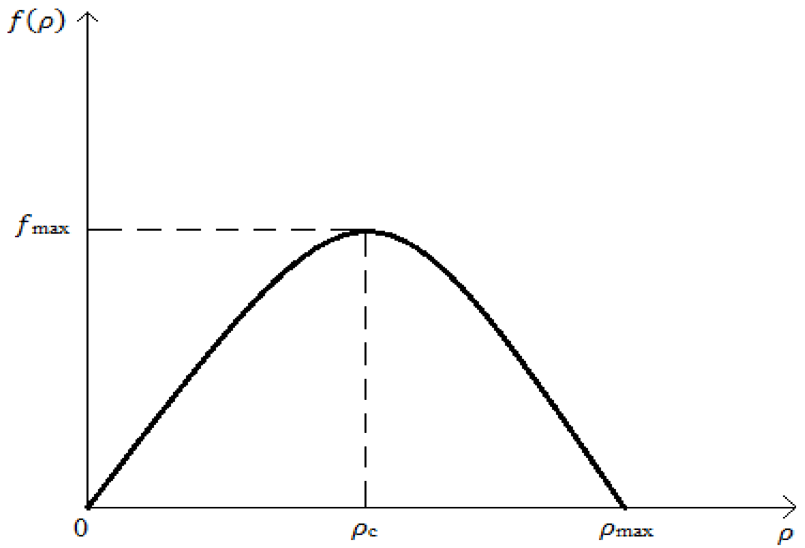
where v_{max} is the limit speed



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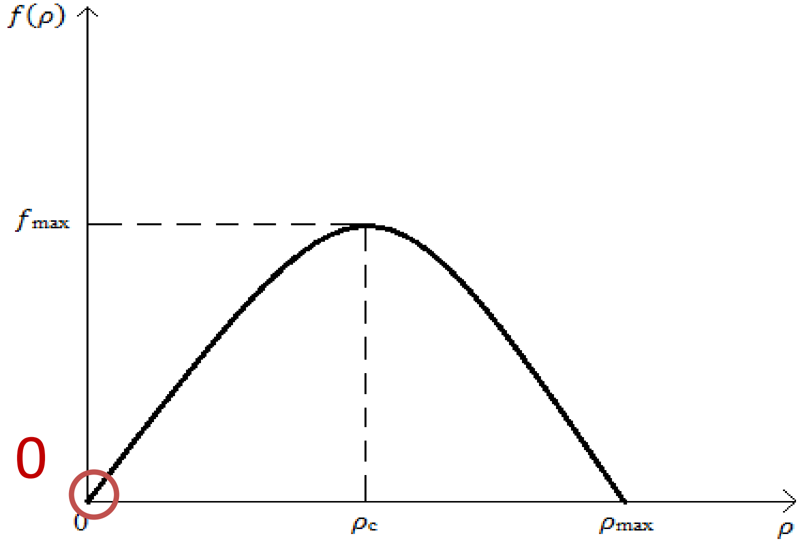

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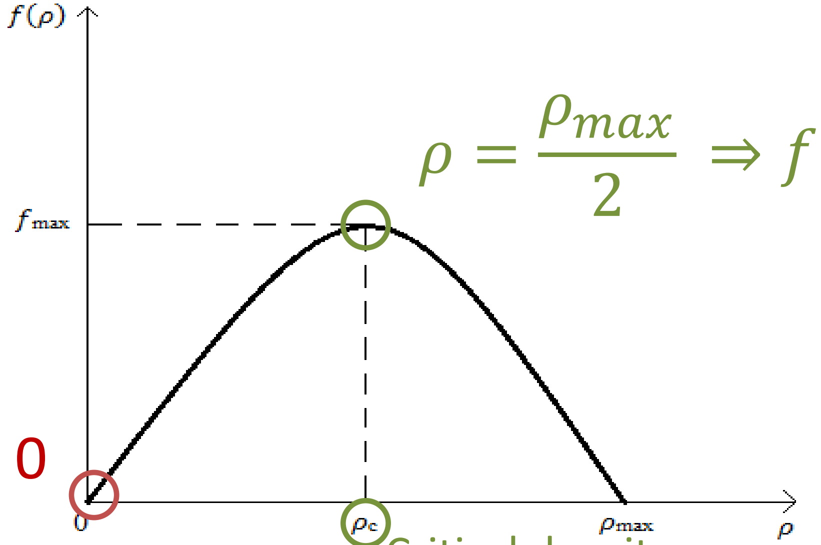

$\rho = \frac{\rho_{max}}{2} \Rightarrow f(\rho) = f_{max}$

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Critical density

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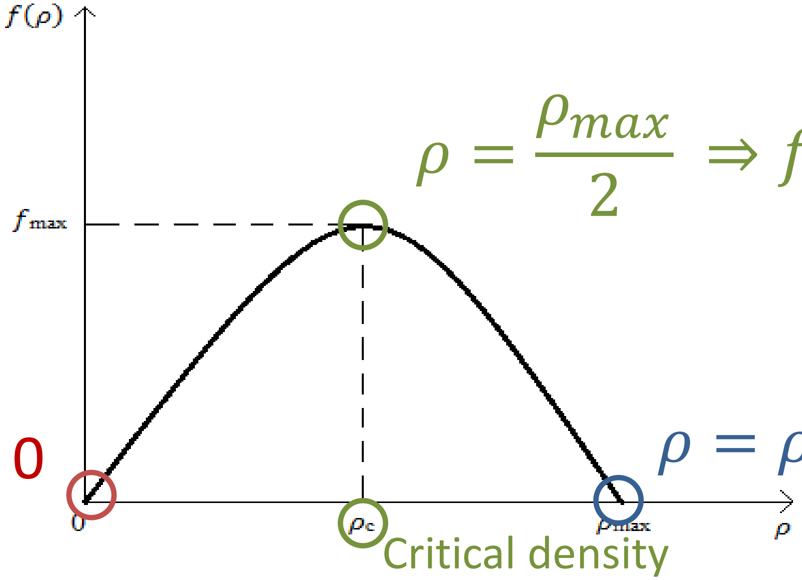

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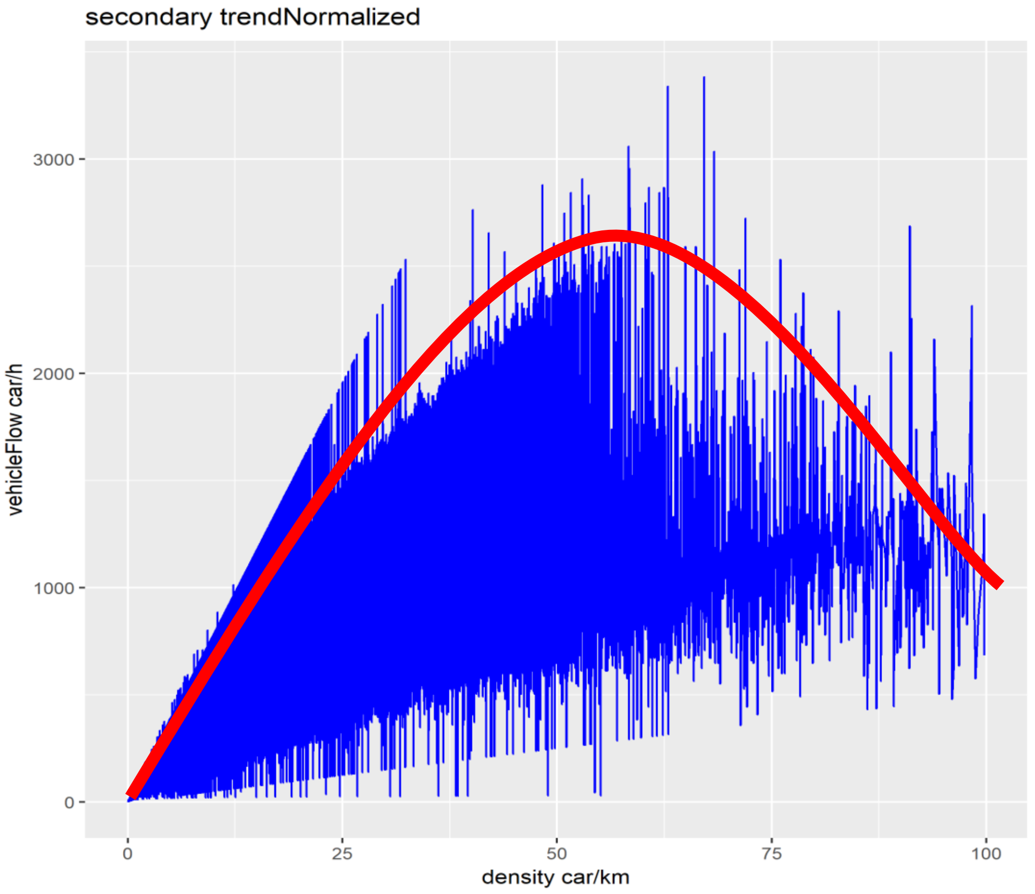
Fundamental diagram: data analysis

- Observation from traffic sensors (Florence, year 2019)



Discretization scheme

The following discretization and simplification of the model is operated:

- Each road is partitioned in segments Δ*x* long.
- The time is partitioned in intervals Δ*t* long.
- Denote (h,m) a bounded time-space region (cell) of duration h and length m.
- Let $u_m^h = u(t_h, x_m) = u(h\Delta t, m\Delta x)$ be a continuous function defined on (h,m).
- Denote *F* the numerical flux. Then, the vehicular density results from:

$$u_m^{h+1} = u_m^h - \frac{\Delta t}{\Delta x}\Big(F\big(u_m^h, u_{m+1}^h\big) - F\big(u_{m-1}^h, u_m^h\big)\Big)$$

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Density at time *h+1* in segment *m*

Density at time *h* in segment *m*

Changes due to neighborhood segments

Sensors’ measurements

- The measured data sensor is interpreted as the **source of traffic** leading into the outcoming roads of the considered junction.
- Suppose to assign a condition at the incoming boundary for $x = 0$ as $\rho(t, 0) = \rho_b^{inc}(t)$.
- We proceed by inserting an **incoming ghost cell** and the discretization becomes

$$u_0^{h+1} = u_0^h - \frac{\Delta t}{\Delta x}\left(F\left(u_0^h, u_1^h\right) - F\left(v_{(inc)}^h, u_0^h\right)\right)$$

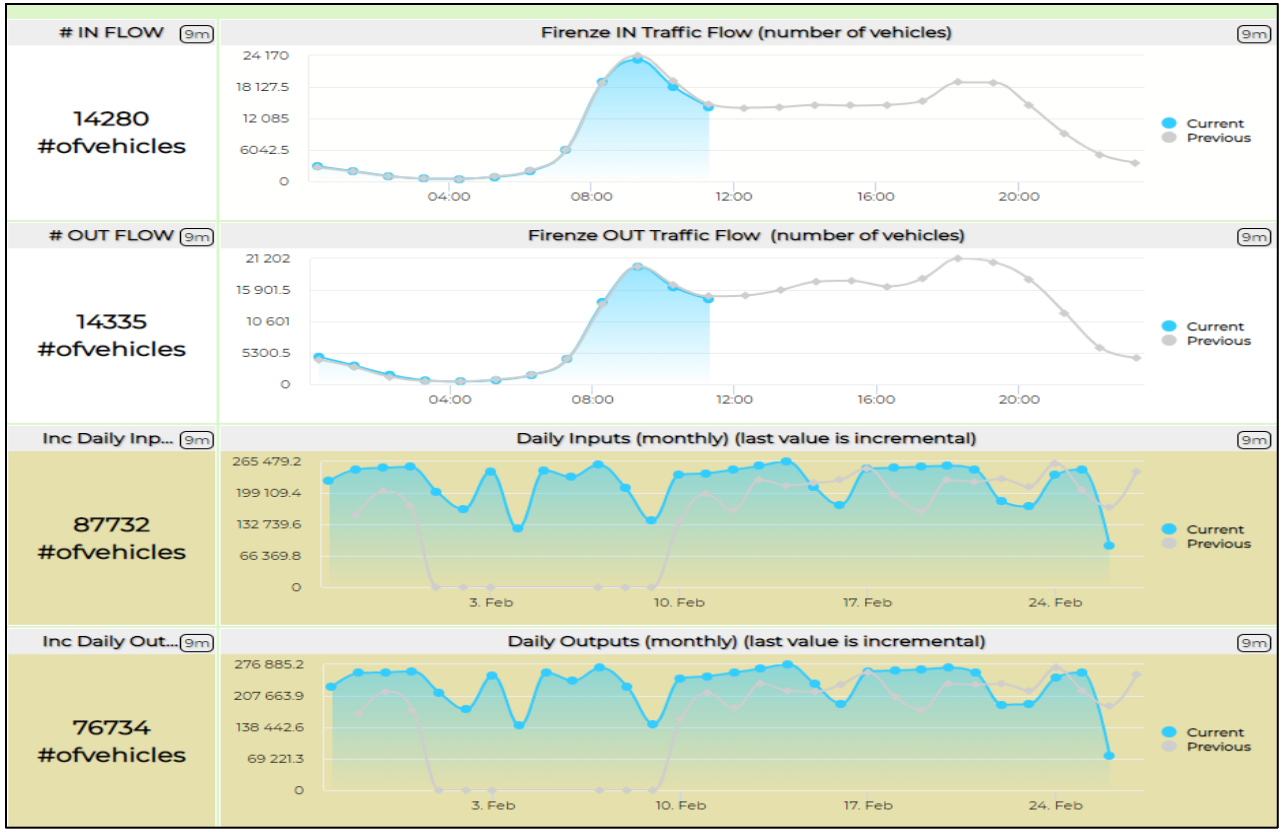
where

$$v_{(inc)}^h = \frac{1}{\Delta t}\int_{t_h}^{t_h+1} \rho_b^{inc}(t)\, dt$$

replaces the ghost value u_{-1}^h

Flow conservation

- The assessment has been performed verifying in real-time the conservation of the flow in the area. Figure reports the real-time dashboard for controlling the conservation of flow



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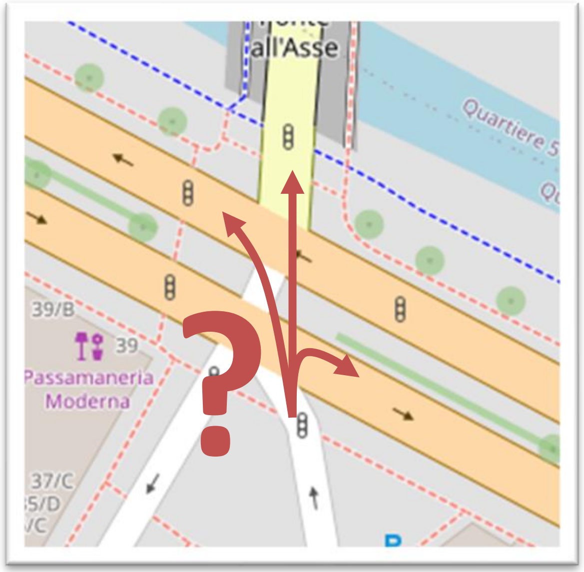
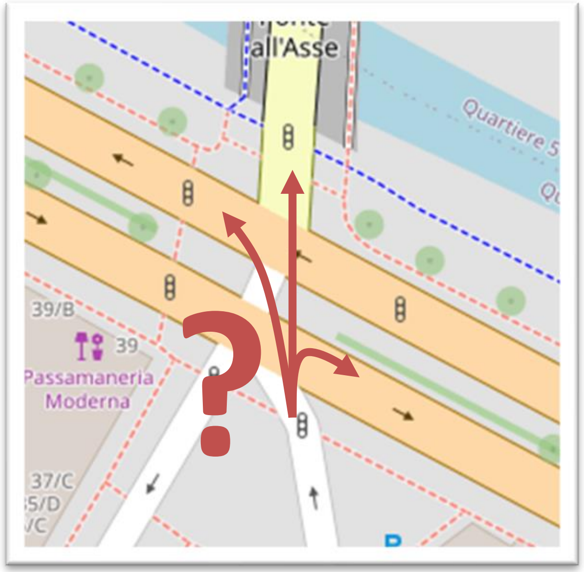


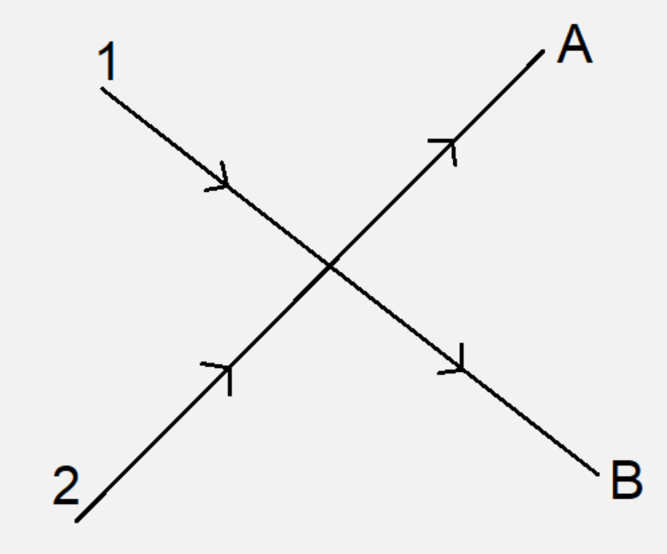
Application of the model

- The vehicular traffic flow is propagated in the network according to the fluid dynamic model



- The distribution of the traffic at crossroads is governed by a **Traffic Distribution Matrix** whose coefficients are based on the **weights** of the segments of roads that make the crossroad.

Traffic distribution on a junction



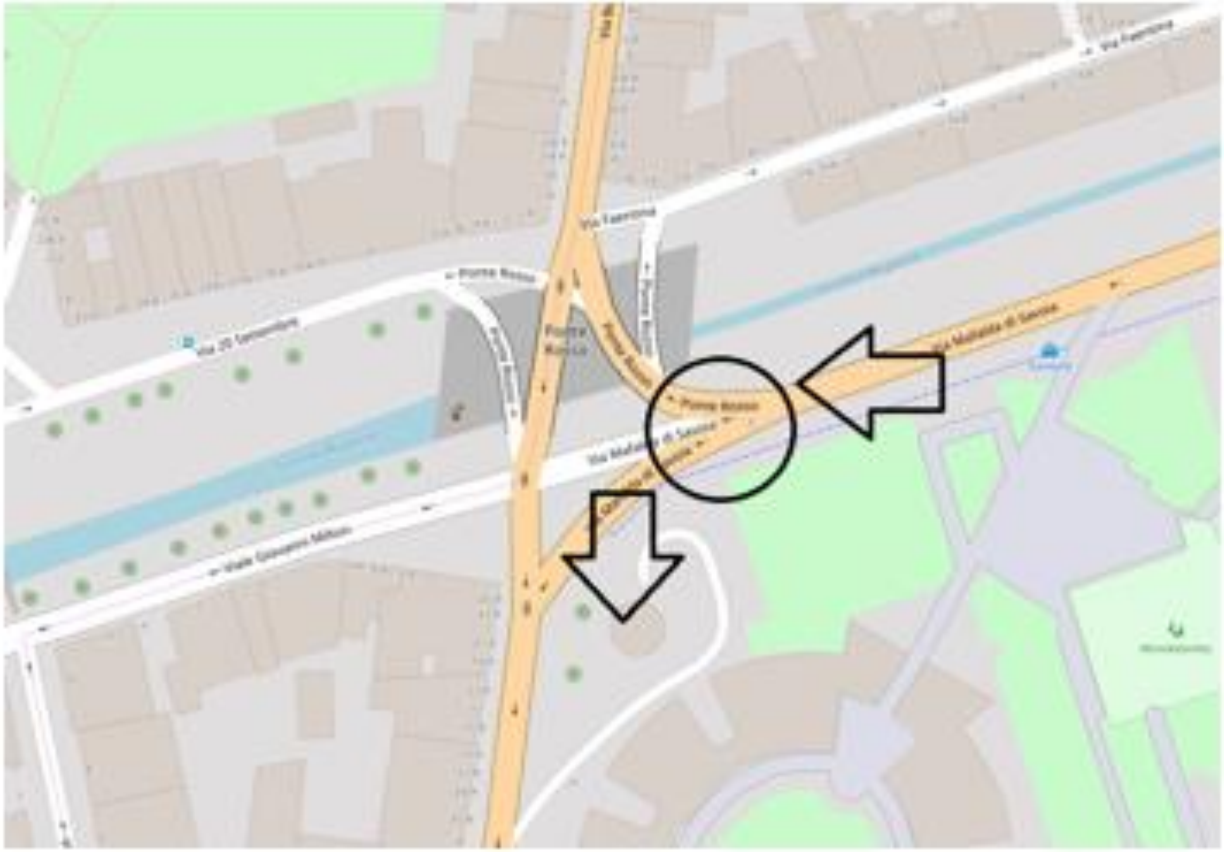
$$\begin{pmatrix} d_{1A} & d_{2A} \\ d_{1B} & d_{2B} \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} = \begin{pmatrix} f_A \\ f_B \end{pmatrix}$$

Junction distribution learning

The fork of via Mafalda di Savoia (East), in via Mafalda di Savoia (South), Viale Giovanni Milton (West) and Via del Ponte Rosso (North), in Florence.

Junction distribution learning

Road Type: primary
Lanes: 2
Designated Lanes: 0
Restrictions: none
Learning Factor: 61
Elem. Type: T.O.C.
Length: 63
Direction: positive
...
Weight: 31.122%



Junction distribution learning

Road Type: tertiary

Lanes: 1

Designated Lanes: 0

Restrictions: none

Learning Factor: 24

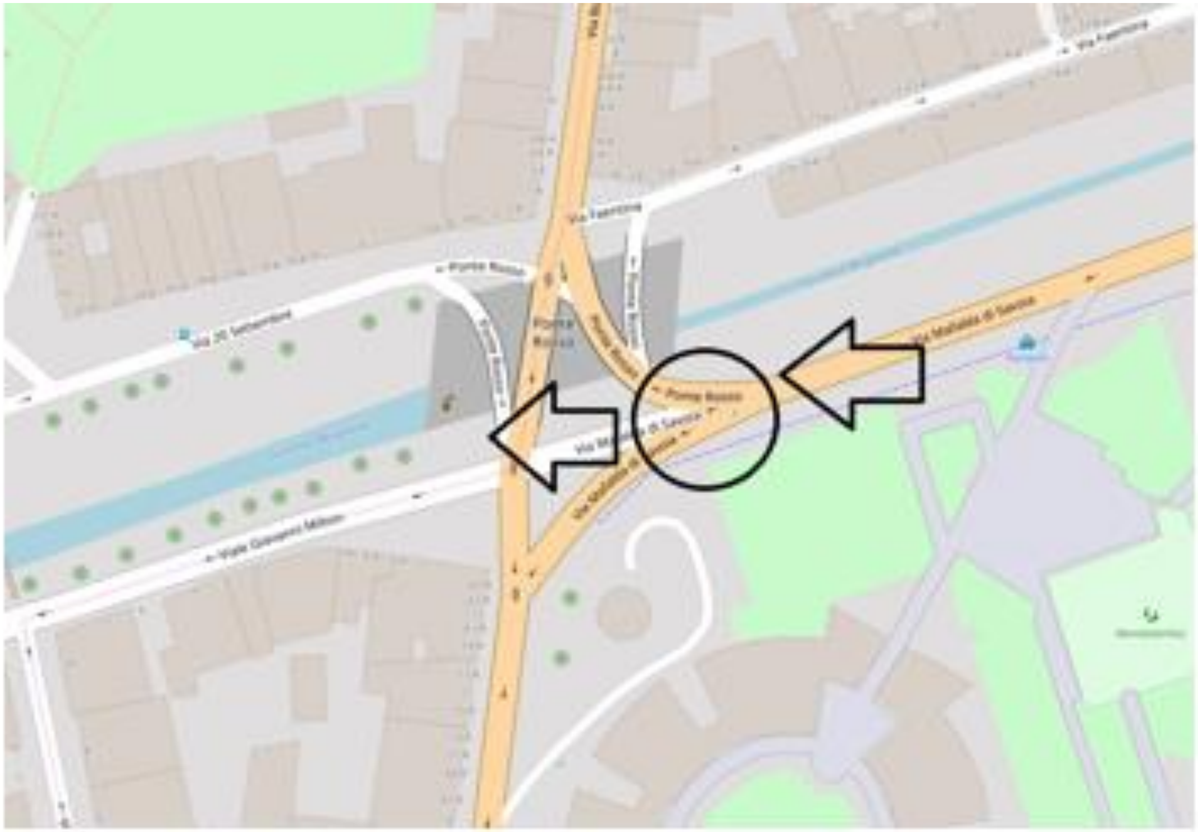
Elem. Type: T.O.C.

Length: 51

Direction: positive

…

Weight: 12.245%



Junction distribution learning

Road Type: primary

Lanes: 2

Designated Lanes: 0

Restrictions: none

Learning Factor: 111

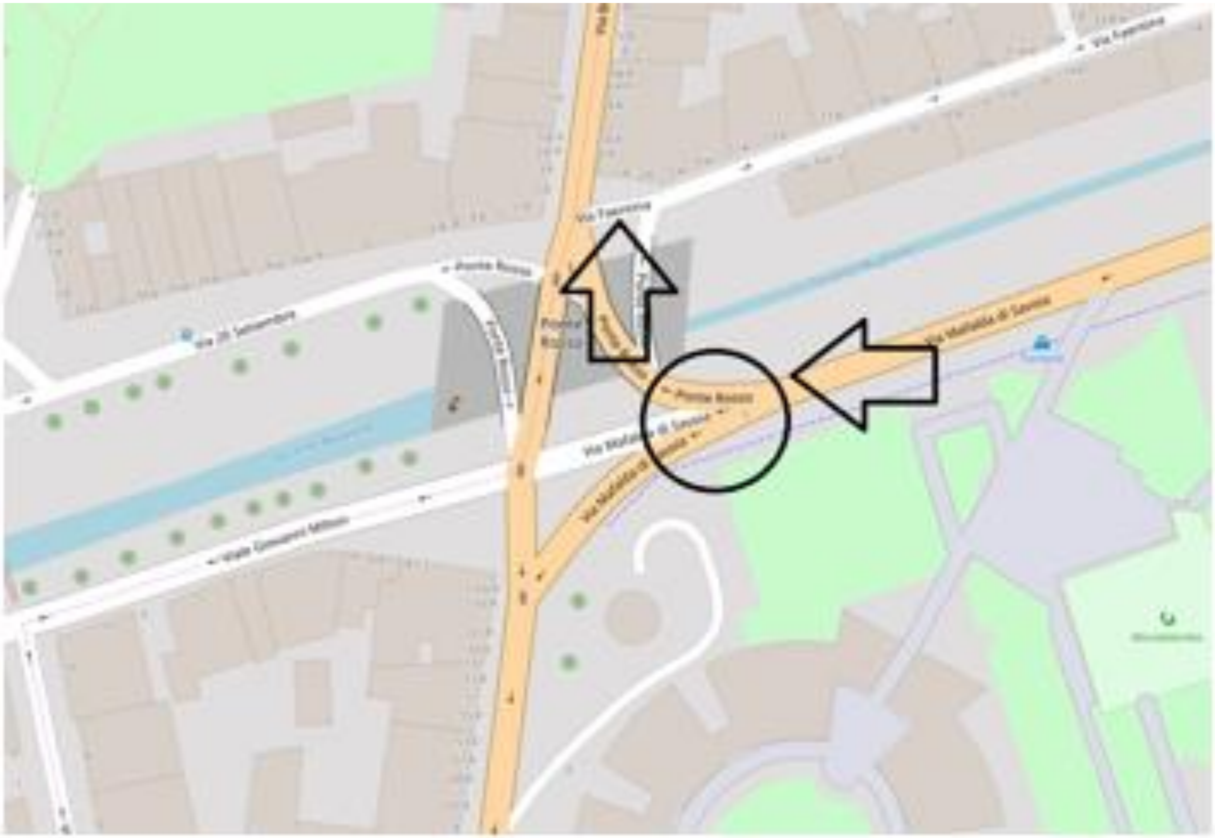
Elem. Type: T.O.C.

Length: 60

Direction: positive

…

Weight: 56.633%



Weight initialization

Weights are **initialized** based on the following:

- **Road type**: motorway, trunk, primary, secondary, tertiary, unclassified, residential, service;
- **Lanes**: how many lanes are drawn on the asphalt, also considering possible restrictions (e.g. lanes reserved to public transport);
- **Traffic restrictions**: examples are mandatory/forbidden directions at crossroads, speed limits, limited traffic zones.

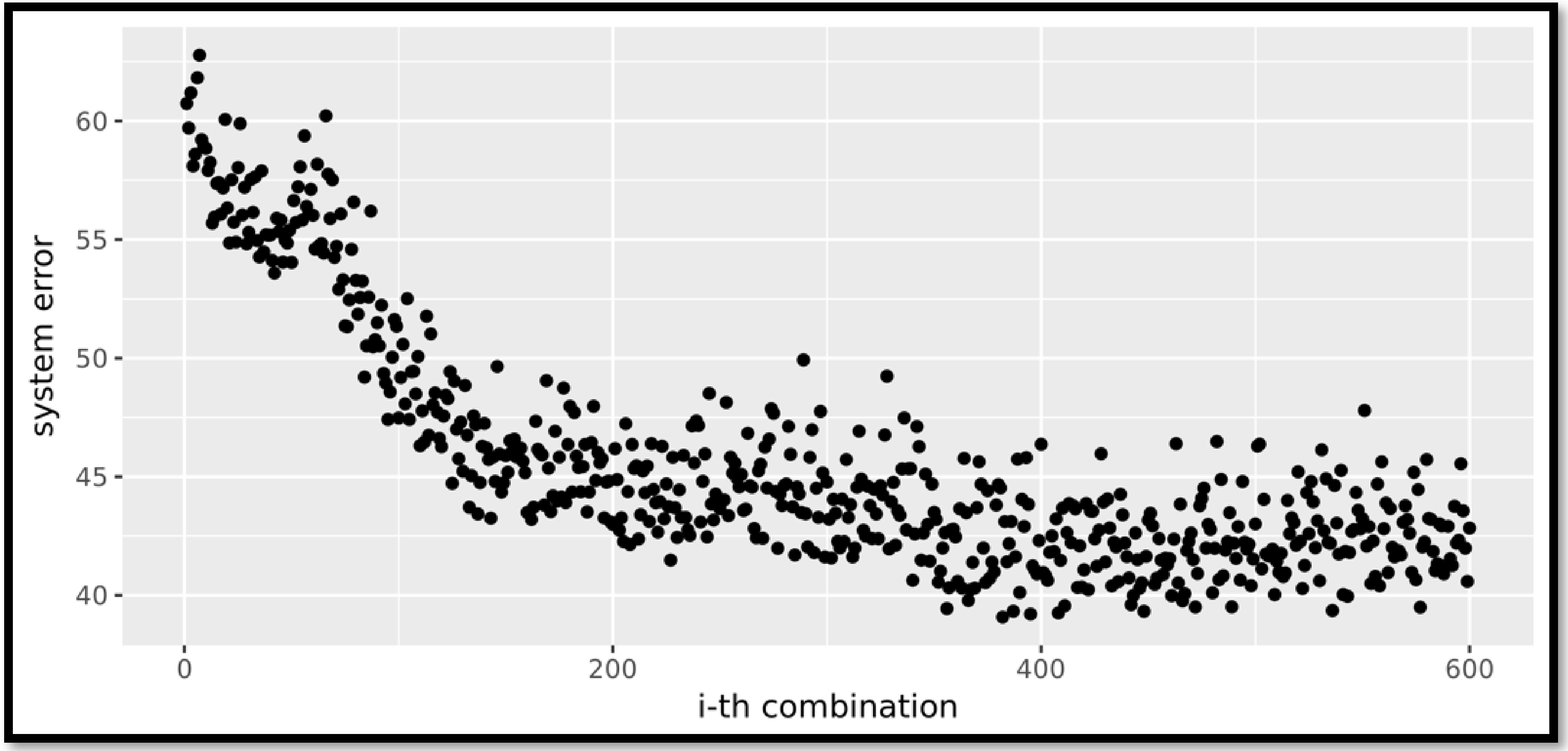
Stochastic learning

It has been observed that:

- The way how vehicles distribute at crossroads varies depending on the day of the week, and of the time of the day;
- A random variation of some weights is very likely to lead to an improved accuracy;
- If no improvements are achieved after *n* attempts, it is reasonable to move anyway to the best of the last *n* configs.

An offline process is run, based on the above, that leads to time-based weight adjustments, aimed at an improved accuracy.

Stochastic learning

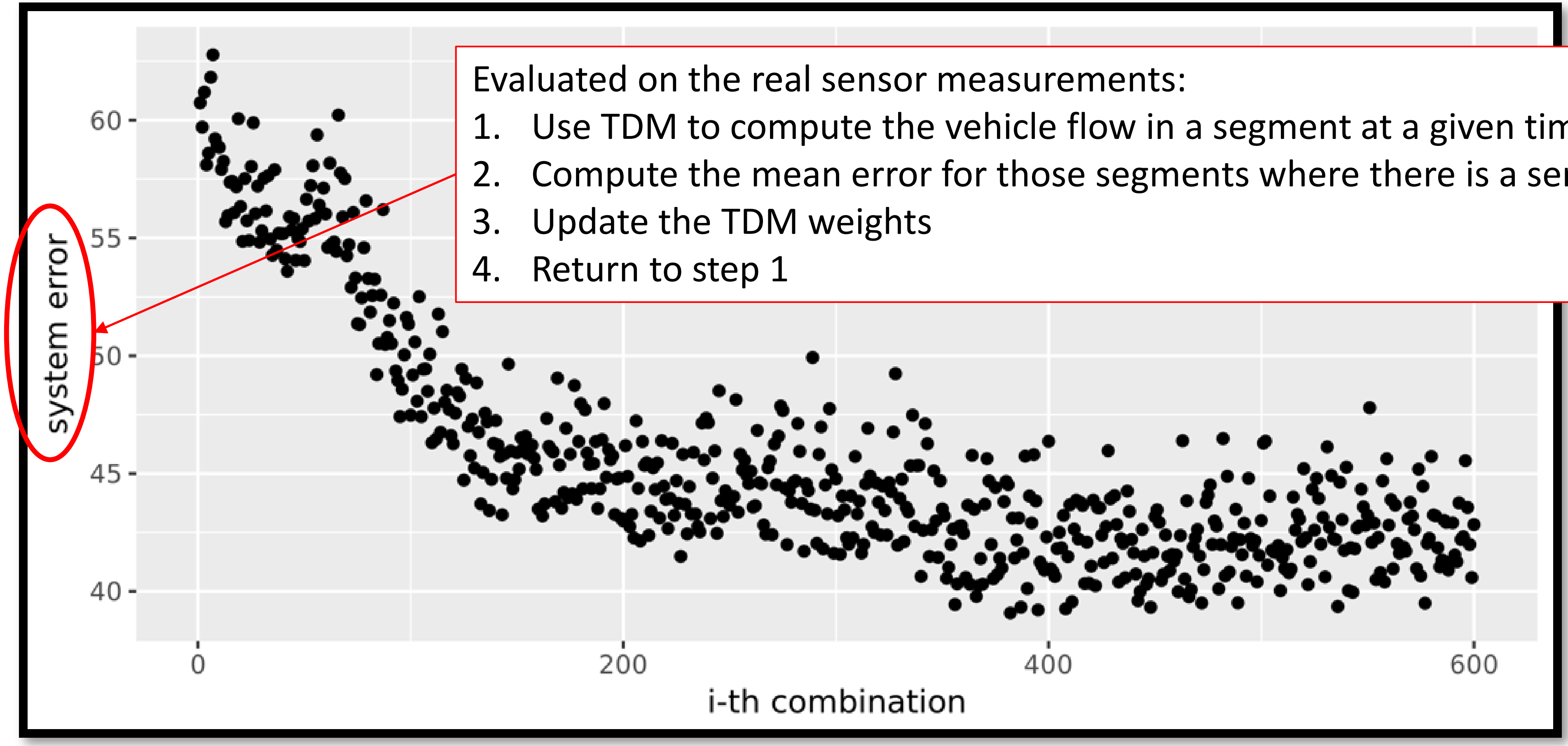


In the x axis, the number of the learning iterations. In the y axis, the (decreasing) system error.

Stochastic learning

Evaluated on the real sensor measurements:

1. Use TDM to compute the vehicle flow in a segment at a given time
2. Compute the mean error for those segments where there is a sensor
3. Update the TDM weights
4. Return to step 1



In the x axis, the number of the learning iterations. In the y axis, the (decreasing) system error.

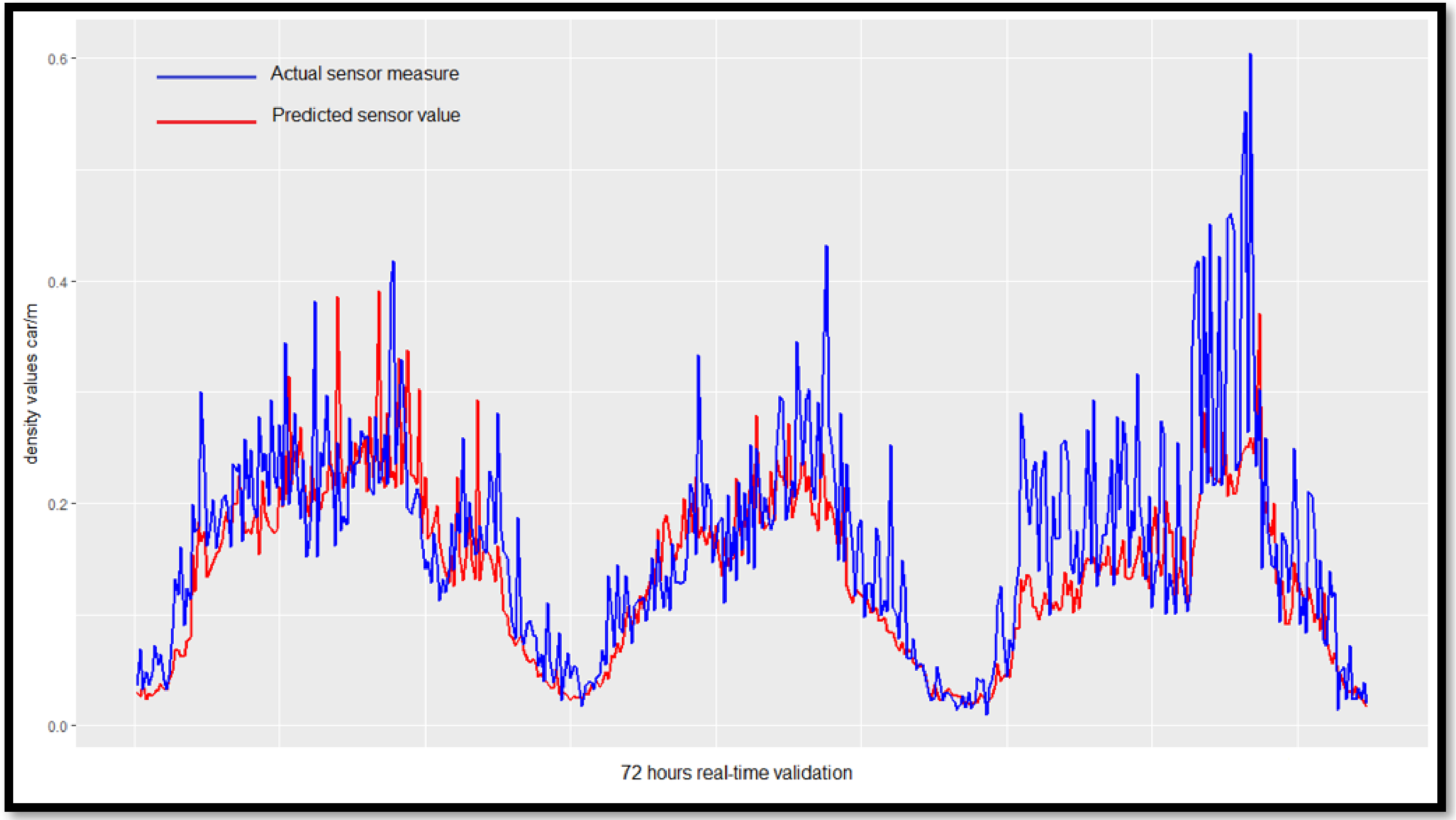
Validation approach

- Let the **error at a sensor at a given time *t*** be the percentage error computed removing a *given sensor* from the inputs and comparing the traffic flow *reconstructed* at the sensor with the traffic flow *detected* by the sensor, at the given time

- Let the **system error over a time period *T*** be the average of the system errors computed over all the traffic sensors and all the times ***t*** ∈ ***T***

The system error has been computed to be around 30%

Validation approach



The diagram refers to one in particular of the sensors, and it displays the predicted vs actual values over the time in the 72 hours validation.

Error analysis

A deeper analysis of the results to be achieved by the solution we presented can be obtained by assessing the resulted traffic flow reconstruction during the real-time execution in order to understand:

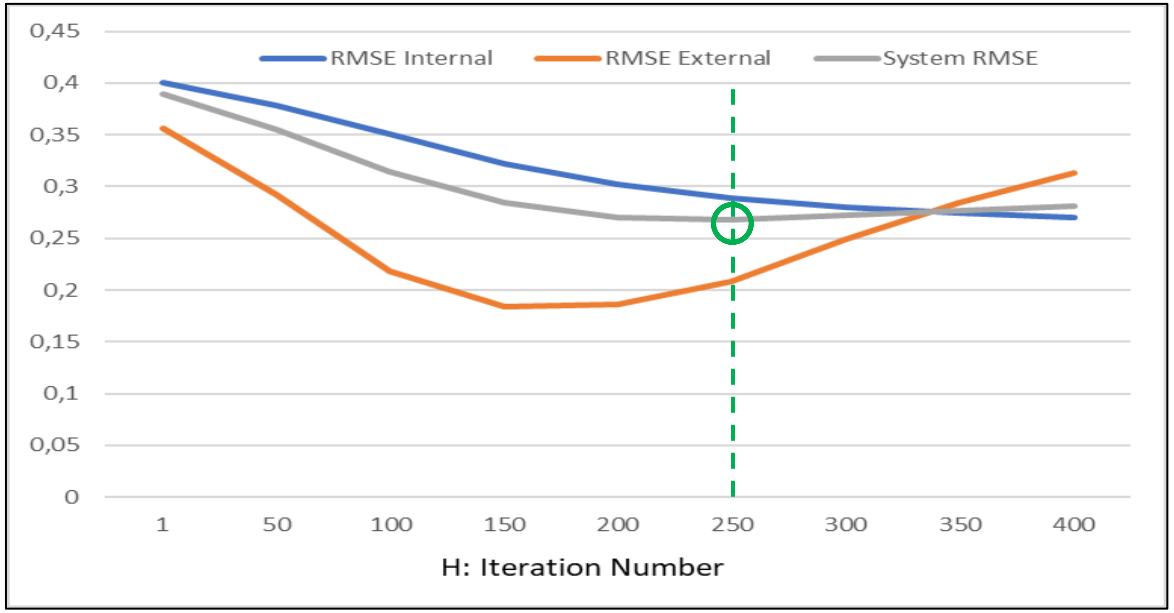
- Identification of the most suitable number of iterations *H*
- Solution accuracy
- If the error in reconstruction depends on structural parameters of the urban network (i.e., sensor location)

Error analysis

- The accuracy of the solution primarily depends on the **number of iterations *H*** which are applied to the execution
- This is performed by computing the solution which excludes data from each different sensor (all of them), so as to estimate the deviation from the calculated traffic density $\rho_c(t)$ in the road where the selected sensor is located, with respect to the density $\rho_M(t)$ measured by the sensor, for each time t.
- At a given location the **RMSE** is estimated as $\sqrt{\frac{\Sigma_{t=1}^{T}(\rho_C(t)-\rho_M(t))\hat{}2}{T}}$, where *T* is the total number of observations
- At each iteration the RMSE for each sensor has been measured and also the so-called **system RMSE**, which is the average value of the measured RMSE of all the sensors.

Error analysis

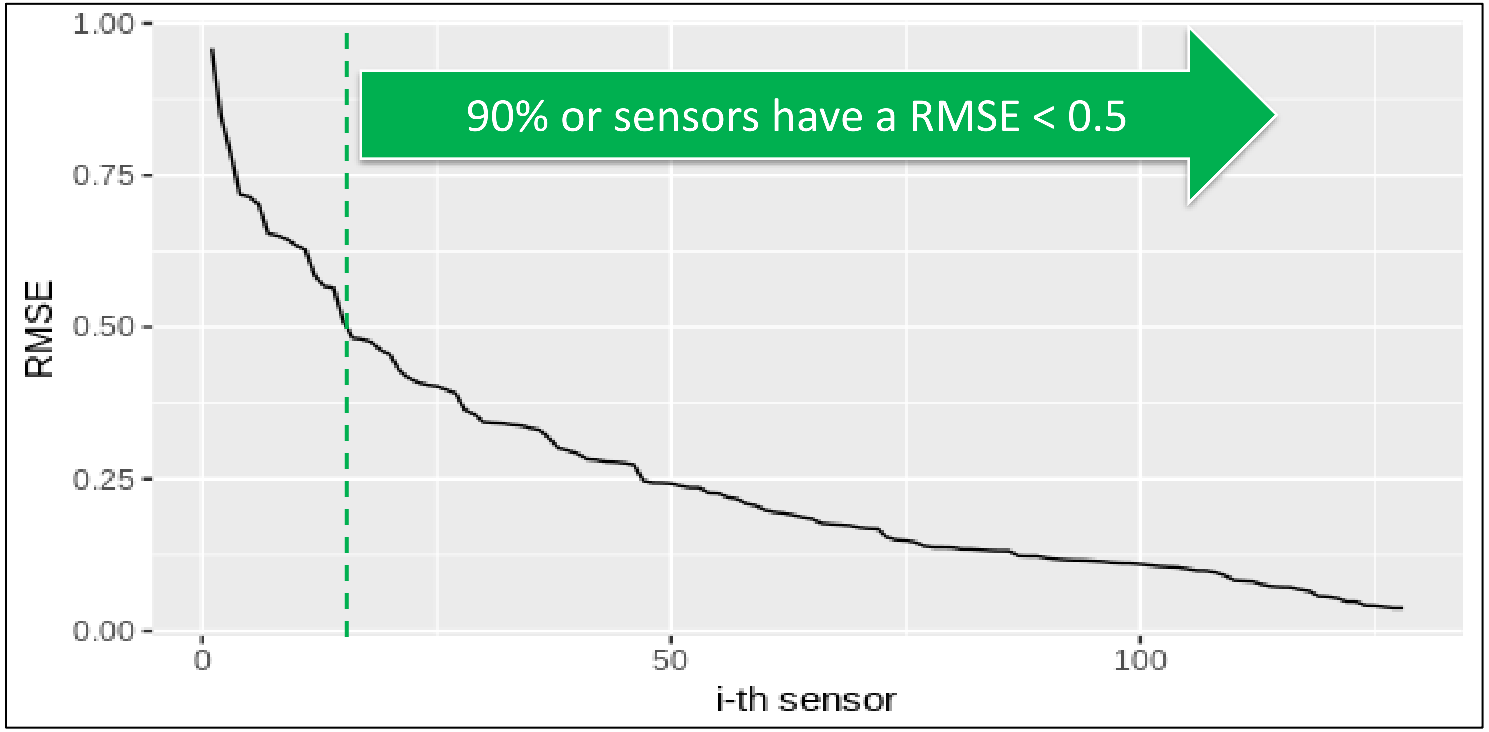
- The RMSE trends with respect to the iterations number *H* in the traffic flow reconstruction are shown.
- The average RMSE trend of the internal sensors is represented by the blue line, the average RMSE trend of the external sensors is represented by the orange line.
- In grey is reported the System RMSE having its minimum when H=250.



- Sensors on internal roads
- Sensors on external (edge) roads

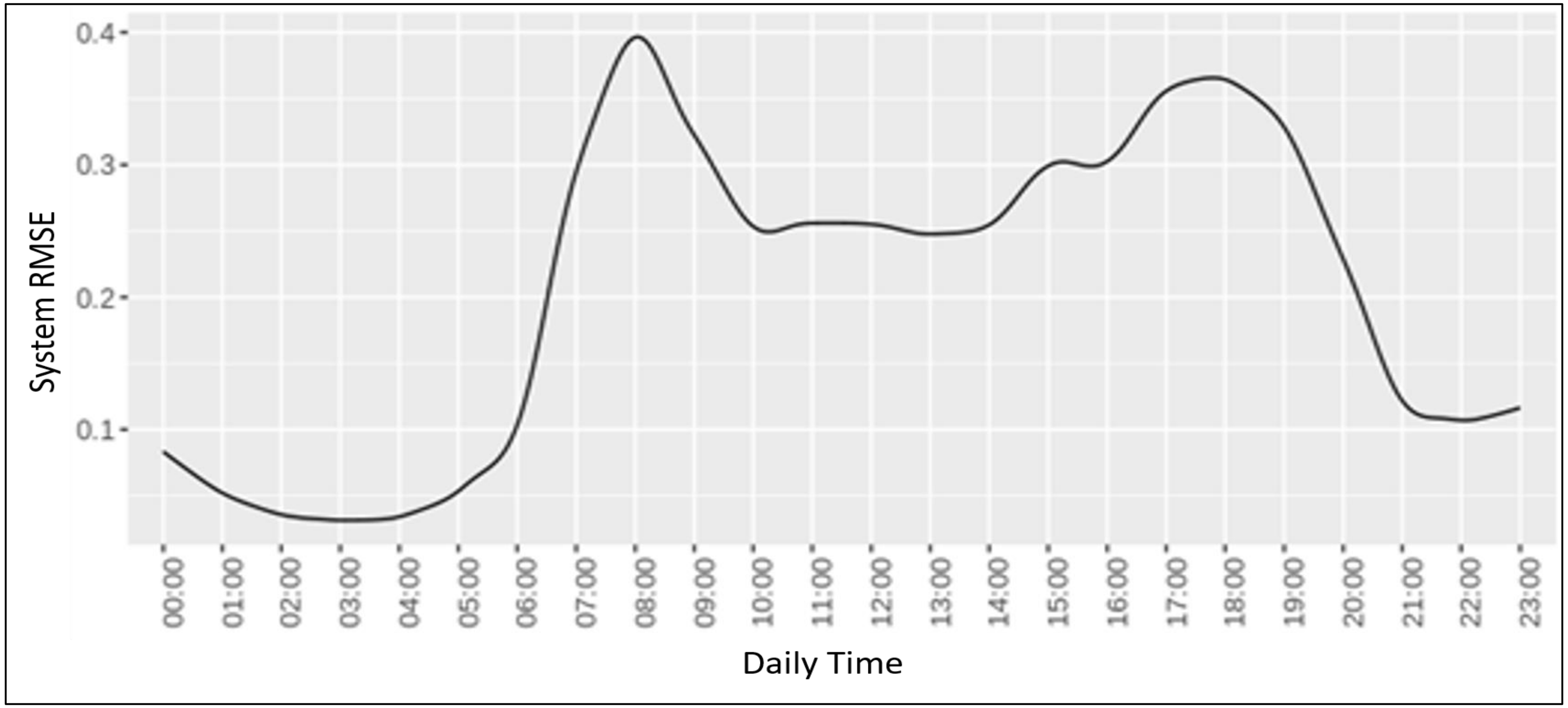
Error analysis

- The distribution of RMSE for each traffic sensor using H=250
- 90% of sensors have a RMSE value less than 0.5



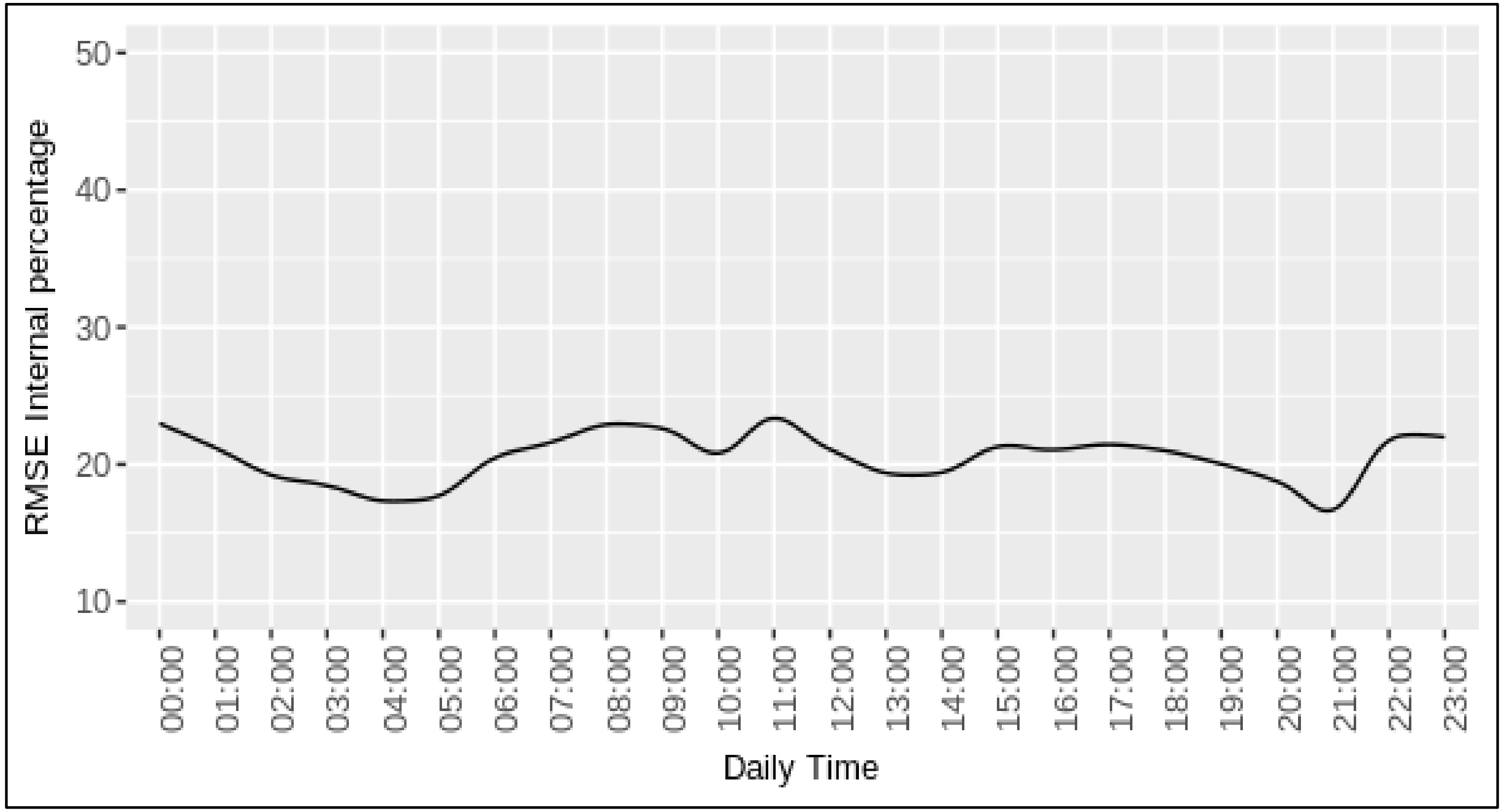
Error analysis

- Since traffic congestion in the city is typically related to the city incoming/outcoming flow according to the working activities of citizens, then also the RMSE value is affected to such behavior in the day.



Error analysis

- The RMSE is an absolute error measure with respect to the traffic density.
- The **ratio between the RMSE and the traffic density** (actual values) is almost constant



Error analysis

- The RMSE has a certain non-uniform distribution and a clear dependency on traffic volume.
- The error behavior is related to the topological characteristics of the road network.
- The error behavior of sensors are related to two topological features: **betweenness** and **eccentricity**

Error analysis

- The RMSE has a certain non-uniform distribution and a clear dependency on traffic volume.
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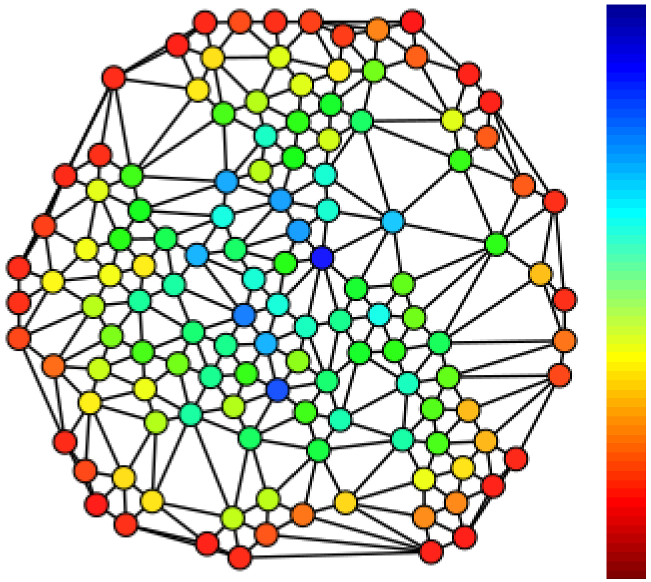
- The error behavior of sensors are related to two topological features: **betweenness** and **eccentricity**

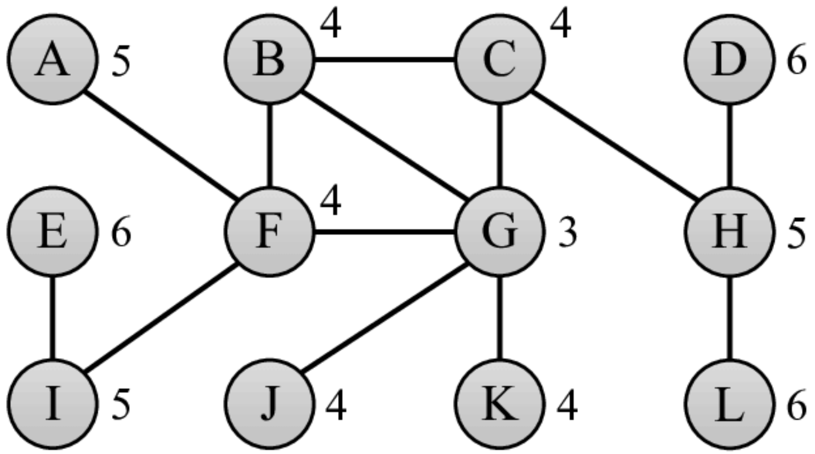
The **vertex betweenness** is a measure of centrality in a graph based on shortest paths. For every pair of vertices in a connected graph, there exists at least one shortest path between the vertices such that the number of edges that the path passes through (unweighted graphs) is minimized. The betweenness for each vertex is the number of these shortest paths that pass through the vertex



Error analysis

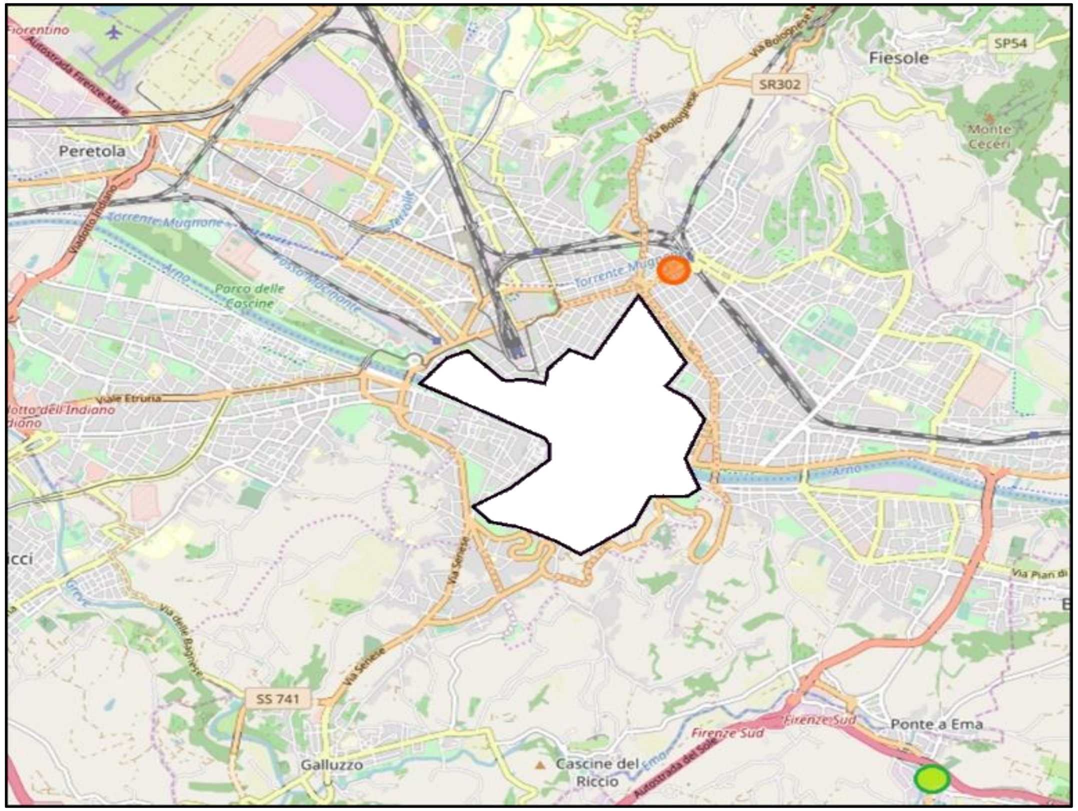
- The RMSE has a certain non-uniform distribution and a clear dependency on traffic volume.
- The error behavior is related to the topological characteristics of the road network.
- The error behavior of sensors are related to two topological features: **betweenness** and **eccentricity**

The **vertex eccentricity** is defined as the greatest shortest path distance between a vertex and any other vertex in the graph



Error analysis

- In orange the node having the maximum betweenness value, while in green the node having the maximum eccentricity value. The main restricted traffic zone is depicted in the center of the city in grey.



Error analysis

- A multilinear regression model has been conceived to verify the presence of an effective relationship between the RMSE and the topological metrics.
- Results:

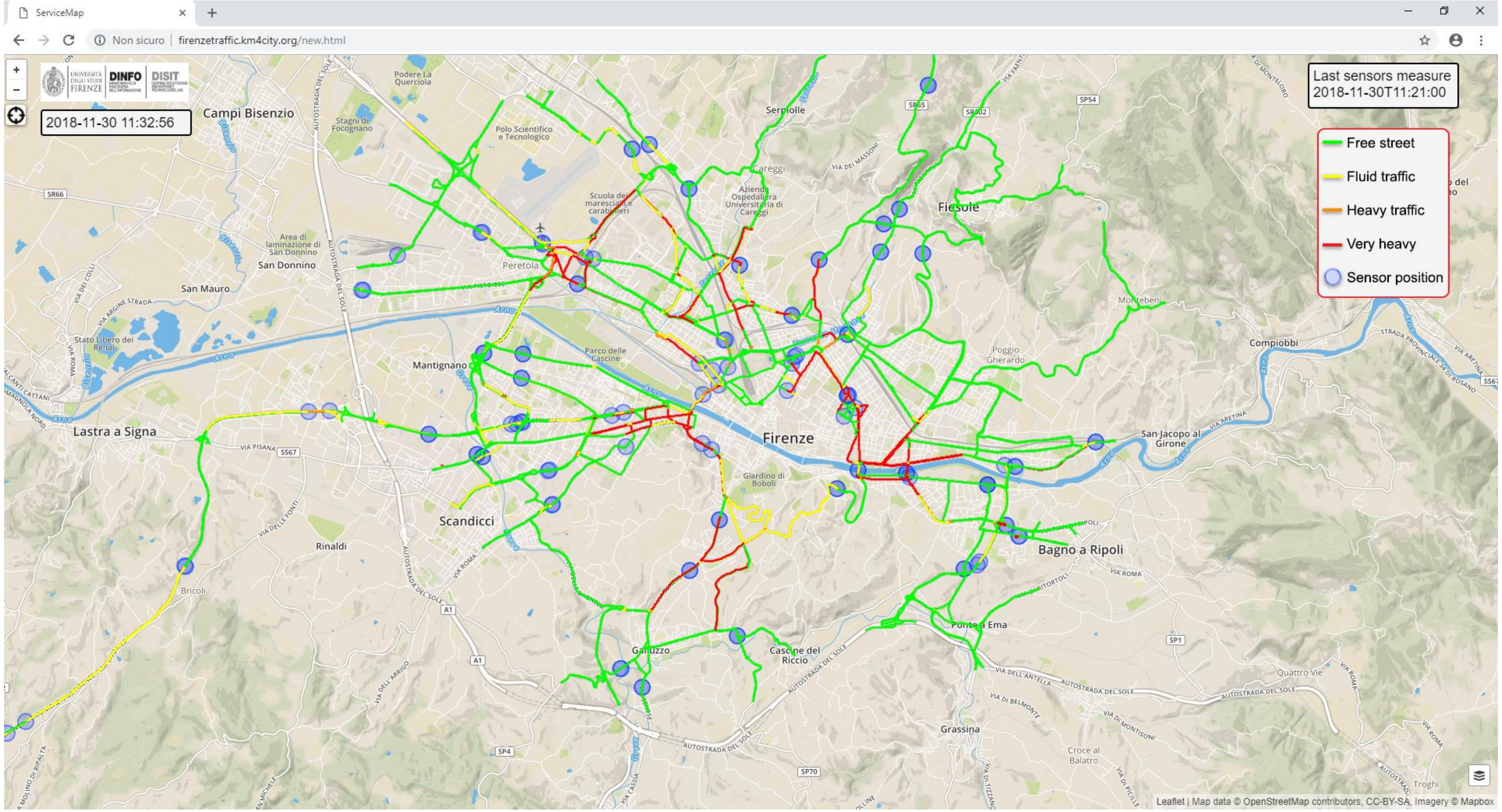
Coefficient	Estimate		Std. Error	t-value	p-value
betweenness	β	0.80224	0.13097	6.125	< 0.05
eccentricity	γ	0.23256	0.02657	8.752	< 0.05

- The identified model is $Y_i = \beta x_i + \gamma z_i$ where Y_i, x_i, z_i are the RMSE, betweenness and eccentricity, respectively

Displaying results

- Segments of road are categorized based on the road type and the number of lanes.
- Segments of each category that have one at least of the extremities that coincide with a traffic sensor, are used for determining the range of the traffic flows that can be observed on the specific category of segments.
- For each segment category, the range is partitioned into four subranges, that correspond to the four colors that you can find on the map.
- The reconstruction is presented to users through colored lines traced over the road paths on the city map.
- The date and time when the most up-to-date values from the sensors have been acquired can also be seen at the top-right corner of the map.

Displaying results



Data structure in real-time computing

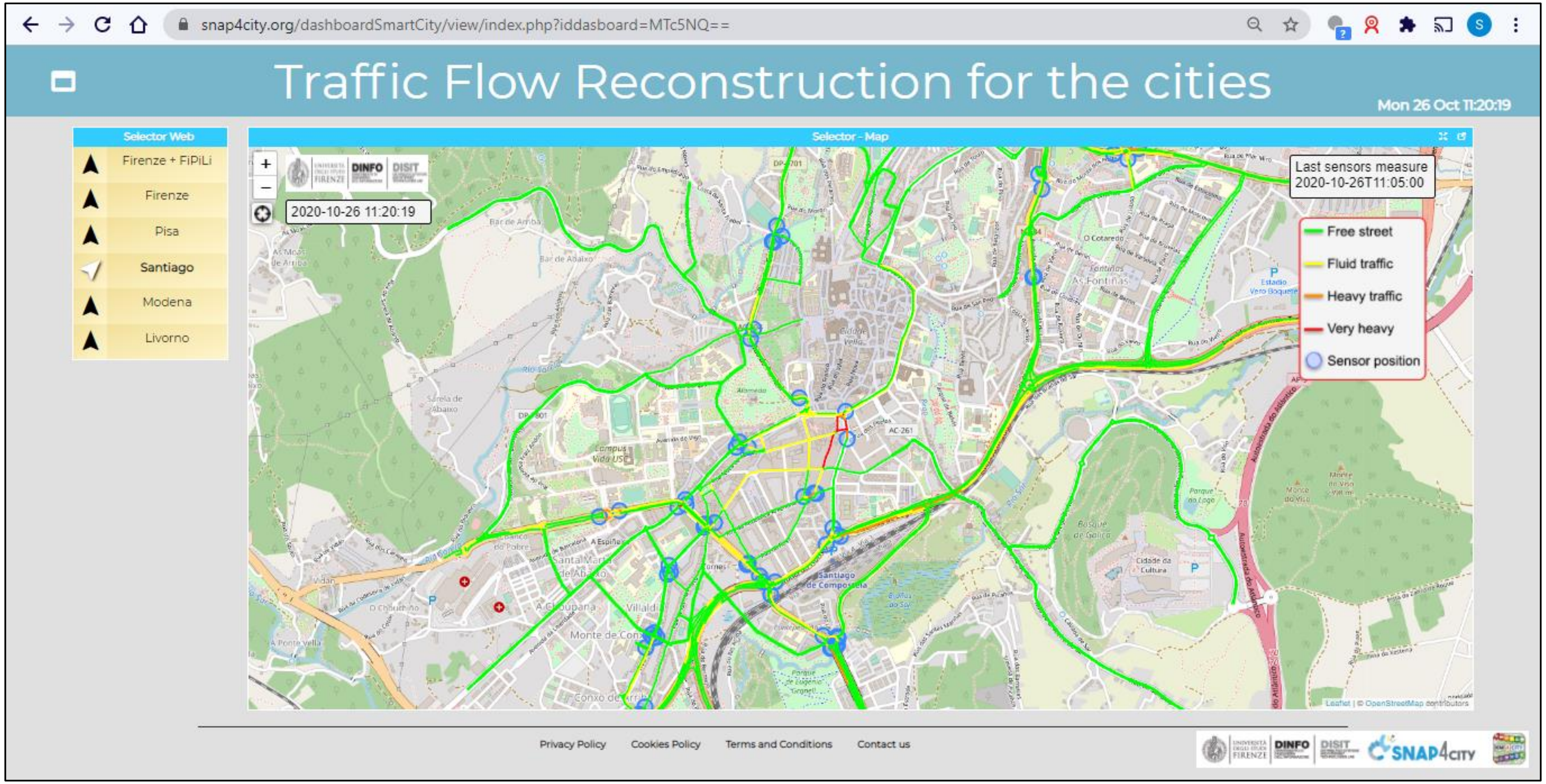
- A network area of Florence consisting of
  - 173 data sensors
  - 1532 junctions
  - 1377 road-segments

  giving the estimation of the vehicular density in 31217 road-units having length 20/30 meters is considered to test the model

- Parallel computing solutions have been adopted

General Approach

More cities



https://www.snap4city.org/dashboardSmartCity/view/index.php?iddasboard=MTc5NQ==

Traffic reconstruction: Application

- Create input for pollution dispersion models: