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BI-LEVEL OPTIMIZATION MODELS FOR ADJUSTMENT OF TIME-SLICED OD MATRICES

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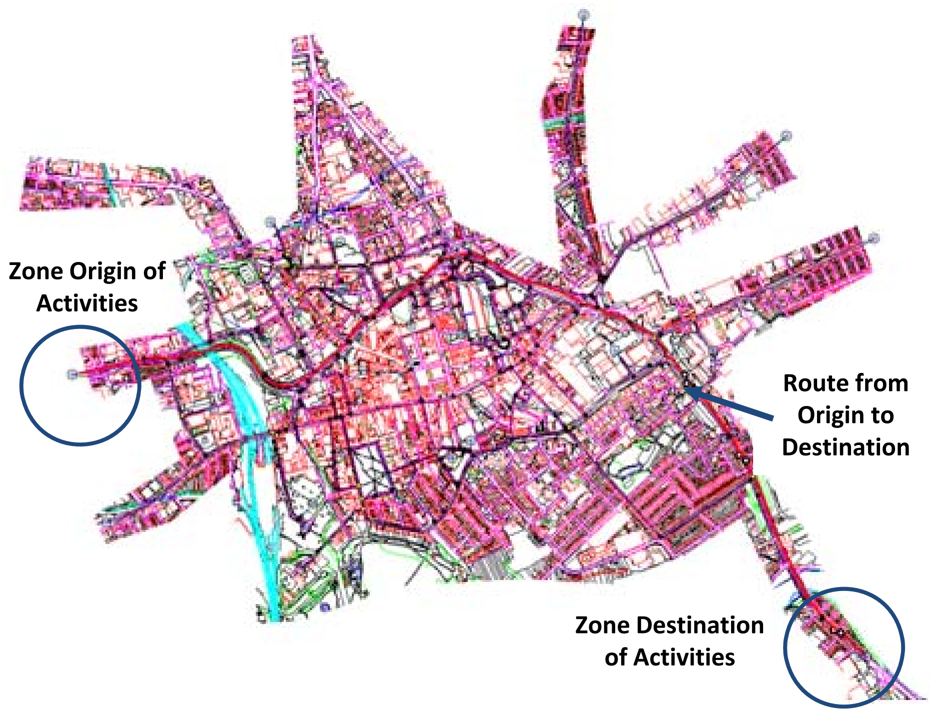
THE SYSTEMS MODELING APPROACH

- Applying the OR methodology to transportation systems
- Understanding the system and how the system works:
  - Components and interactions
  - Formulate modeling hypothesis capturing them
  - Translate modeling hypothesis in terms of a formal representation of the system: the model (or theory)
- "Toda a teoria deve ser feita para poder ser posta em prática, e toda prática deve obedecer a uma teoria…. teoria e a prática complementam-se. Foram feitas a uma para a outra"

(Fernando Pessoa, Revista da Contabilidade, No. 1, p. 5, Janeiro de 1926).

UNDERSTANDING THE MOBILITY OF PERSONS AND FREIGHT

- Mobility is the movement of people and goods efficiently and safely and may be regarded as the ability to travel (When and where the traveler needs, in the most efficient way)
- Mobility is a derived demand and, as such, means for enabling people and freight to ***access*** other people and places to realize activities
- Mobility is thus a mean to the end of ***accessibility***
- Mobility must ensure the realization of accessibility: ***citizens and freight must reach destinations to satisfy needs and have access to places where activities happen***

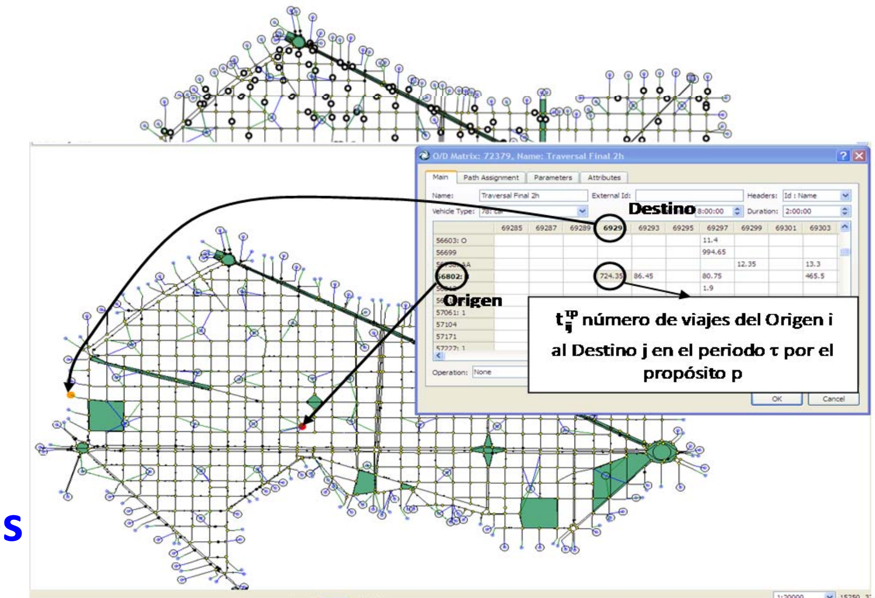


- ***Mobility patterns*** are a consequence of the space and time distribution of these activities
- $\Rightarrow$ Points (zones) where activities are either "***generated***" or "***attracted***" (TAZ transport analysis zones)
- $\Rightarrow$ ***Paths*** connecting (giving access) origins and destinations

CARACTERIZING MOBILITY

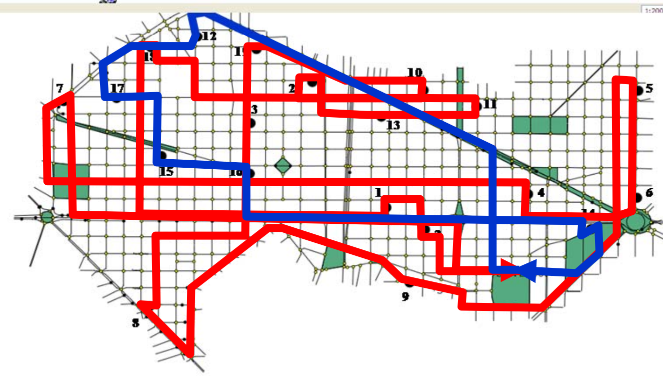
In terms of mobility patterns:

- **Trip matrices (origin-destination)**
- **Number of trips from an origin to a destination for a given purpose (home to work, leisure, shopping, others) in a given time period.**



In terms of itineraries, alternative routes between origins and destinations:

- **Computation of time dependent paths**
- **Modeling the route choice selection processes**



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FORMULATING MODELING HYPOTHESIS USER EQUILIBRIUM (WARDROP)

BEHAVIORAL ASSUMPTION
Each user chooses the route that he perceives the best in terms of travel time

⇩

CONSEQUENCE
If there exists a shorter route than the one a user is using, he will choose it

⇩

EQUILIBRIUM
No user can improve (unilaterally) his travel time

MODELING USER EQUILIBRIUM

Flows on a network are in equilibrium that satisfies Wardrop's user principle when for (r, s) OD-pair, path flows f^*_{rsp} and minimum path costs θ^*_{rs} :

Smith's Variational Inequality (1979)

$$\left.\begin{array}{l} \left(\tau_{rsp}-\theta^*_{rs}\right)f^*_{rsp}=0, \forall p\in P_{rs}, \forall(r,s)\in\Im \\ \left(\tau_{rsp}-\theta^*_{rs}\right)\geq 0 \quad \forall p\in P_{rs}, \forall(r,s)\in\Im \\ \sum_{p\in P_{rs}} f_{rsp}-d_{rs}=0 \quad \forall(r,s)\in\Im \\ f^*_{rsp}\geq 0,\ \theta^*_{rs}\geq 0 \end{array}\right\} \Leftrightarrow \left\{\begin{array}{l} f(v^*)(v-v^*)\geq 0 \\ v\in\Theta=\left\{\begin{array}{l} v: v_a=\sum_{p\in P_{rs}}\sum_{(r,s)\in\Im}\delta_{ap}f_{prs}, \\ \sum_{p\in P_{rs}} f_{rsp}-d_{rs}=0 \quad \forall(r,s)\in\Im \end{array}\right\} \end{array}\right.$$

M. Florian and D. Hearn, Network Equilibrium Models and Algorithms, Chapter 6 in: M.O. Ball et al., Eds., Handbooks in OR and MS, Vol.8, Elsevier Science B.V. (1995).

MATHEMATICAL MODEL (Separable case)

$$\mathrm{Min} \sum_{a \in A} \int_0^{v_a} s_a(x)dx + \sum_{c \in C} \sum_{a \in A} v_a^c \theta^c t_a^c$$

s.t.

$$\sum_{k \in K_i} h_k = g_i \quad \forall i \in I, \quad (I = \{\text{set of O/D pairs}\})$$

$$h_k \geq 0, (\text{flow on path k}), v_a = \sum_{i \in I} \sum_{k \in K_i} h_k \delta_{ak}$$

g_i, demand for the i-th O/D pair

$K_i = \{\text{set of paths connecting the i-th O/D pair}\}$

- **Mathematical model: non-linear network flow model**
- **Algorithms: Frank and Wolfe, RSD, etc.**
- **Model size: usually large networks (urban or metropolitan road networks**
- **Model uses: strategic transport planning, medium to long term effects**

MICROSCOPIC SIMULATION MODEL BUILDING

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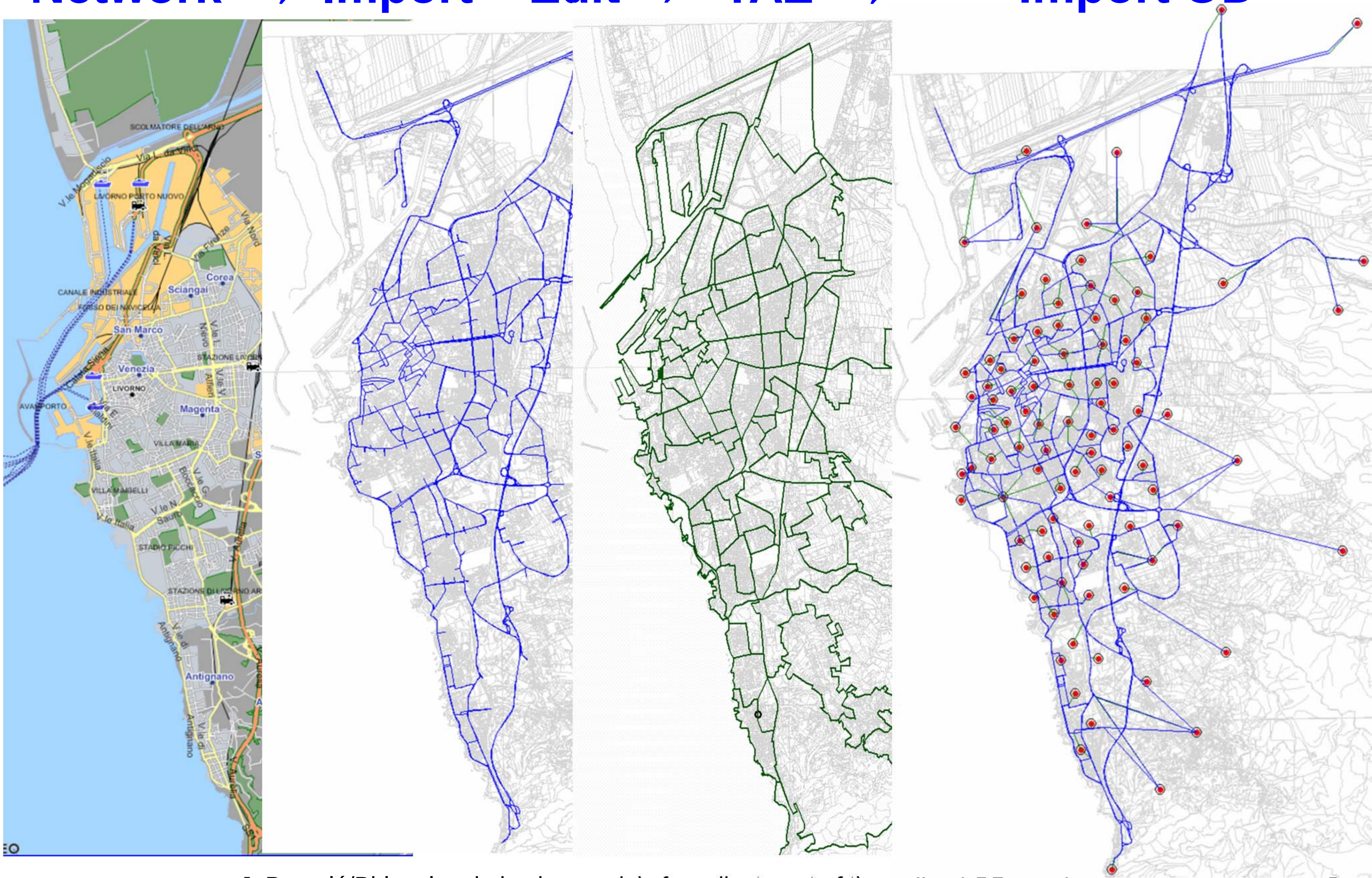
Network → Import + Edit → TAZ → Import OD



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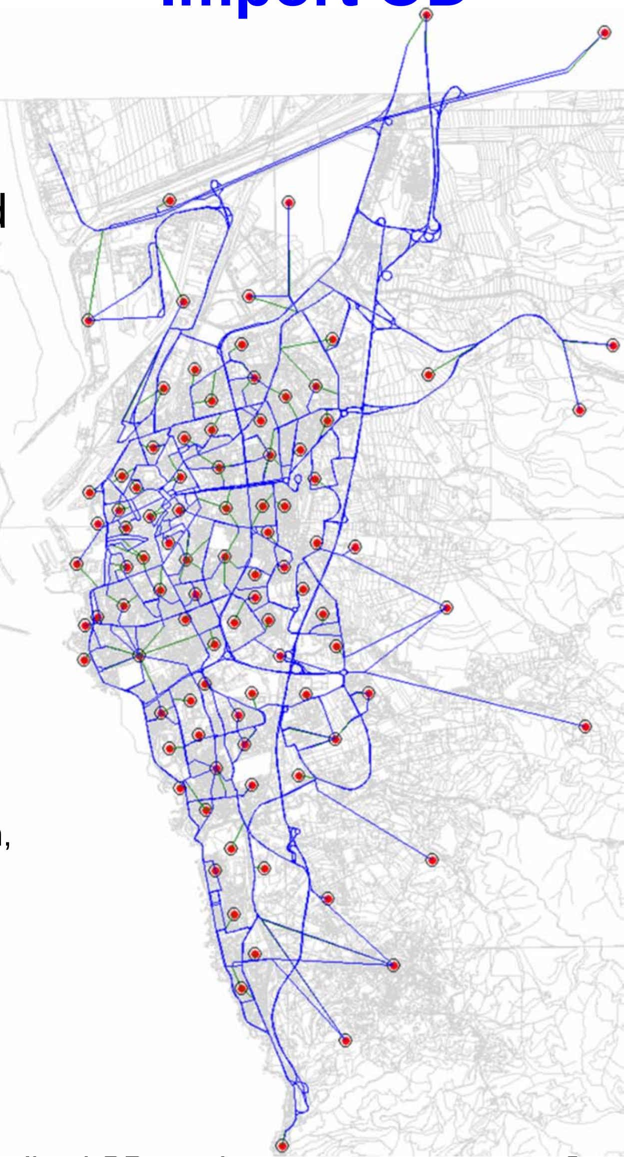
MICROSCOPIC SIMULATION MODEL BUILDING

Network → Import + Edit → TAZ → Import OD

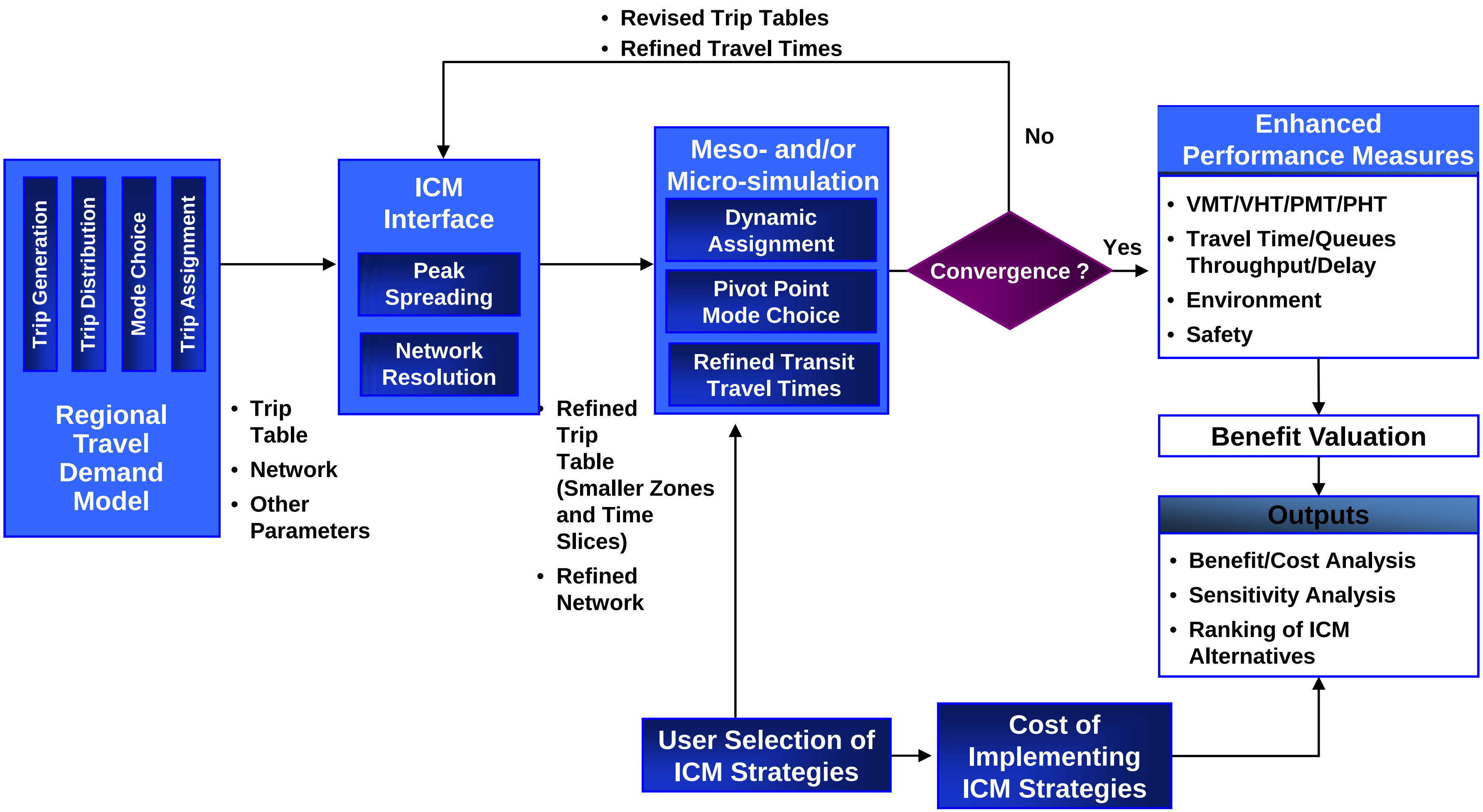
- For a long time the current practice has been based on using as input the same static OD matrices from strategic transport planning demand models
- "Improved" after an adjustment process exploiting traffic data (e.g. flow measurements at detection stations[1])
- Combined with heuristics for time slicing[2]

- Low quality static or "quasi static" inputs to highly sophisticated dynamic traffic models



- [1]H. Spiess (1990), A gradient approach for the OD matrix adjustment problem, Publication 693 Centre de Recherche sur les Transports, Univ. Montréal.
- [2]Spiess H. and Sutter D. (1990), Modeling the daily traffic flows on an hourly basis, Proceedings of the 18th Summer Annual Meeting of PTRC.

INTEGRATED CORRIDOR MANAGEMENT (ICM) ANALYSIS, SIMULATION MODELING (AMS) APPROACH



Source: V. Alexiadis and D. Sallman, Cambridge Systematics; A. Armstrong, SAIC, (2012), Traffic Analysis Toolbox Volume XIII: Integrated Corridor Management Analysis, Modeling, and Simulation Guide, Report No. FHWA-JPO-12-074

MODELS USED IN INTEGRATED TRANSPORTATION ANALYSIS

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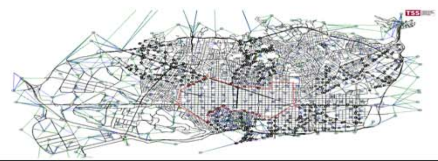
	Travel Demand Models	Mesoscopic Simulation Models	Microscopic Simulation Models
Geographic Coverage	Regional Network / Metropolitan Area 	Regional Network / Metropolitan Area 	Small to medium size subarea networks 
Demand	Static O-Ds	Dynamic OD-s	Dynamic OD-s
Traffic Control	No signal settings	Detailed signal setting & phasing schemes	Detailed signal setting & phasing schemes
Analysis	User equilibrium assignment link costs defined in terms of volume-delay functions	Dynamic user equilibrium based on simulation based network loading	Behavioral modeling based on car-following, lane changing and route choice of individual vehicles
Advantages	Available from local MPO; can analyze mode shift. Low calibration effort	Can analyze regional dynamic diversion. Brings the dynamic dimension into planning analysis. Moderate calibration effort	Suitable for detailed dynamic analysis of operational strategies such as ramp metering, traffic signal coordination and ITS
Limitations	Not sensitive to operational strategies; not capable of analyzing regional dynamic diversion	Not yet capable of analyzing mode shift	Data availability for proper calibration

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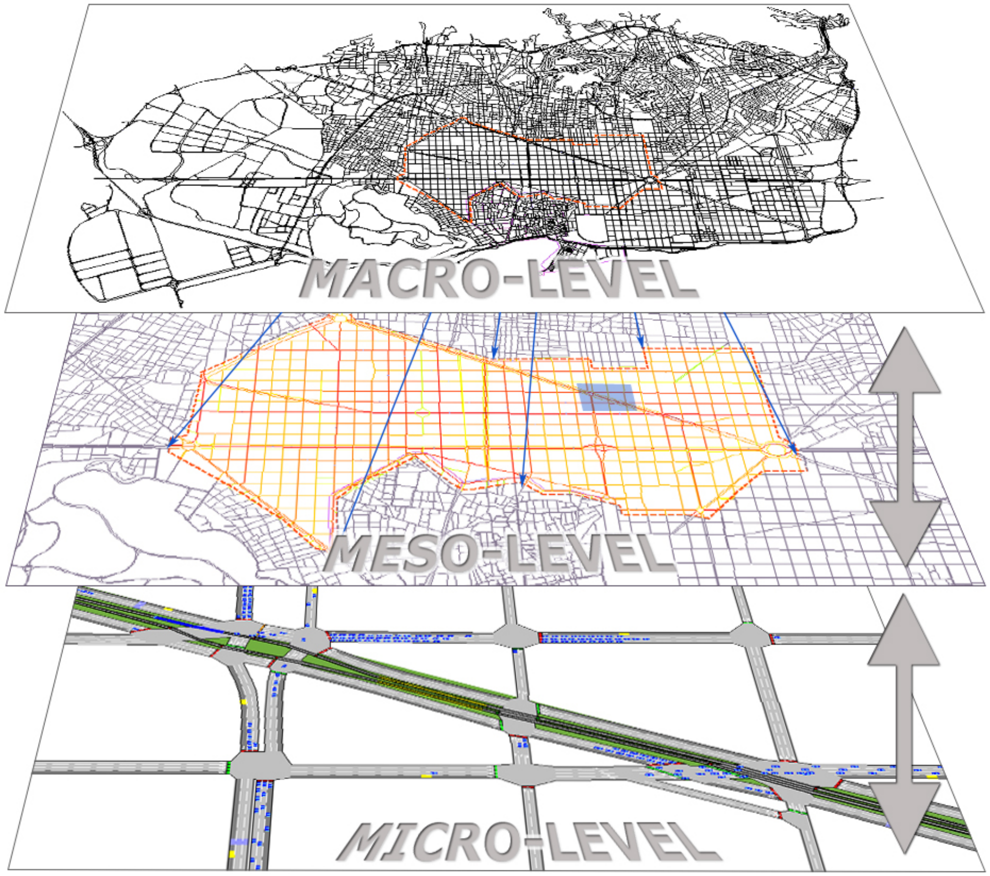
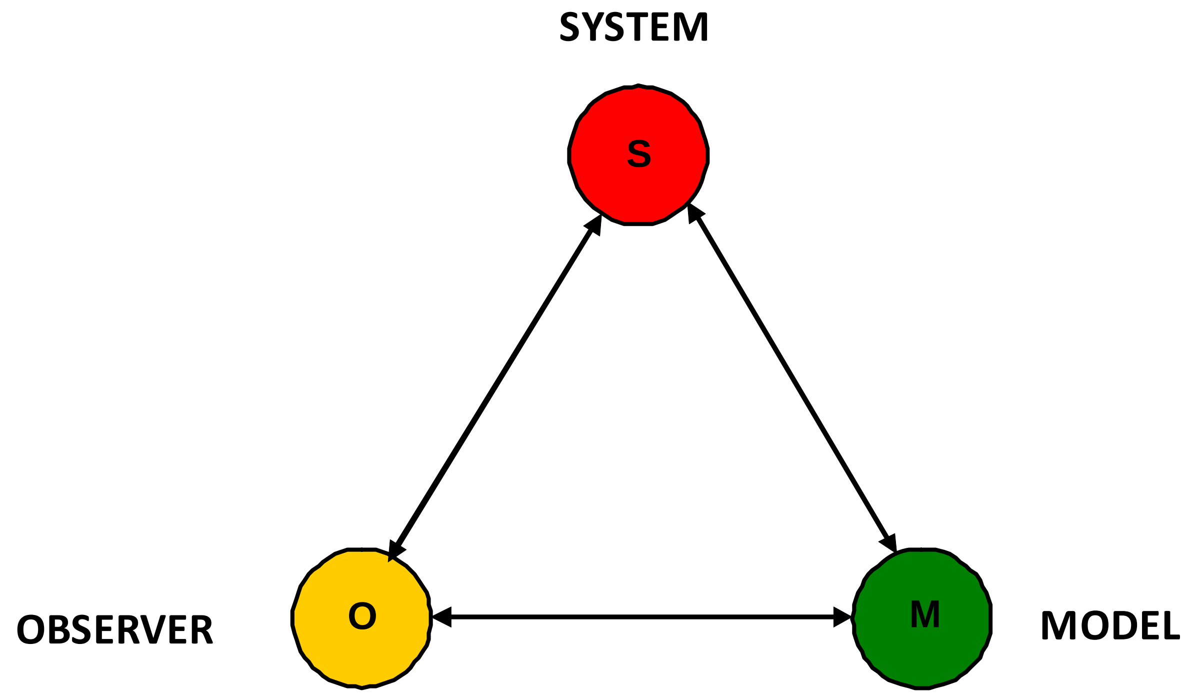
FROM MACRO TO MESO AND MICRO

- The question is not whether one approach is better or more appropriate than other
- Or if there is a unique approach that can replace satisfactorily all others
- But which is the most appropriate use of each approach and how can them work together in a fully integrated common framework



J. Barceló et al. (2005), Methodological notes on combining macro, meso and micro models for transportation analysis, Workshop on Traffic Modeling(*Simulation Models: From the Labs to the Trenches)*, Sedona, 2005.
J. Barceló, J. Casas, D. García and J. Perarnau , A hybrid simulation framework for advanced transportation analysis, ISTS06 (International Symposium on Traffic Simulation 2006), Lausanne, 2006

SYSTEMS, OBSERVERS, MODELS



- An ***object*** **M is a *model* of a *system* S if it can provide valid answers to the questions of an *observer* O on the system S (Minsky)**

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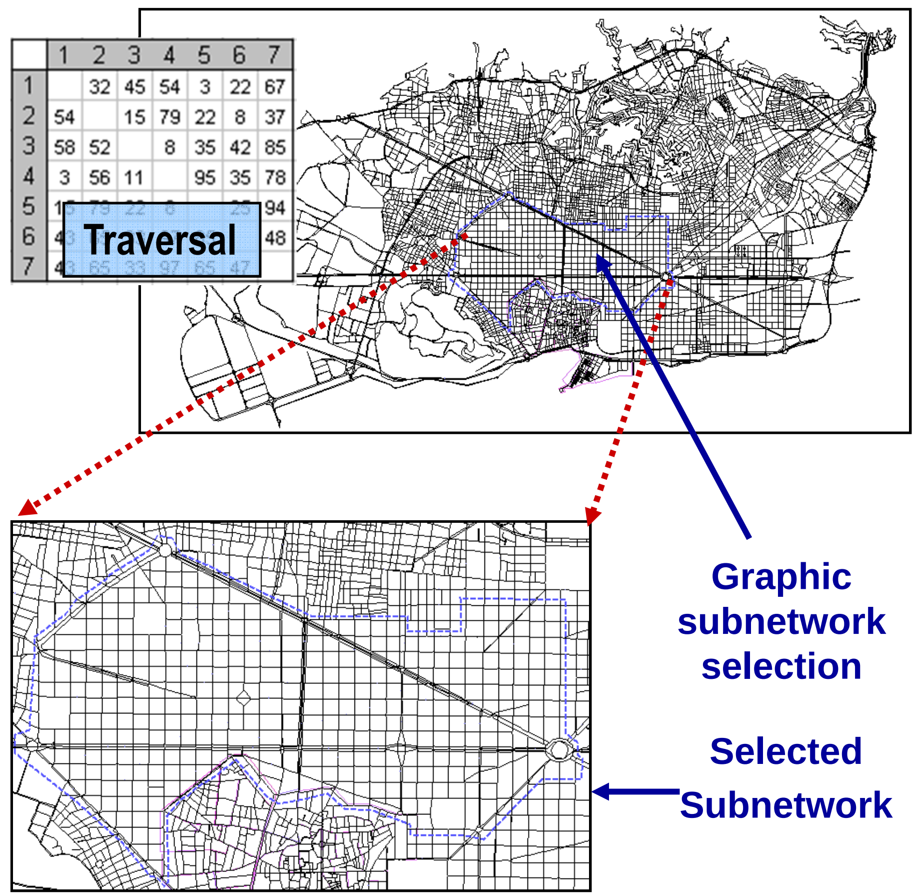
THE METHODOLOGICAL PROCESS COMBINING MACRO⇔MESO⇔MICRO

1. MACRO LEVEL: TRANSPORT PLANNING MODEL OF A REGIONAL OR METROPOLITAN AREA
2. IDENTIFICATION OF CRITICAL SUBAREAS OF INTEREST
3. WINDOWING INTO THE SELECTED SUBAREA
4. AUTOMATIC GENERATION OF SUBAREA MICRO OR MESO MODEL
5. AUTOMATIC GENERATION OF SUBAREA TRAVERSAL OD (IF REQUIRED)
6. ADJUSTMENT OF THE SUBAREA TRAVERSAL OD
7. INPUT TO MESO OR MICRO MODEL AND SUBAREA SIMULATION



DYNAMIC TRAFFIC ASSIGNMENT (DTA)

- Advanced Traffic Management Systems and Advanced Traffic Information Systems (ATIS) need models accounting for flow changes with time, that is
- Dynamic models able to appropriately describe the time dependencies of traffic demand and the corresponding induced traffic flows
- The Dynamic Traffic Assignment Problem (DTA) is the extension of the Traffic Assignment Problem able of determining such time varying link or path flows.
- DTA should have the capability of describing how traffic flow patterns evolve in time and space on the network (Mahmassani 2001).

DUE FORMULATION

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- **It can be shown that the DUE approach can be implemented in terms of solving the following mathematical model:**

$$\left[\tau_{rsp}(t)-\theta_{rs}(t)\right]f_{rsp}(t)=0 \quad \forall p \in P_{rs}(t), \forall (r,s) \in \Im, t \in [0,T]$$

$$\tau_{rsp}(t)-\theta_{rs}(t)\geq 0 \quad \forall p \in P_{rs}(t), \forall (r,s) \in \Im, t \in [0,T]$$

$$\tau_{rsp}(t), \theta_{rs}(t), f_{rsp}(t) \geq 0$$

- **And the flow balancing equations**

$$\sum_{p \in P_{rs}(t)} f_{rsp}(t) = d_{rs}(t) \quad \forall (r,s) \in \Im, t \in [0,T]$$

- **Where $f_{rsp}(t)$ is the flow on path p from r to s departing origin r at time t**
- **$\tau_{rsp}(t)$ is the actual path cost from r to s on route p at time t**
- **$\theta_{rs}(t)$ is the cost of the shortest path from r to s departing from origin r at time t**
- **$P_{rs}(t)$ is the set of all available paths from r to s at time t**
- **$\Im$ is the set of all origin-destination pair (r,s) in the network**
- **$d_{rs}(t)$ is the demand (number of trips) from r to s at time interval t.**

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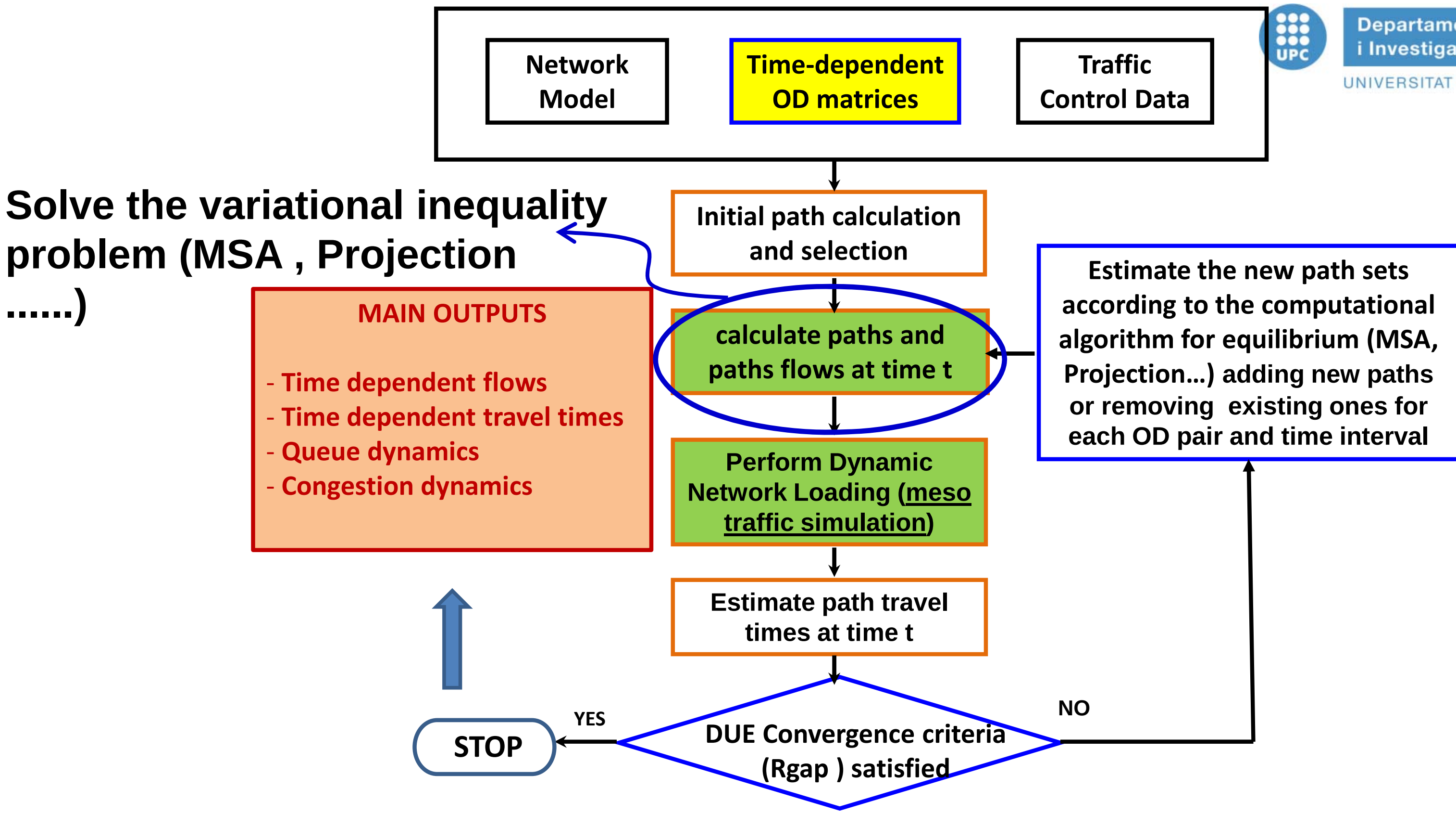
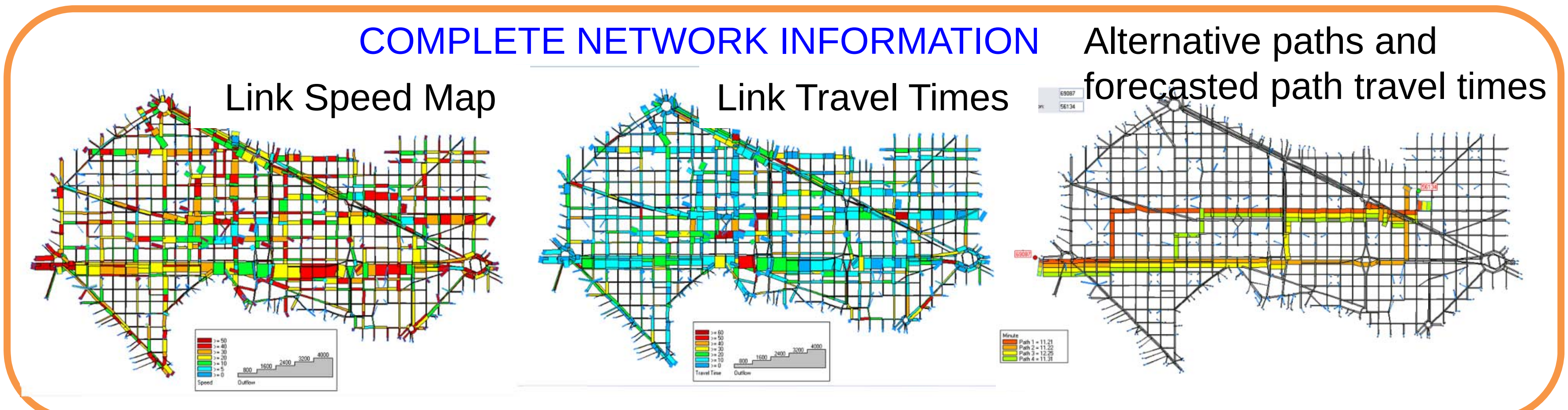
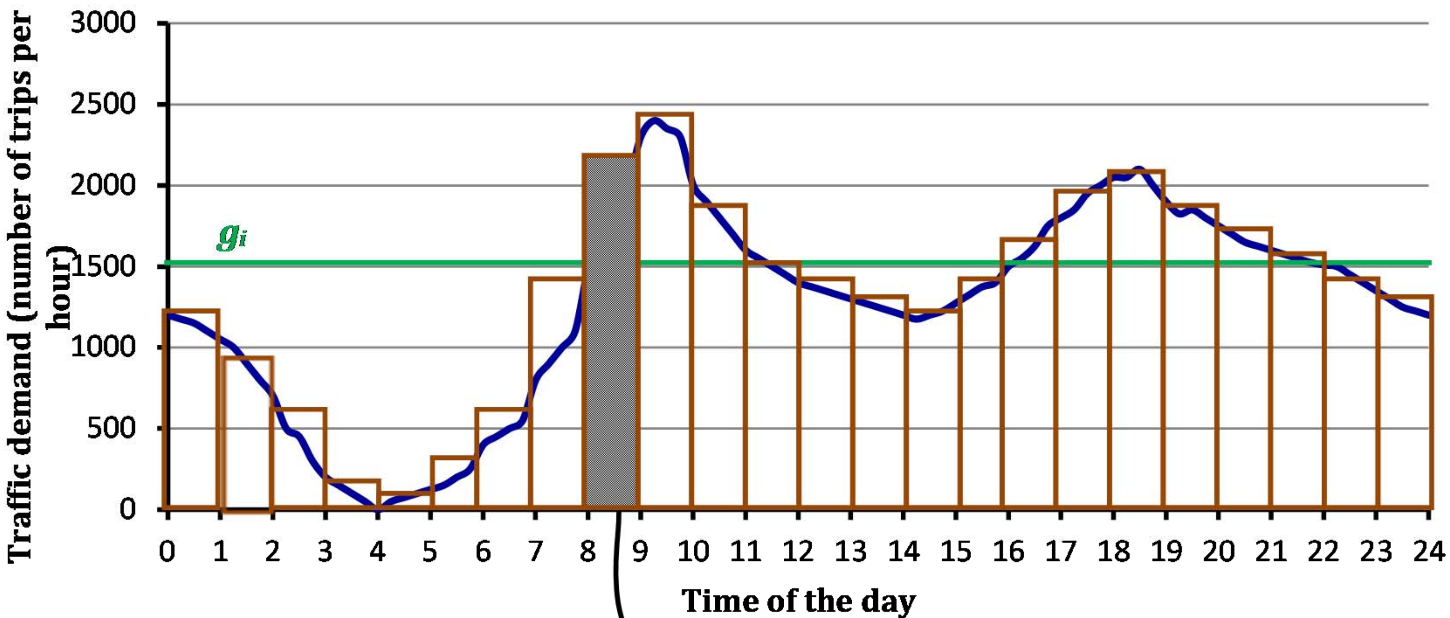
Traffic Network Space State Estimation and Short Term Forecasting Based on a Dynamic Traffic Model Mesoscopic Traffic Simulation





A COMMON PRACTICAL HEURISTIC APPROACH TO ESTIMATE TIME-SLICED OD MATRICES

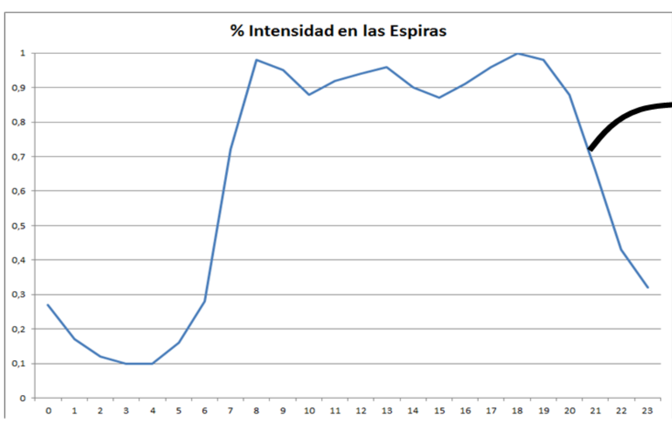
Within-day time variability of traffic demand $g_i(t)$ of i-th OD pair



$$
\left.\begin{array}{c} g(t) \to \{g^1(t),\ldots,g^j(t),\ldots,g^{n_h}(t)\} \\ g_i^j(t) \sim g_i^j = \alpha^j g_i \\ \hat{v}_a^j, a \in \hat{A} \subseteq A \end{array}\right\} \to \tilde{g}_i^j
$$

α^j

Adjusted OD matrix for time-slice j^th from link flow counts



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THE OD MATRIX IS USUALLY AJUSTED FROM LINK FLOW COUNTS USING A BILEVEL OPTIMIZATION APPROACH

$$\min_g F(g,v) = \gamma_1 \cdot F_1(g,\hat{g}) + \gamma_2 \cdot F_2(v,\tilde{v})$$
$$s.t.: v = assign(g)$$
$$v, g \geq 0$$

Upper level
γ_1,γ_2 weights, F_1, F_2 Distance Functions
Non Linear Optimization Problem

$$\underset{g,v}{\text{MIN}}\, F(g,v) = \gamma_1 F_1(g,\hat{g}) + \gamma_2 F_2(v(g),\hat{v})$$
$$g \in \Omega$$

g → (to lower level)

v ← (to upper level)

Lower level
User Equilibrium Traffic Assignment

$$v(g) = \arg\min \sum_{a \in A} \int_0^{v_a} s_a(x)dx$$
$$\text{s.t.} \sum_{k \in K_i} h_k = g_i, \quad \forall i \in I$$
$$h_k \geq 0, \quad \forall k \in K_i, \ \forall i \in I$$
$$v_a = \sum_{i \in I} \sum_{k \in K_i} \delta_{ak} h_k$$

A MODIFIED BILEVEL IN WHICH

THE LOWER LEVEL EQUILIBRIUM ASSIGNMENT IS REPLACED BY A DUE

IMPROVED ACCOUNTING FOR ICT (BLUETOOTH) MEASURED TRAVEL TIMES

A BILEVEL –DUE (*)

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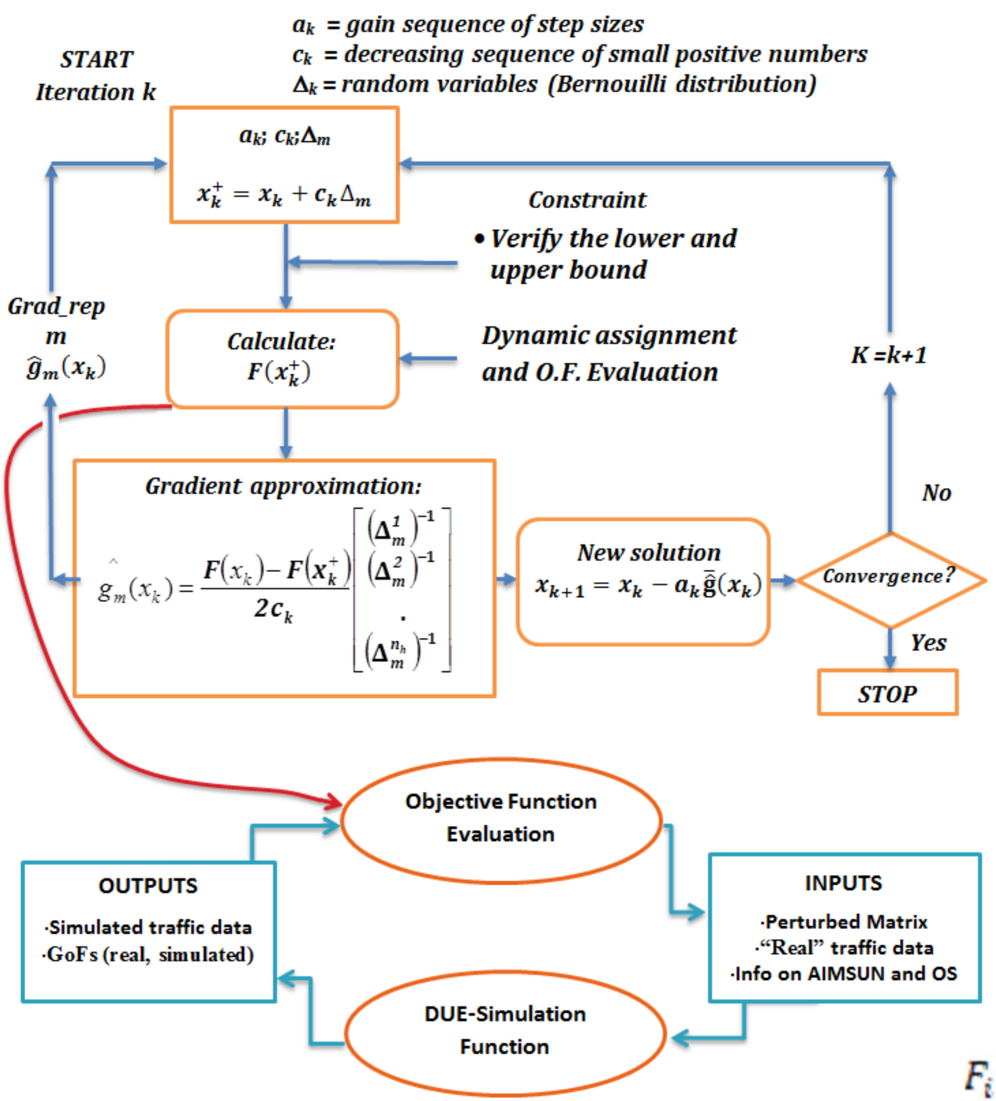

- Replace the lower level assignment problem by a DUE
- Conducted with Aimsun Meso in the computational experiences in EU COST ACTION, TU903, MULTITUDE
- Solve upper level optimization

$$MIN\ F(g^1 \dots g^{n_h}) = \sum_i^m \gamma_i F_i(x^1 \dots x^{n_h}; \hat{x}^1 \dots \hat{x}^{n_h})$$

$$(g^{lw1} \dots g^{lwn_h}) \leq (g^1 \dots g^{n_h}) \leq (g^{ub1} \dots g^{ubn_h})$$

$$\sum_{i=1}^{n_h} G_o^i \leq G_o^*, \forall o \in \{Origins\ Set\}$$

- by a derivative free method based on Simultaneous Perturbation Stochastic Approximation (SPSA) that evaluates the objective function

$$F_i(x^1 \dots x^{n_h}; \hat{x}^1 \dots \hat{x}^{n_h}) = (x - \hat{x})^T V_i^{-1}(x - \hat{x}), i = 1,2,3$$

- by simulation

(*) Cipriani E., Florian M., Mahut M. and Nigro M. (2011), A gradient approximation approach for adjusting temporal origin-destination matrices, Transportation Research Part C 19 270–282

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A MODIFIED SPSA ALGORITHM USING PROJECTED GRADIENT AND TRUST REGION

J. Barceló, L. Montero A robust framework for the estimation of dynamic OD trip matrices for reliable traffic management. 18th Euro Working Group on Transportation, EWGT 2015, 14-16 July 2015, Transportation Research Procedia 10 (2015) 134 – 144

ENHANCED BILEVEL-DUE APPROACH INCLUDING BLUETOOTH MEASURED TRAVEL TIMES

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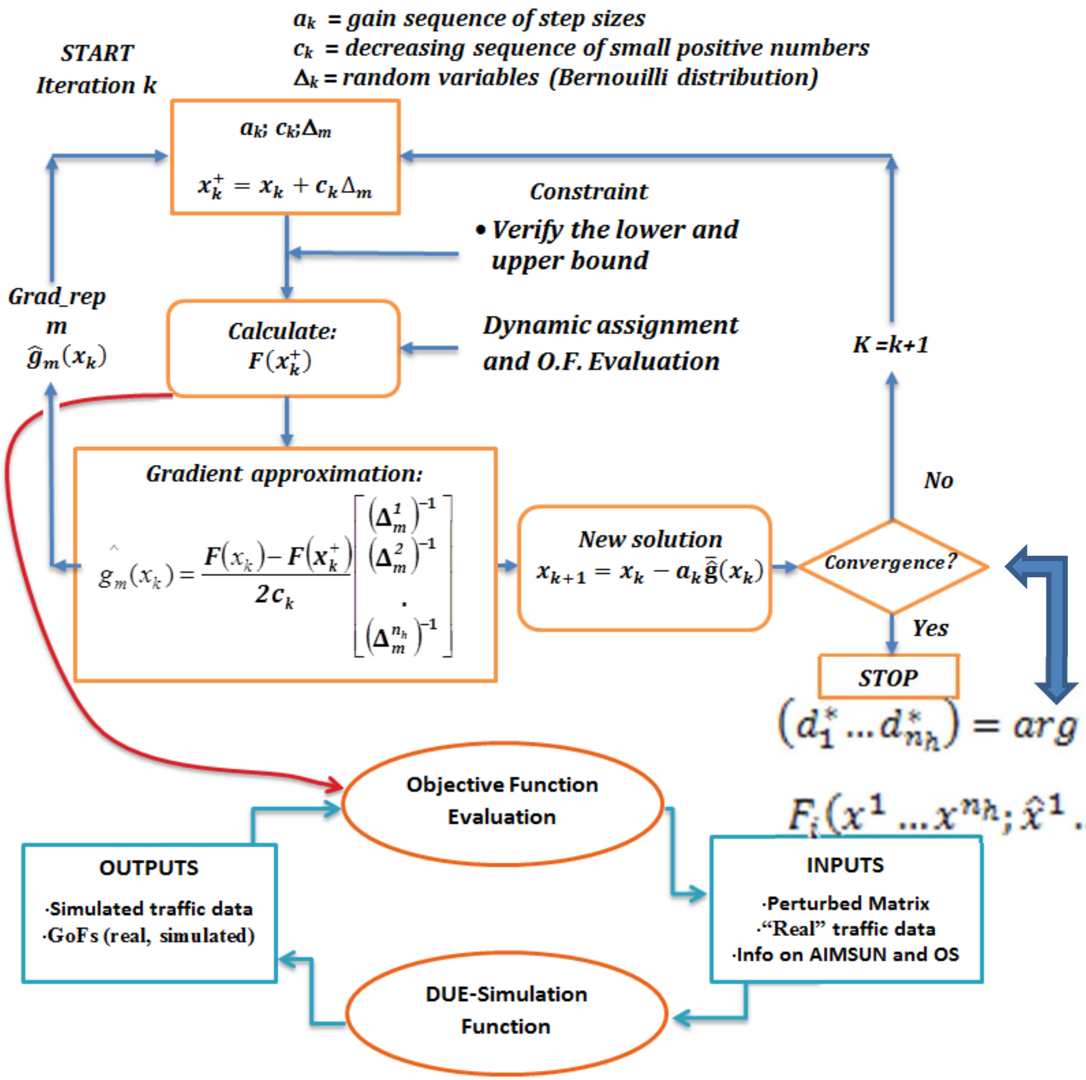

- The objective function has now 4 terms, for distances:
- Between measured and estimated OD terms, link flows, link speeds and
- Travel times between pairs of Bluetooth antennas along specific subpaths

$$f_4(t_1 \dots t_{n_h}, \hat{t}_1 \dots \hat{t}_{n_h})$$

$$(d_1^* \dots d_{n_h}^*) = arg \quad min_{(x_1 \dots x_{n_h}) \geq 0} [\sum_i^m \gamma_i f_i(x^1 \dots x^{n_h}; \hat{x}^1 \dots \hat{x}^{n_h})]$$

$$F_i(x^1 \dots x^{n_h}; \hat{x}^1 \dots \hat{x}^{n_h}) = (\mathbf{x} - \hat{\mathbf{x}})^T V_i^{-1} (\mathbf{x} - \hat{\mathbf{x}}), i = 1,2,3,4$$

- SPSA has been modified to accomodate the new terms
- Estimated travel times have to be computed from Mesoscopic model

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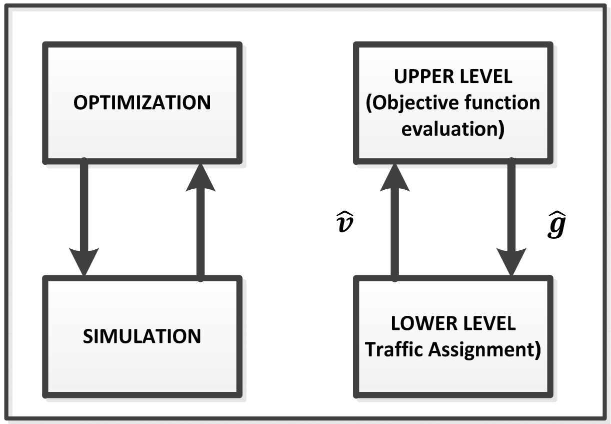
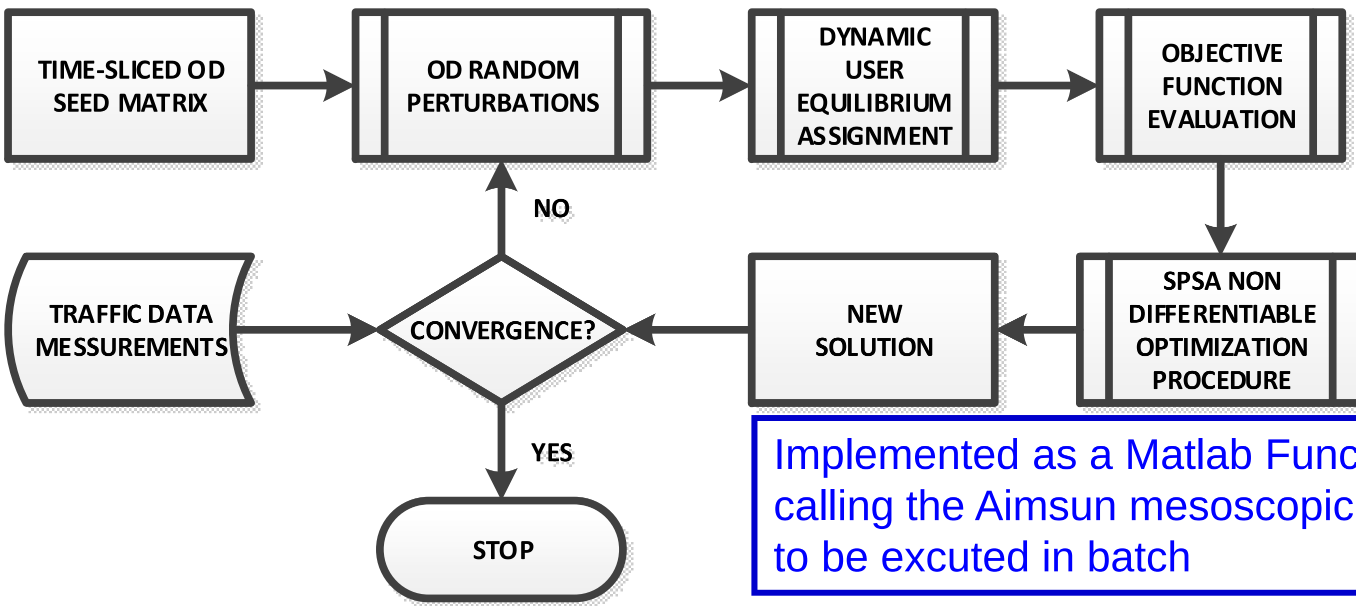
OUTLINE OF THE SPSA BILEVEL DUE ASSIGNMENT



Iteration k
Matrix g^k → Call to DUE-Simulation Function → objective
M gradient approximations
g^k→ Perturbation (g^{k+})
Matrix g^{k+} → Call to DUE-Simulation → objectiveplus
Gradient = ((objectiveplus - objective)/ck)* (SPV);



Implemented as a Matlab Function calling the Aimsun mesoscopic model to be excuted in batch

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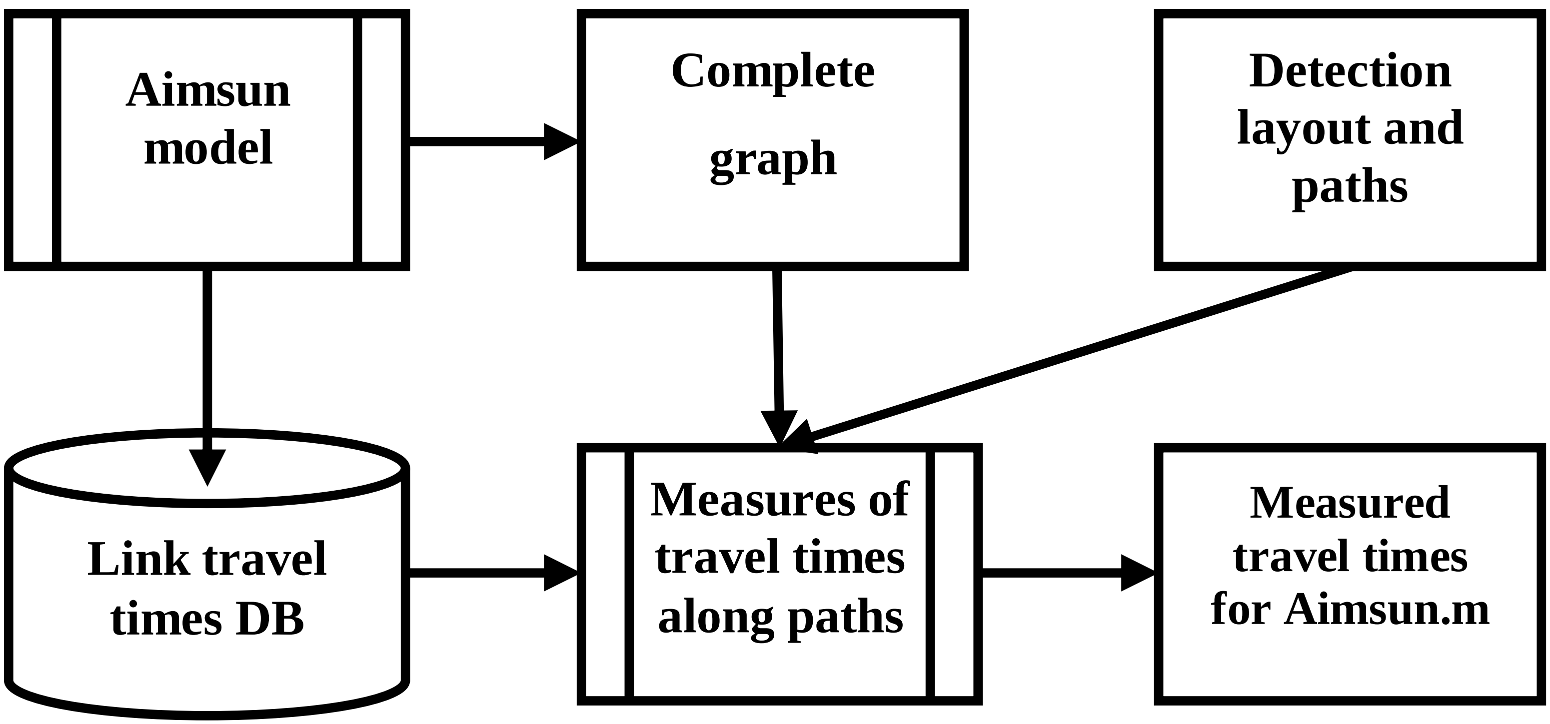
INTERMEDIATE STEP TO ESTIMATE PATH TRAVEL TIMES BETWEEN PAIRS OF BLUETOOTH ANTENNAS



MODIFIED SPSA

- Replace gradient optimization by conjugated gradient optimization:

$$\boldsymbol{x}_{k+1} = \boldsymbol{x}_k - \boldsymbol{a}_k(\overline{\widehat{\boldsymbol{g}}}(\boldsymbol{x}_k) + \boldsymbol{\beta}\overline{\widehat{\boldsymbol{g}}}(\boldsymbol{x}_{k-1})) \qquad \boldsymbol{\beta} = \frac{\left\|\overline{\widehat{\boldsymbol{g}}}(\boldsymbol{x}_k)\right\|^2}{\left\|\overline{\widehat{\boldsymbol{g}}}(\boldsymbol{x}_{k-1})\right\|^2}$$

- Restrict the search to a trust region to build, at each iteration, a search range which "trusts" in a neighborhood of the current solution.
  - **Analyze the size and number of trips of the seed matrix.**
  - **Based on this analysis, a search range is established for each time slice in particular and for the number of trips of the entire matrix in general.**
  - **Let n_s be the number of time slices. Then the trust region is:**

$$(\boldsymbol{1} - \boldsymbol{\gamma}_1) * \boldsymbol{TS}_j(\widehat{\boldsymbol{d}}) < \boldsymbol{TS}_j(\boldsymbol{X}^+) < (\boldsymbol{1} + \boldsymbol{\gamma}_1) * \boldsymbol{TS}_j(\widehat{\boldsymbol{d}}) \qquad \boldsymbol{\gamma}_1 \boldsymbol{\epsilon}\ (\boldsymbol{0.01}, \boldsymbol{0.1})$$

$$(\boldsymbol{1} - \boldsymbol{\gamma}_2) * \widehat{\boldsymbol{d}} < \boldsymbol{X}^+ < (\boldsymbol{1} + \boldsymbol{\gamma}_2) * \widehat{\boldsymbol{d}} \qquad \boldsymbol{\gamma}_2 \leq \boldsymbol{\gamma}_1$$

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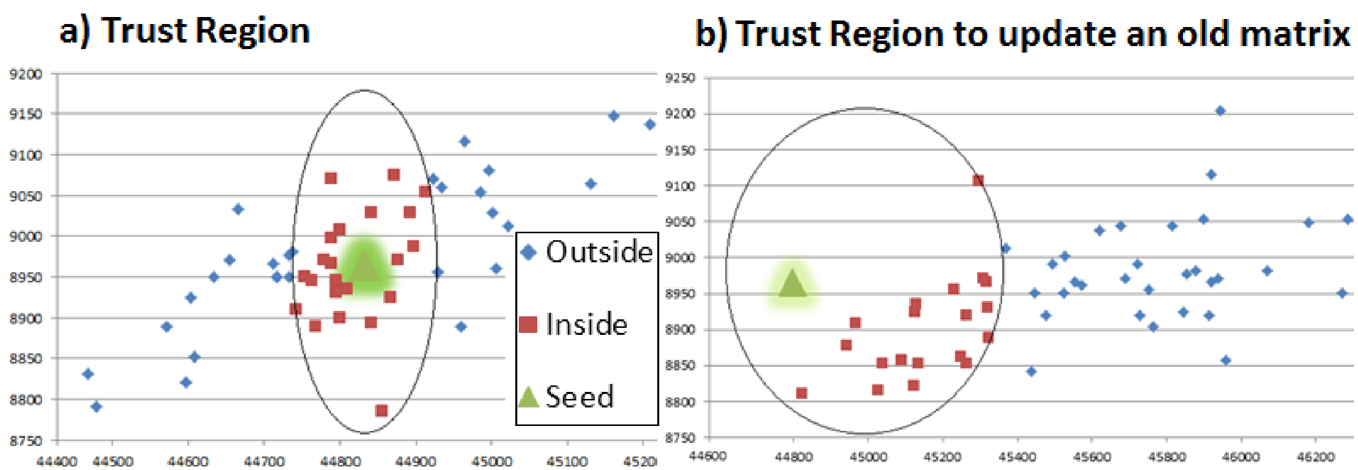
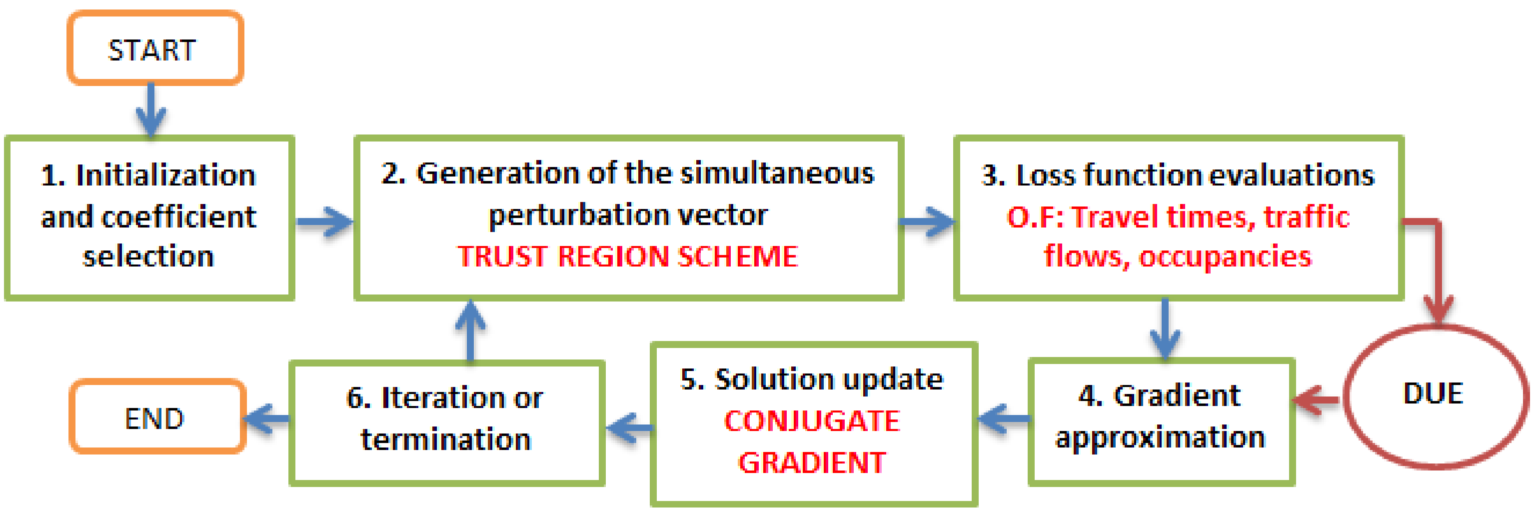
BILEVEL DUE MODIFIED SPSA ALGORITHM (CONJUGATED GRADIENT & TRUST REGION)





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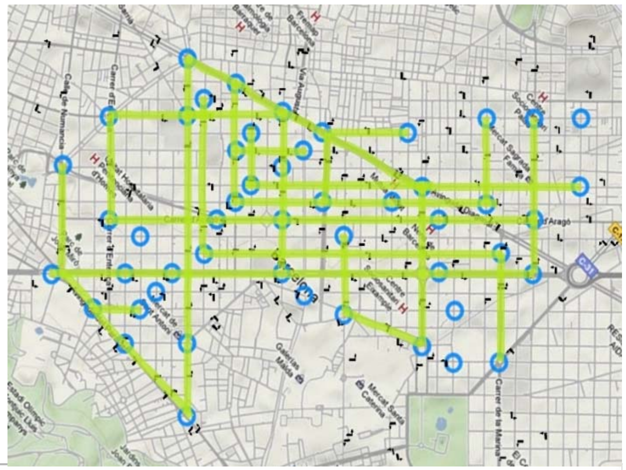
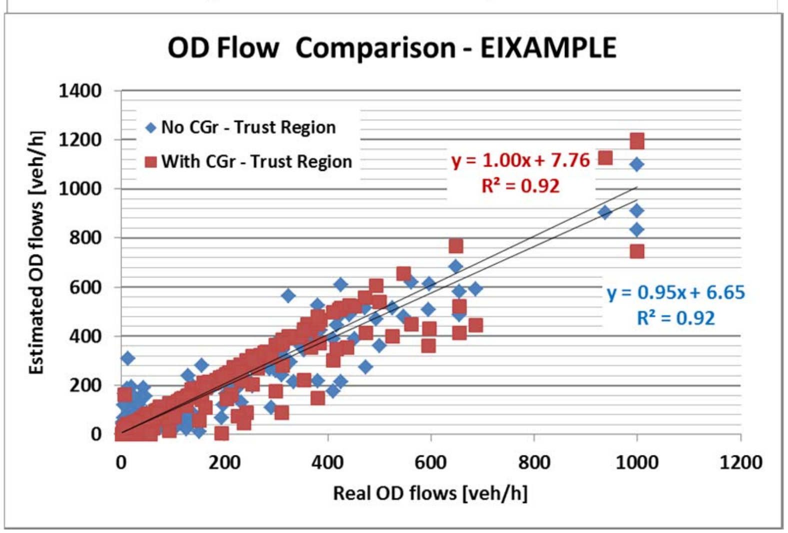
COMPUTATIONAL RESULTS (BARCELONA & VITORIA)

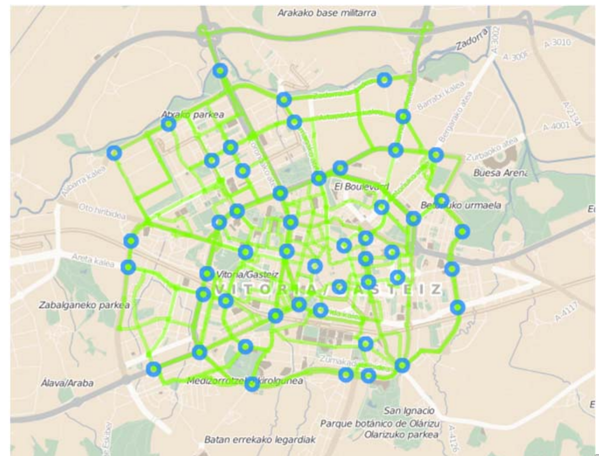
Barcelona's Central Business District (CBD), Eixample, 2111 sections, 1227 nodes 120 generation centroids, 130 destination centroids (877 non-zero OD pairs) 116 Loop detector Stations & 50 Bluetooth Antennas

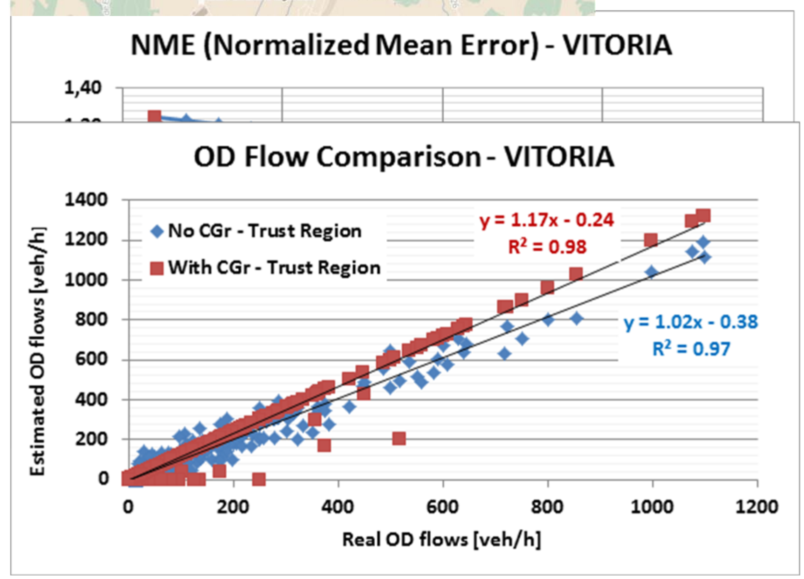


NME (Normalized Mean Error) - EIXAMPLE



Vitoria (Basc 57 centroids and 2800 intersections. 389 loop detectors and 50 ICT sensors





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Identification of time-dependent mobility patterns in terms of Origin-Destination (OD) Matrices Exploiting ICT measurements

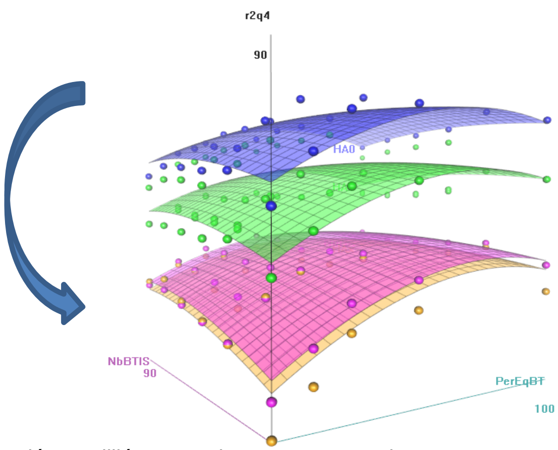
Off-line estimation of a good input OD seed per time interval

$$\min_g F(g,v) = \gamma_1 \cdot F_1(g,\hat{g}) + \gamma_2 \cdot F_2(v,\tilde{v})$$
$$s.t.: v = assign(g)$$
$$v, g \geq 0$$

Nonlinear bilevel nondifferentiable optimization problem solved using:

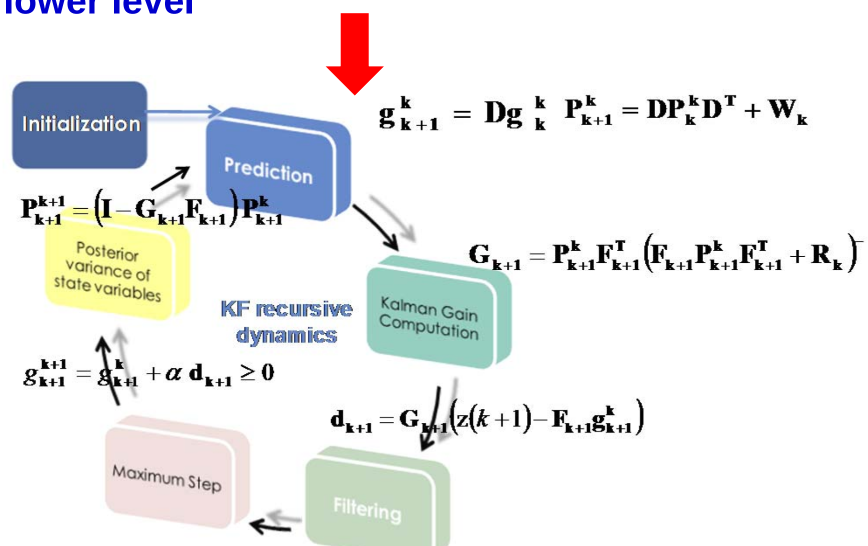
-A special version of Stochastic Perturbation Stochastic Approximation at the upper level

- A Dynamic User Equilibrium Assignment at the lower level



Factors determining the quality of the estimation:

1. **% technology penetration**
2. **Detection layout**
3. **Input OD seed**



Barceló, J., Gilliéron, F., Linares, M.P., Serch, O., Montero, L., (2012). Exploring Link Covering and Node Covering Formulations of Detection Layout Problem. Transportation Research Records 2308, pp.17-26.
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Online Ad Hoc Kalman Filter to estimate the time dependent OD

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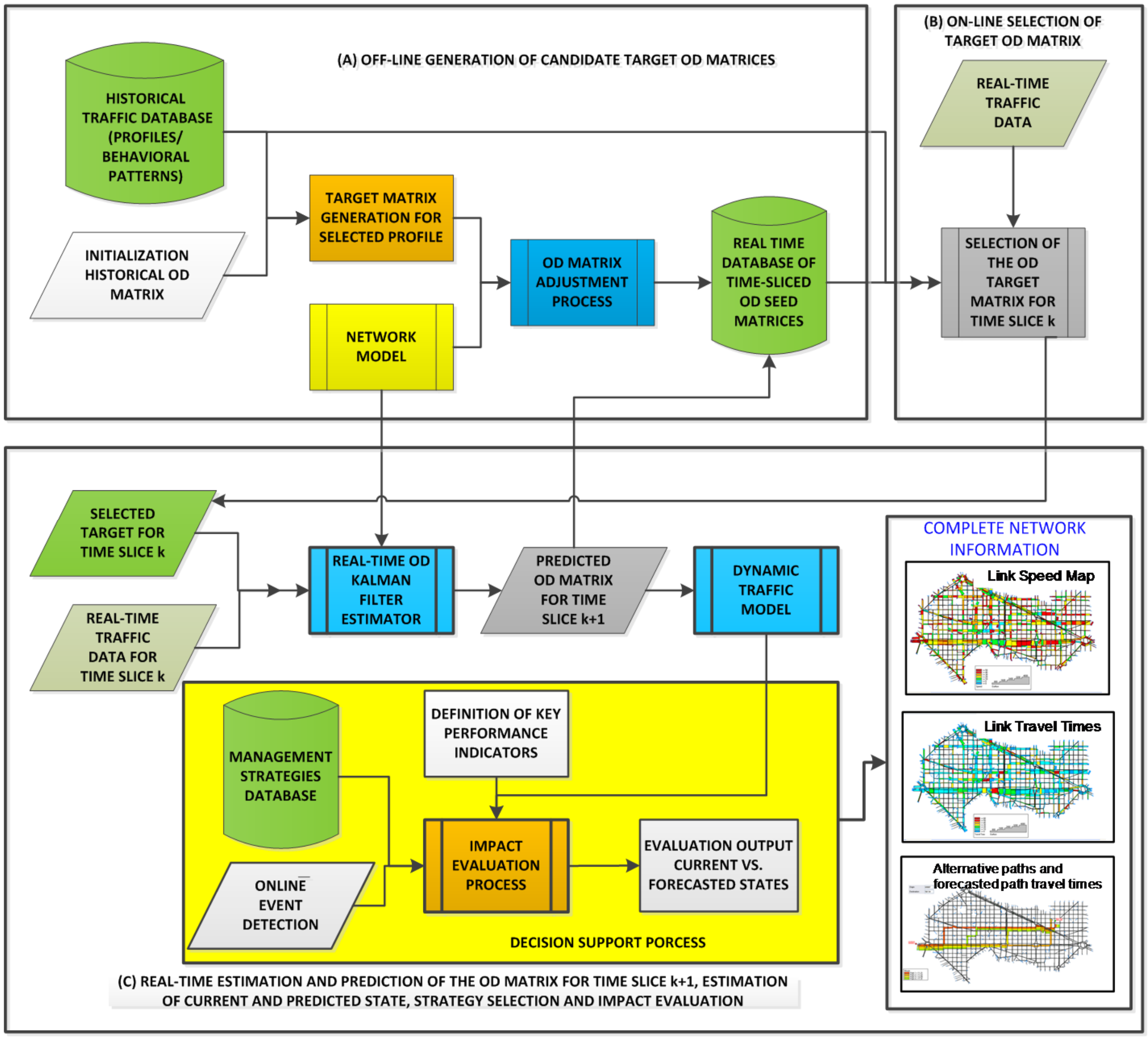
CONCEPTUAL ARCHITECTURE OF THE DECISION SUPPORT SYSTEM FOR ADVANCED TRAFFIC MANAGEMENT AND INFORMATION



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CONCLUSIONS

- ICT measures can be exploited by the modified bilevel, which heuristically solves the lower level optimization with a DUE using a mesoscopic simulation for the DNL.
- However, the computational times make the measures useful only for off-line applications.
- It also provides a quite good time-sliced OD that is suitable for the initialization of Kalman Filter for real-time applications when we require the detection layout, the level of ICT penetration and initialization quality.

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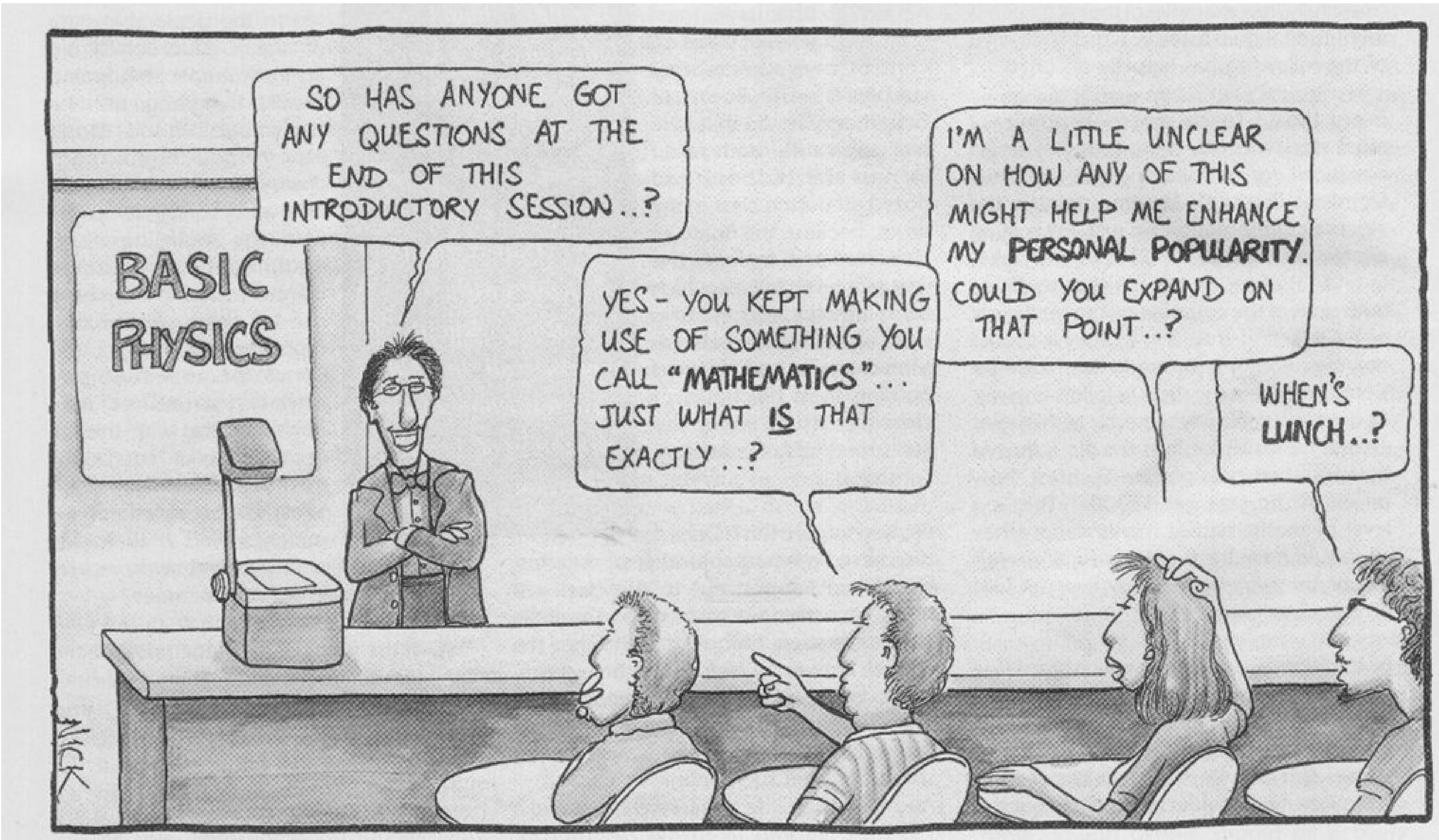
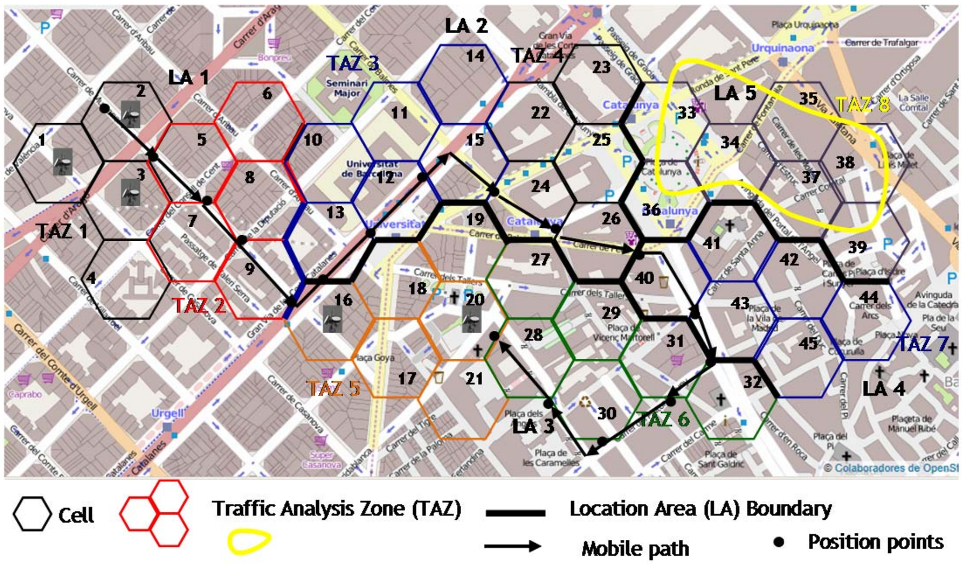
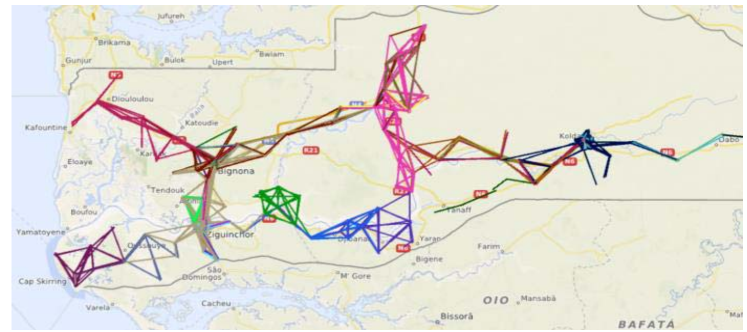
THANK YOU VERY MUCH FOR YOUR ATTENTION

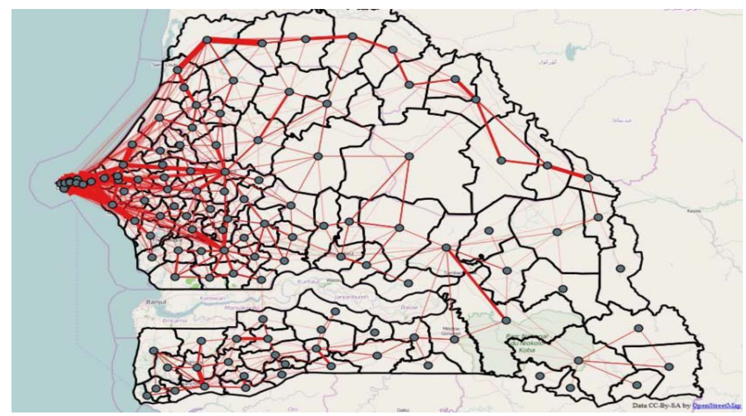


EXPLOITING MOBILE PHONE DATA *(tracking cell phones)*





Example of sequence aggregates



OD demand on the census tract level

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MOBILITY KNOWLEDGE ACQUISITION ⇒
DATA COLLECTION (mobile devices) ⇒
BIG DATA
DYNAMIC INSIGHTS **Smart Steps**

https://dynamicinsights.Telefonica.com/blog/488/smart-steps-2

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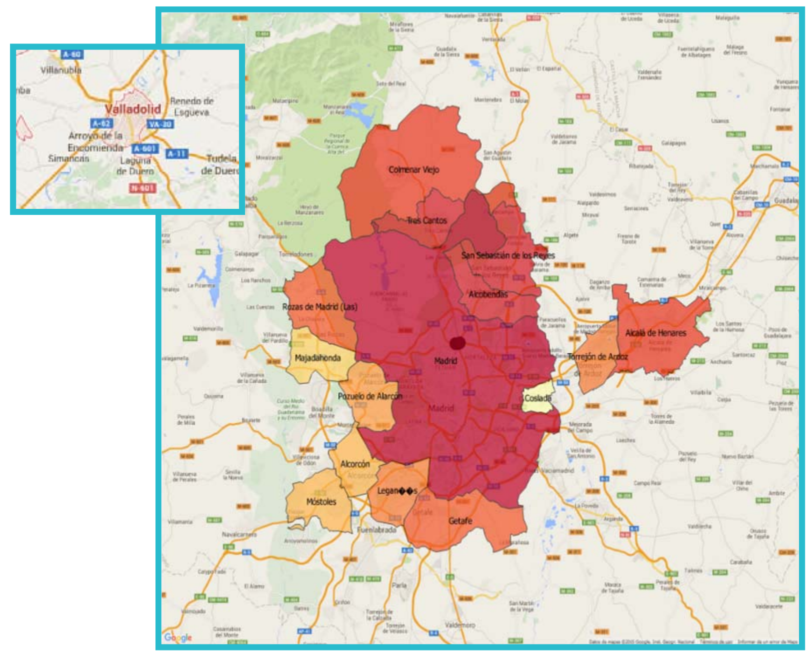
WHICH MUNICIPALITIES GENERATE MOST TRAFFIC IN THE NUDO DE MANOTERAS?

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EXTRACTION
Mobile event data extracted and stored from our network.
ANONYMIZATION
Personal data eliminated and hashed with an ID.
EXTRAPOLATION
Algorithms applied to represent entire population of Spain.
AGGREGATION
IDs grouped to crowd data, no individual is identifiable.
Smart Steps

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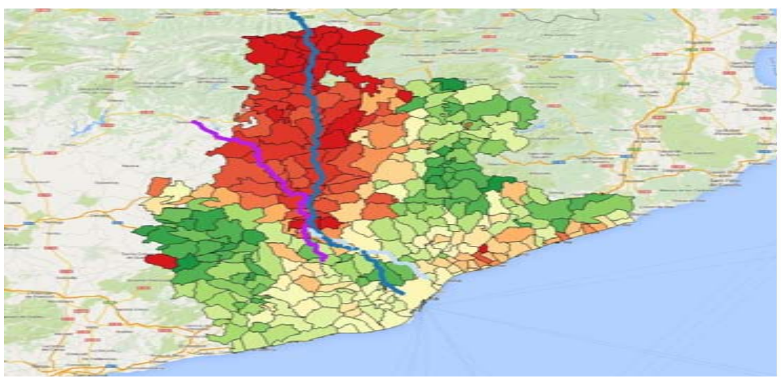
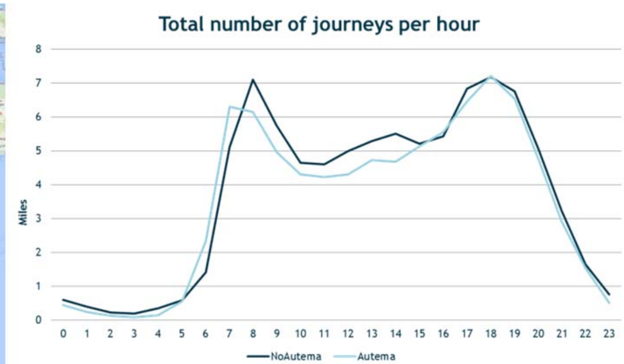
cintra

Analysis of the traffic on the Manresa – San Cugat del Valles road. OD Matrix for all surrounding areas of the road.





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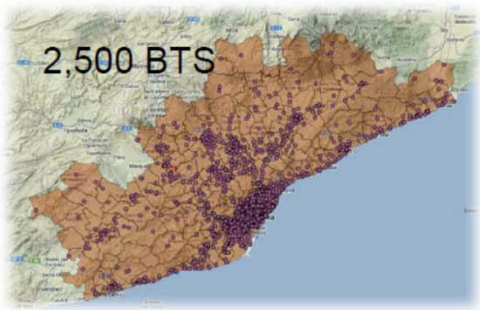
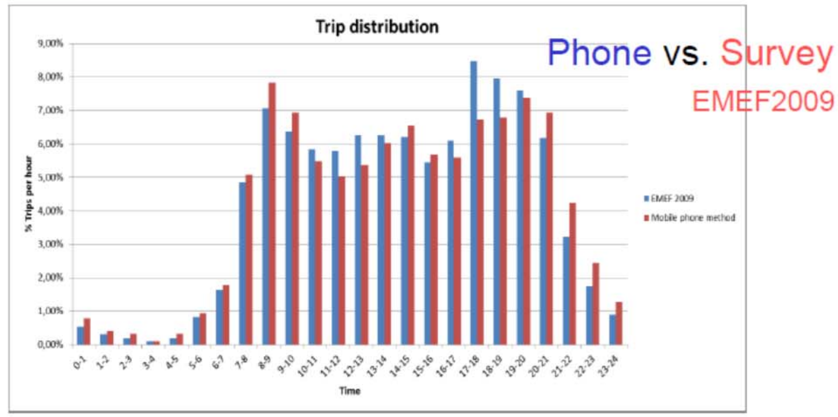
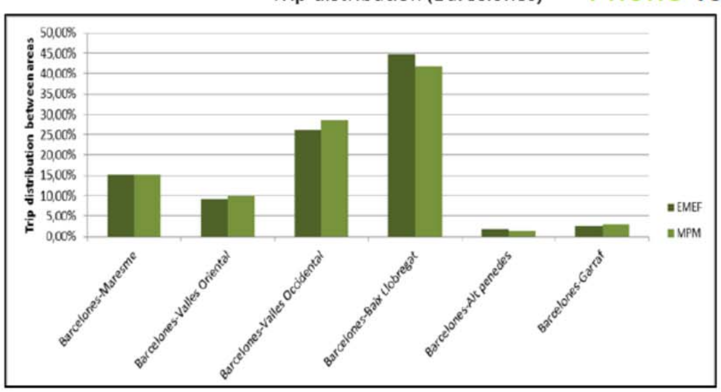
ODs from mobile phone data

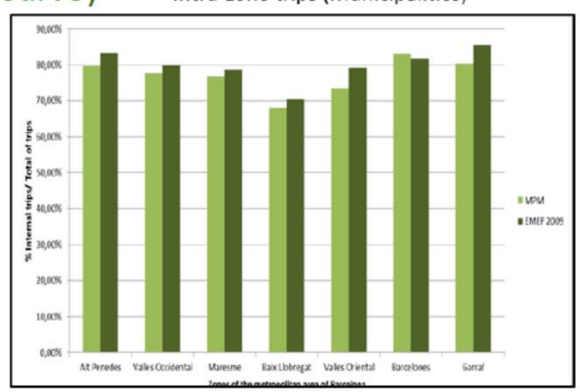




LOW COST ODs

Trip distribution (Barcelonès) Phone vs. Survey Intra-zone trips (Municipalities)





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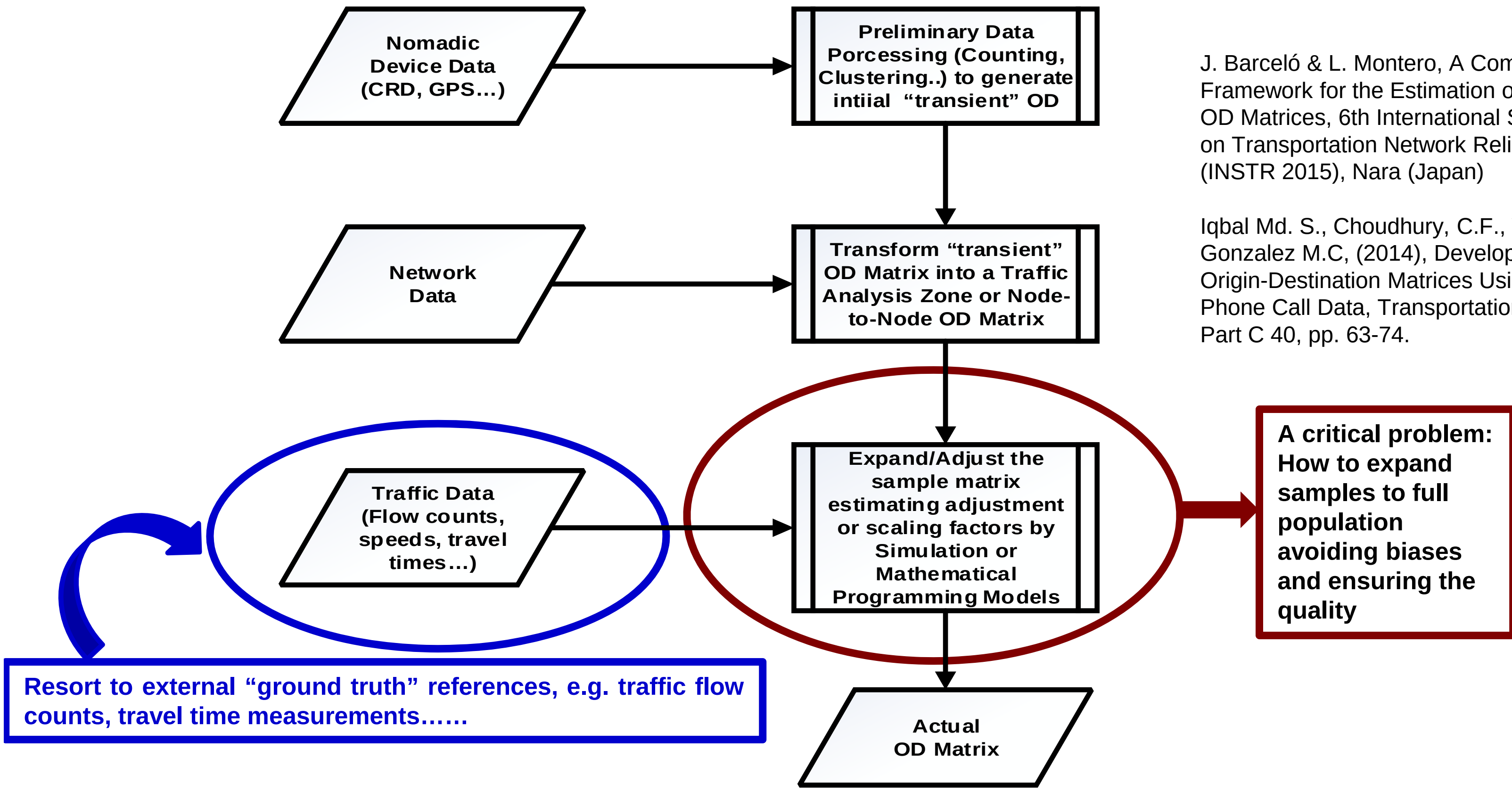
CONCEPTUAL FRAMEWORK FOR THE ESTIMATION OF OD MATRICES COMBINING NOMADIC DEVICES DATA AND TRAFFIC DATA



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