Analysis of intelligent road network, paradigm shift and new applications

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"Smarter Transport" - IT for co-operative transport system section

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Macroscopic analysis

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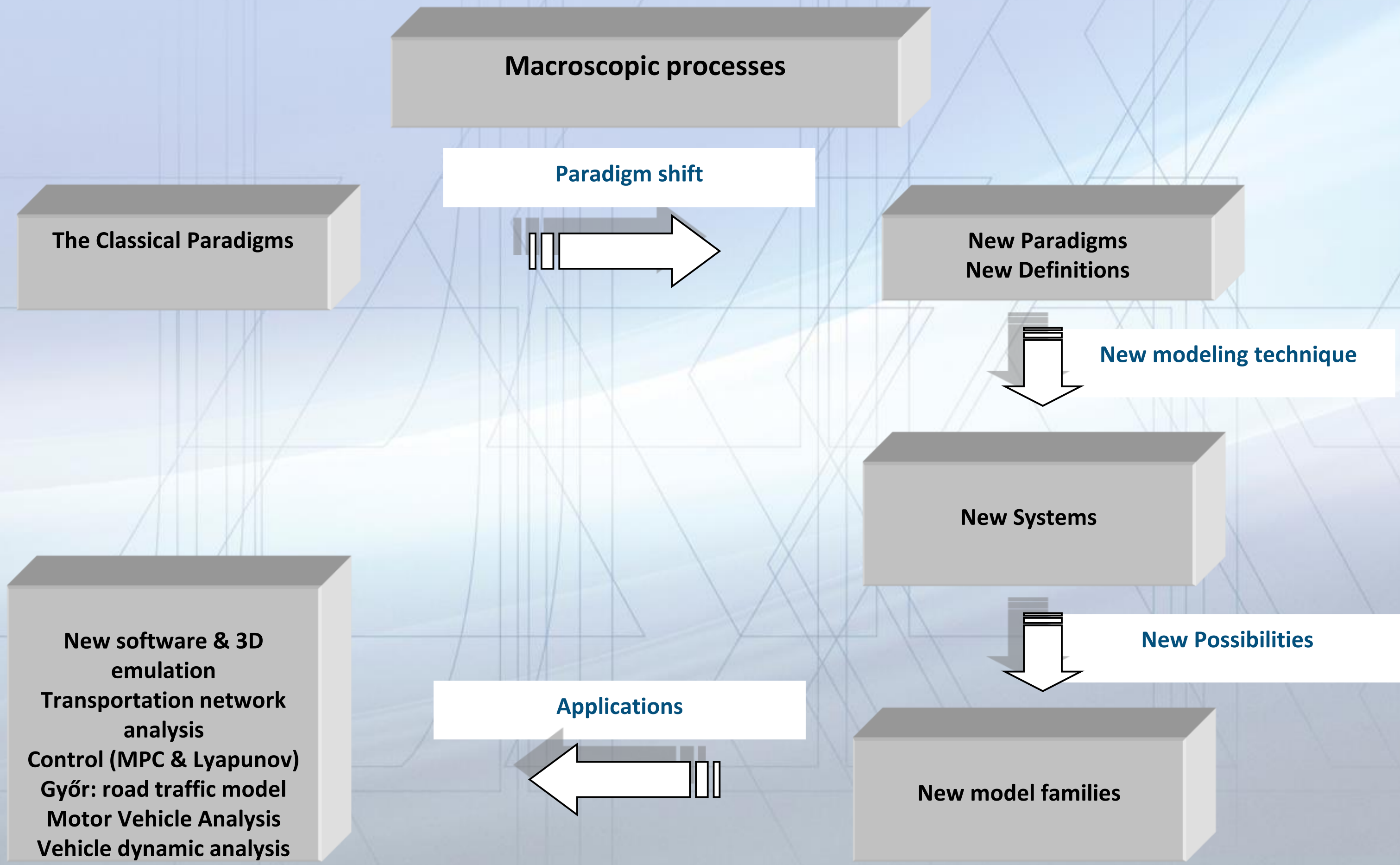
Contents of Presentation



The Classical Paradigms

- Euler's method
- x,y,z, and t, Euler variables

$$\rho = \rho(x, y, z, t); v = v(x, y, z, t);$$

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \cdot v) = 0$$

$$v_x = v_x(x, y, z, t); v_y = v_y(x, y, z, t); v_z = v_z(x, y, z, t);$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho \cdot v_x) + \frac{\partial}{\partial y}(\rho \cdot v_y) + \frac{\partial}{\partial z}(\rho \cdot v_z) = 0$$

Leonhard Euler
(1707-1783)

The Classical Paradigms

- Greenshields (1935), Greenberg (1959)
- Traffic flow: Lighthill and Whitham (1955) and Ashton (1966). fundamental equation:

$$q(x,t) = \rho(x,t)v(x,t)$$

- Papageorgiou model
- Segment lengths: 500 m, [kT, (k+1)T] time intervals (k=0,1,…,n;T= 10 s), vehicle density is constant

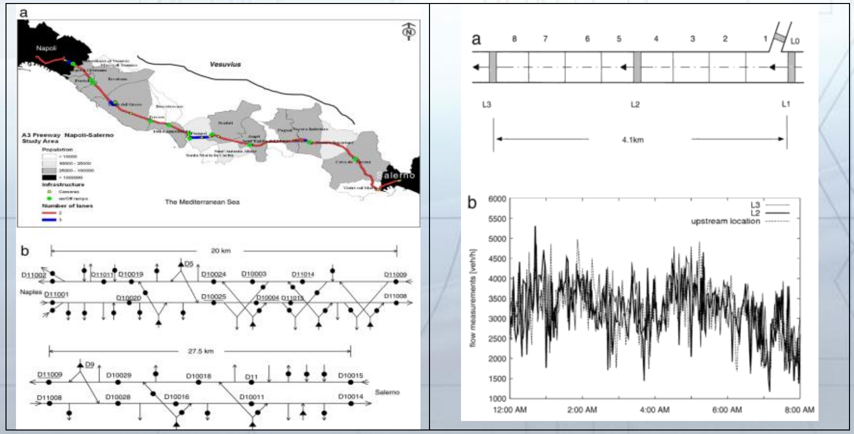
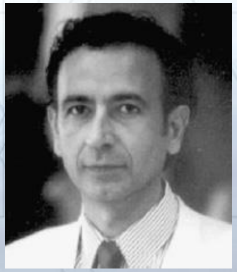


Fig. 1.



Papageorgiou

The Classical Paradigms

1. Application Sectors: Very positive! Partial Differential Equations are not necessary

2. Researchers are familiar with the classical methods

3. Vehicle unit/ Passenger Car Equivalent, is not an exact mathematical definition

Passenger Car Equivalent (PCE), is a metric used in Transportation Engineering. For example, typical values of PCE (or PCU) are:

- private car (including taxis or pick-up) 1
- motorcycle 0.5
- bicycle 0.2
- bus, tractor, truck 3.5

Highway capacity is measured in PCE/hour daily

The Classical Paradigms

- **4. Mathematical models are not general**

Blaise Pascal (1623-1662)

- **5. The traffic flow (flux) is not an exact state parameter**

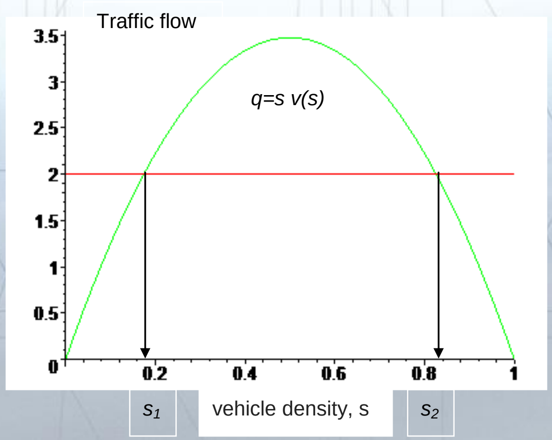


Fig. 2.

The Classical Paradigms

6. Input - Output: "Gates" problem

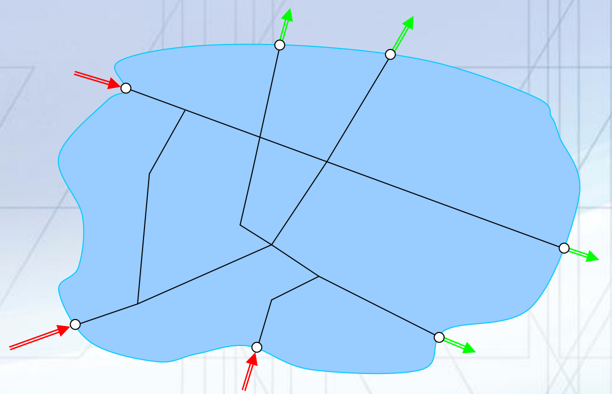


Fig. 3.

7. Conceptual problem: „the network is a static contact graph”

8. I miss the co-operation of parallel lanes

9. Car Parks problem: "foreign elements”

New Paradigms & New Definitions

1. State parameter : x_i (t) vehicle density (exact). $\forall$ $x_i \in [0,1]$.

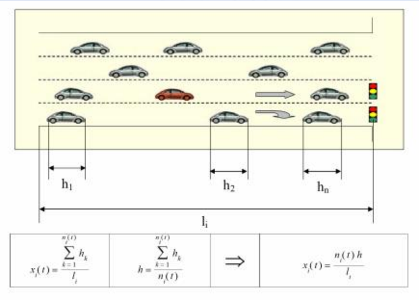


Fig. 4.

$$x_i(t) = \frac{\sum_{k=1}^{n_i(t)} h_k}{l_i} \quad (1)$$

$$l_i = Max\left(\sum_{k=1}^{N_i} h_k\right) \quad (2)$$

Parking also sectors:

New Paradigms & New Definitions

2. A dynamic graph construct

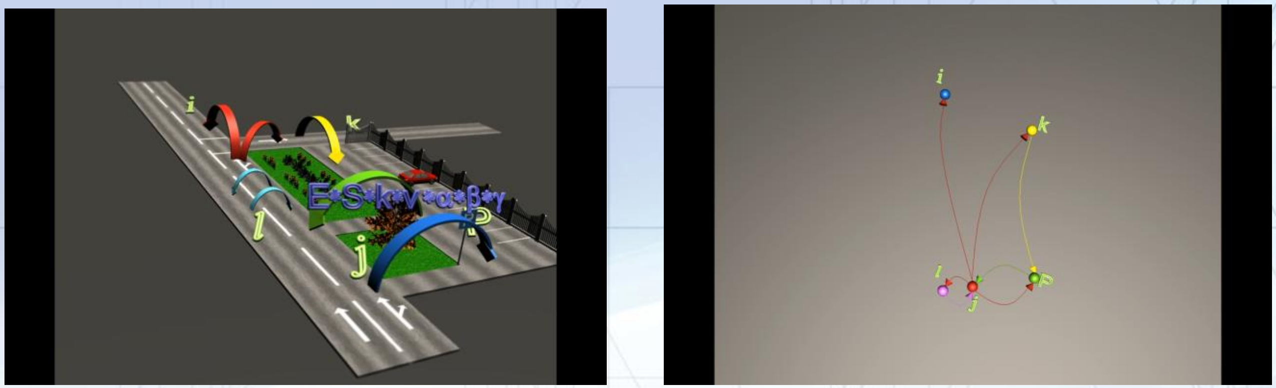


Fig. 5. new pulse graph

3. Virtual closed curve application (G)

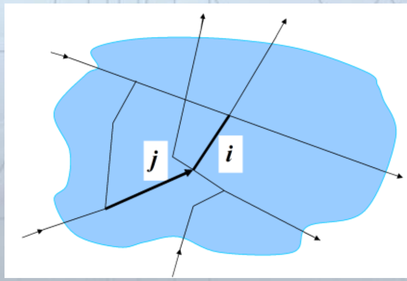


Fig. 6. Domain and virtual closed curve

New Paradigms & New Definitions

4. Dynamic relationships and contact hyper-matrix

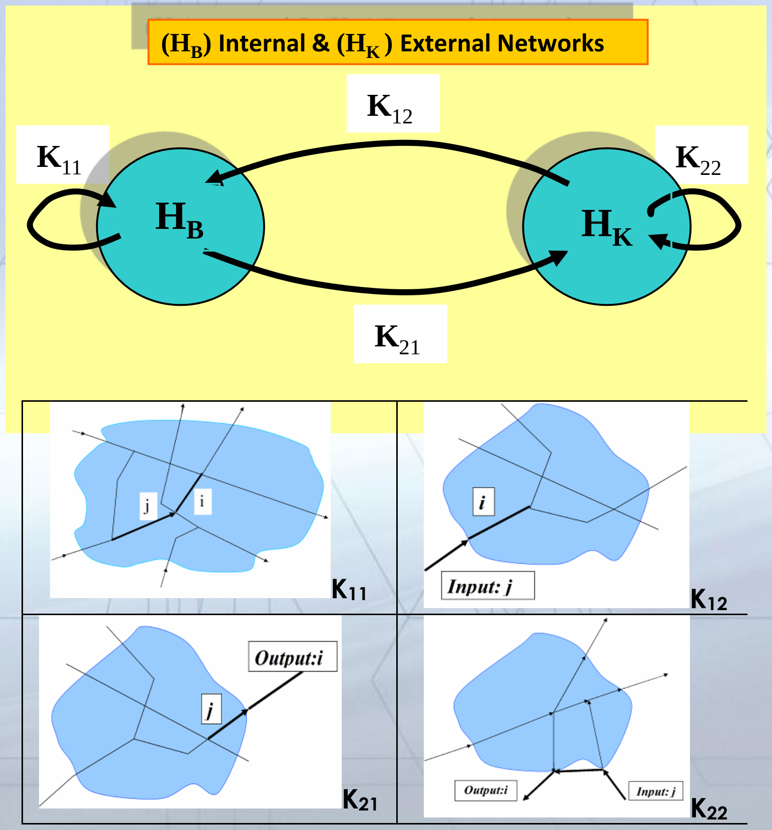


Fig. 7.

New Systems

5. Joint Analysis: Internal and External Network Operation

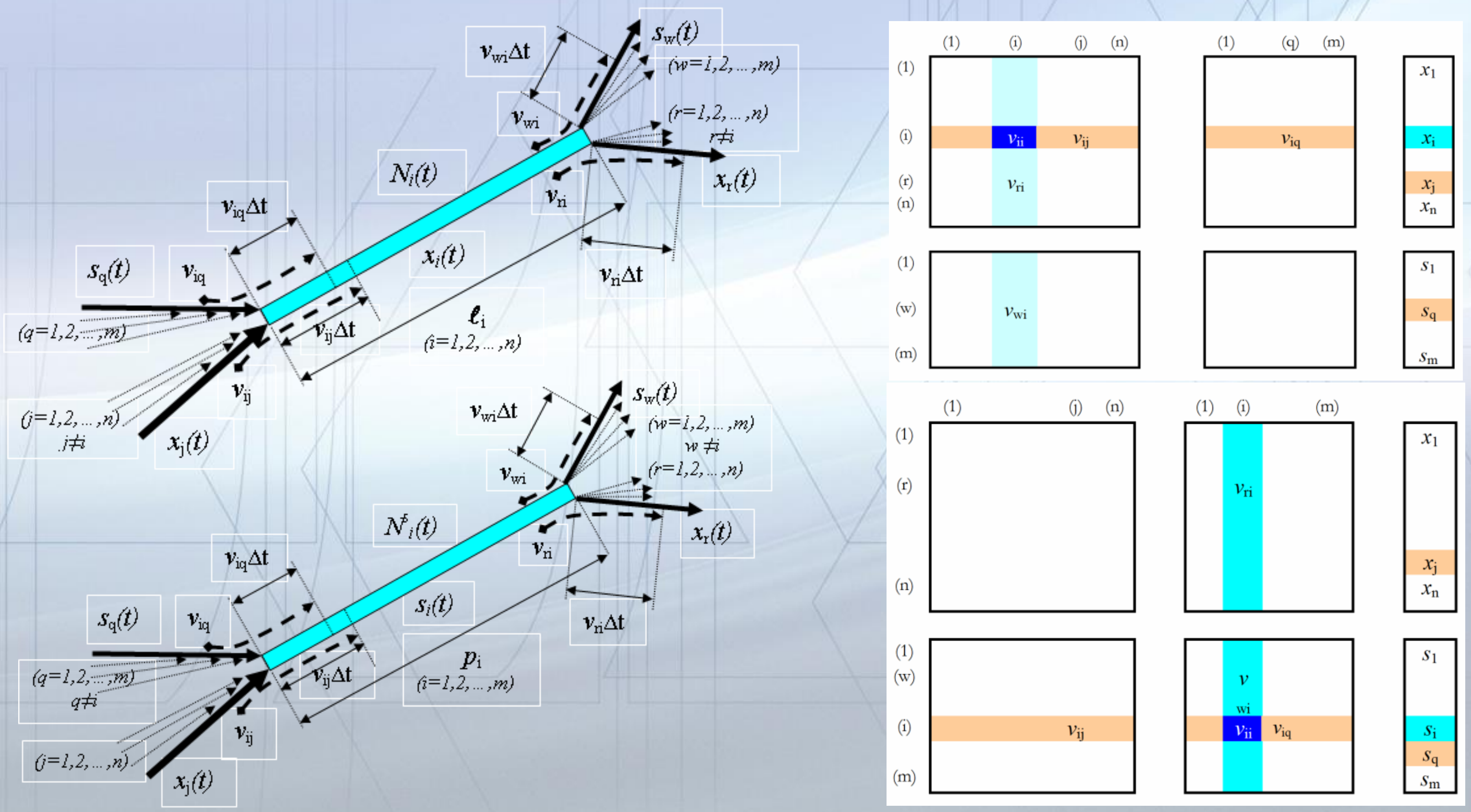


Fig. 8. i th Sectors: Internal and External Relations

New model families

6. Universal model

$$\begin{bmatrix}\dot{x}\\ \dot{s}\end{bmatrix}=\begin{bmatrix}\langle L\rangle^{-1} & \\ & \langle P\rangle^{-1}\end{bmatrix}\begin{bmatrix}K_{11}(x,s) & K_{12}(x,s)\\ K_{21}(x,s) & K_{22}(x,s)\end{bmatrix}\begin{bmatrix}x\\ s\end{bmatrix} \qquad (3)$$

$$v_{ij}=S(x_i(t))\cdot V(x_i(t),x_j(t),\underline{e}_i,\underline{e}_j)\cdot E(x_j(t))\cdot u_{ij}(t)\cdot \beta_{ij}(x(t),t)\cdot \alpha_{ij}(x(t),t)\cdot \gamma_{ij}(x(t),t) \qquad (4)$$

$$v_{ii}=-\left[\left(\sum_{r=1;(r\neq i)}^{n} v_{ri}+\sum_{w=1}^{m} v_{wi}\right)\right]$$

7. Reduced model $\dot{x}$ =<*L*>$^{-1}$ [K_{11}(*x,s*) *x* + K_{12}(*x,s*) *s*] (5)

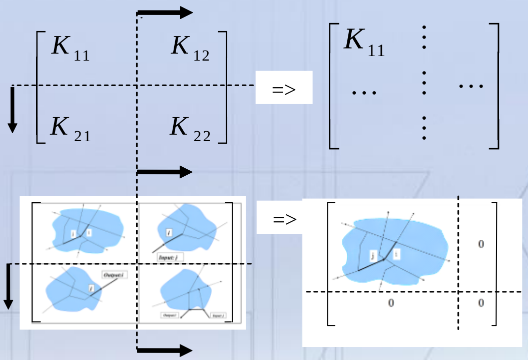
- $x\in\Re^n$, , $s\in\Re^m$, *L* = diag{l1, ... ,ln},, (∀li>0, i=1,2,…,n), $K_{11}\in\Re^{nxn}$, $K_{12}\in\Re^{nxm}$.

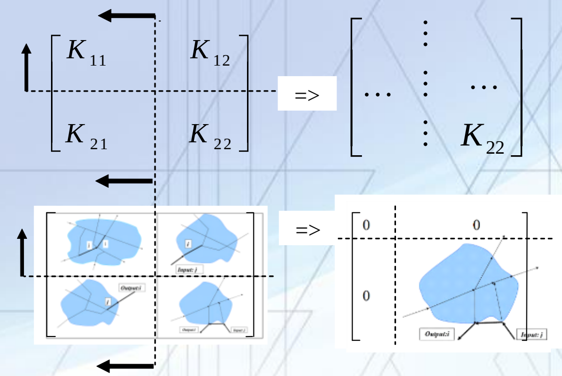
8. Global model

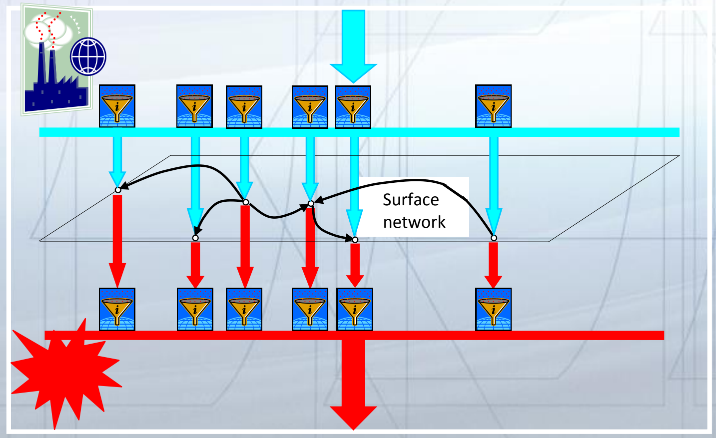
- $s_1= x_{n+1}$,…, $s_m= x_{n+m}$

$$\dot{x}=\langle L\rangle^{-1}K_{11}(x)x \qquad (6)$$

New model families





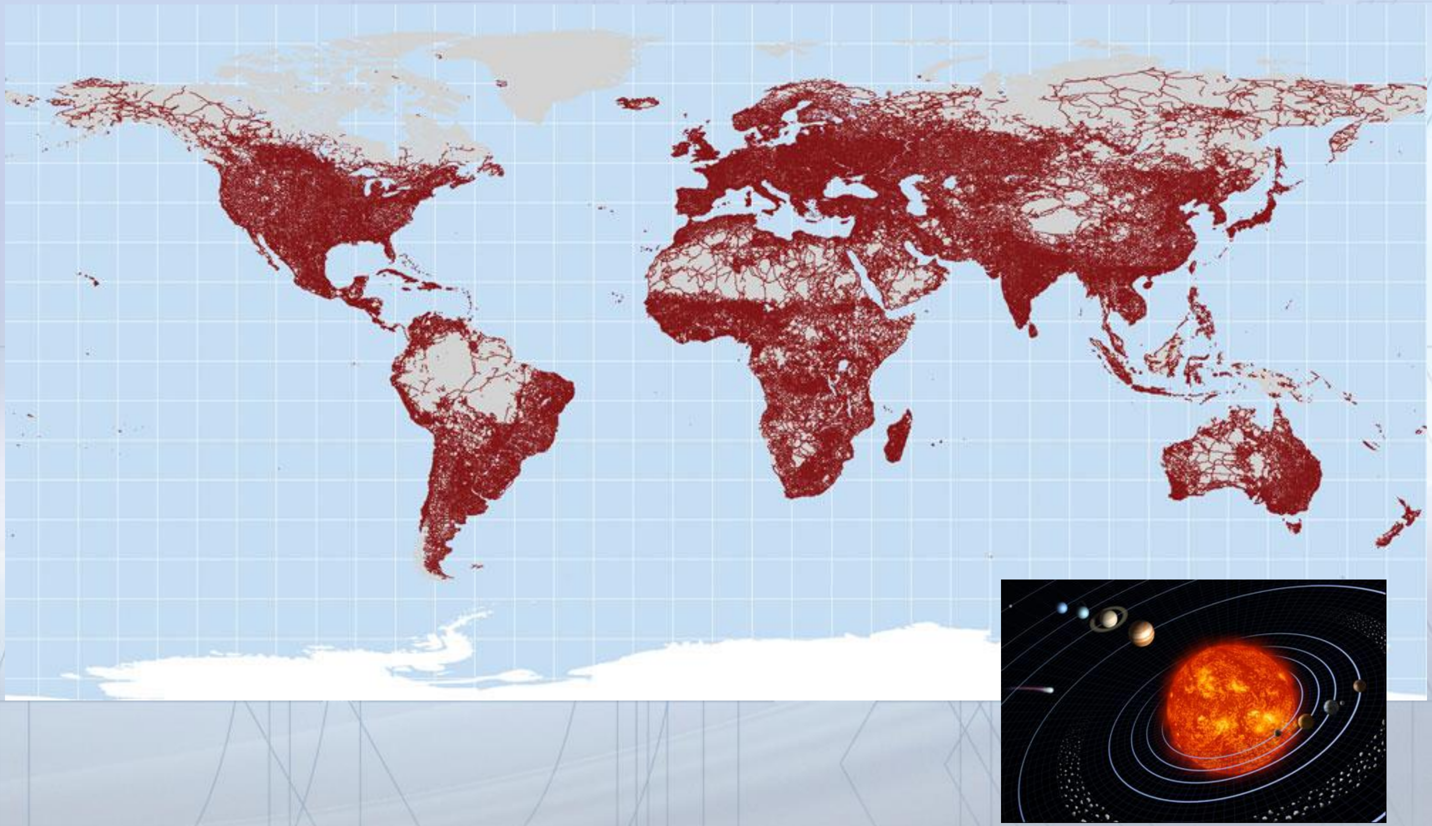


	(1)	(2)	(i)	(n-1)	(n)	(n+1)	
(1)	$v_{1\,1}^*$	$v_{1\,2}$	$v_{1\,i}$	$v_{1\,n-1}$	$v_{1\,n}$	$v_{1\,n+1}$	x_1
(2)	$v_{2\,1}$	$v_{2\,2}^*$				$v_{2\,n+1}$	
(i)			$v_{i\,i}^*$				x_i
(r)	$v_{r\,1}$	$v_{r\,2}$	$v_{r\,i}$	$v_{r\,n-1}$	$v_{r\,n}$	$v_{r\,n+1}$	
(n)	$v_{n\,1}$	$v_{n\,2}$	$v_{n\,i}$	$v_{n\,n-1}$	$v_{n\,n}^*$	$v_{n\,n+1}$	x_n
(n+1)						0	x_{n+1}

$$\dot{x} = \langle L \rangle^{-1} K_{11}(x)x \qquad v_{i,i}^{*} = -\left(\sum_{r=1;(r\neq i)}^{n} v_{rn-1}\right) - v_{i,A} \qquad (7)$$

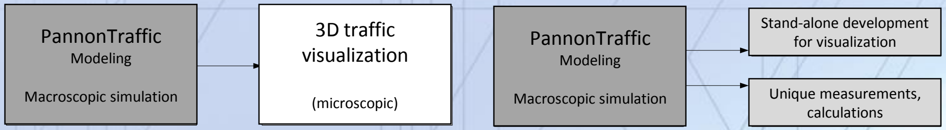
Fig. 9. No Eulerian production model

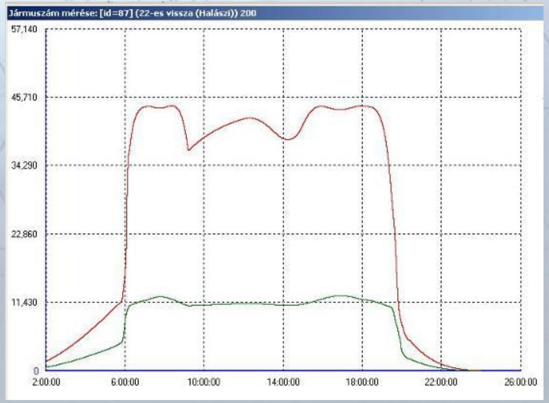
New model families, new possibilities and new dimensions



The total length of the network, (measured in both directions) approximately the Earth-Sun distance!
The total vehicle length is 9 Earth-Moon distance!

New software & 3D emulation





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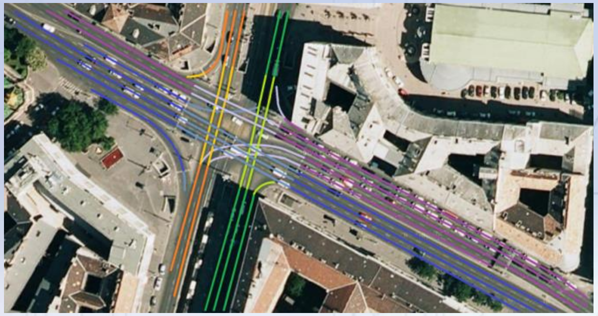
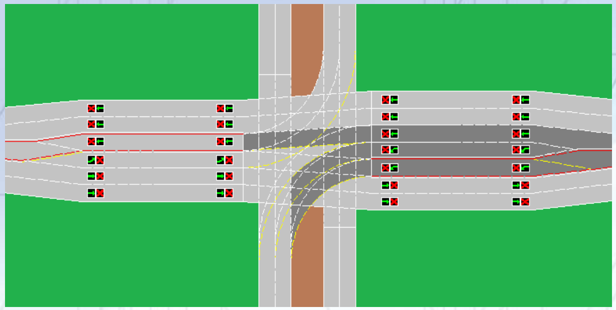
inno mobilitas

3D visualization video

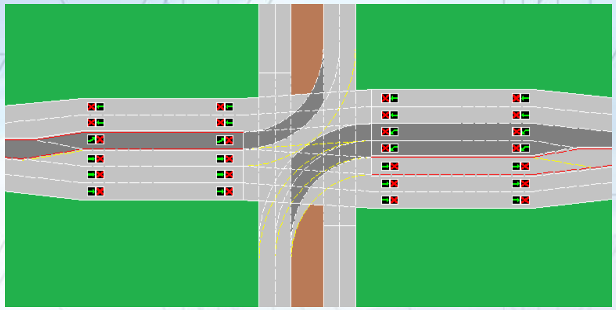
Transportation network analysis

- **Variable network model: Üllő street in Budapest (Corvin-negyed)**





Morning peak design



Afternoon development, (current state)

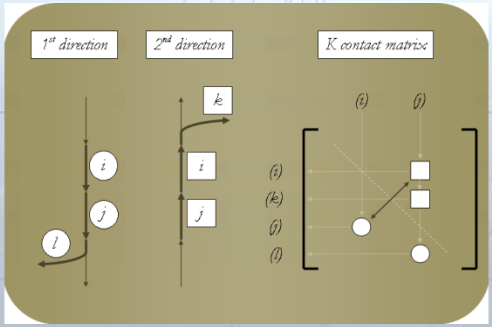
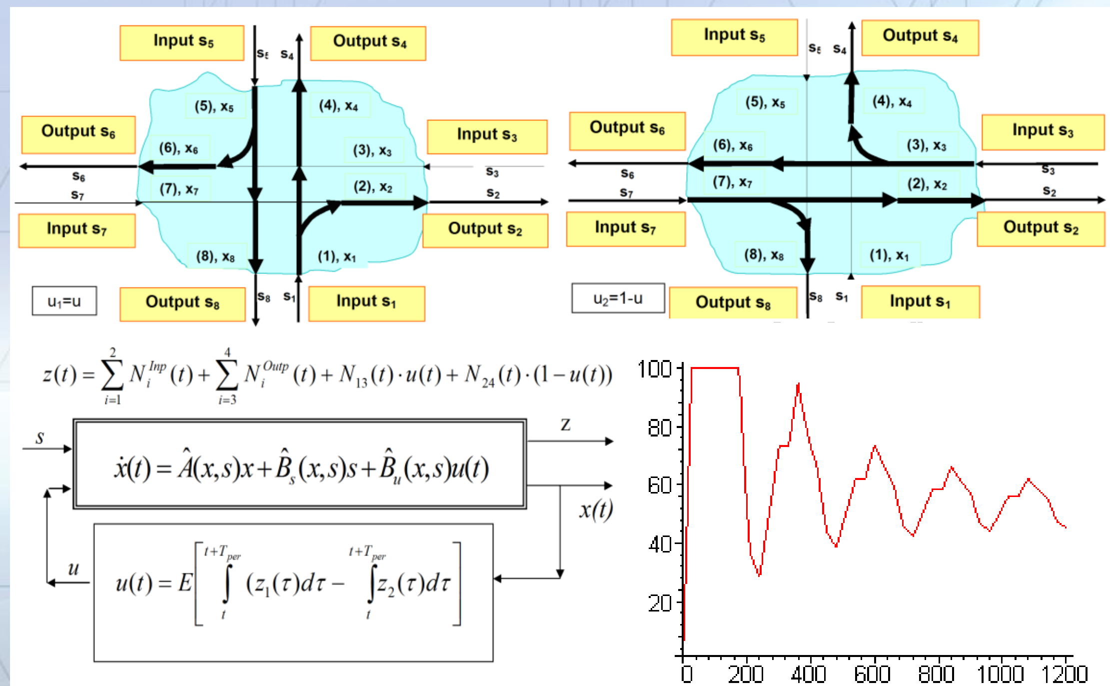


Fig.10. Two traffic flow directions and the connection matrix

Control (MPC)

- **Nodes: MPC-based management**

Performance:



$$z(t) = \sum_{i=1}^{2} N_i^{Inp}(t) + \sum_{i=3}^{4} N_i^{Outp}(t) + N_{13}(t)\cdot u(t) + N_{24}(t)\cdot(1-u(t))$$

$$\dot{x}(t) = \hat{A}(x,s)x + \hat{B}_s(x,s)s + \hat{B}_u(x,s)u(t)$$

$$u(t) = E\left[\int_t^{t+T_{per}} (z_1(\tau)d\tau - \int_t^{t+T_{per}} z_2(\tau)d\tau\right]$$

$$u_k(t) = \prod_{i=1;(i\neq k)}^{n} E(N_k - N_i)$$

$E(x) = 1$ if $x > 0$ and $E(x) = 0$ if $x \le 0$,

(k=1,2,…,n)

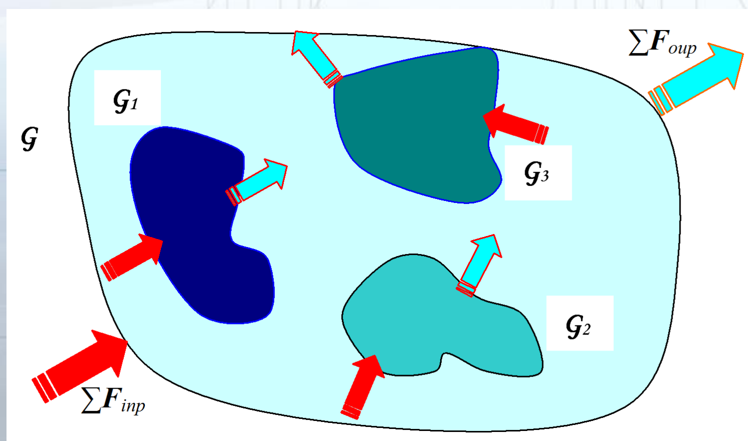
Fig.11.

Control (Lyapunov)

- $V(x_1, x_2, \ldots, x_n) = l_1 * x_1 + l_2 * x_2 + \ldots + l_n * x_n = \underline{L} * \underline{x};$ ($x \geq 0$, $V(x)=0 \leftrightarrow x=0$, $x>0 \Rightarrow V(x)>0$) (8)
- Lyapunov function: The total length of the vehicles
- The derivation of the Lyapunov function:

$$\frac{\partial V}{\partial t} = L \cdot \dot{x} \qquad \dot{x} = < L >^{-1} [K_{11}(x)\, x + K_{12}(x, s)\, s] \qquad (9)$$

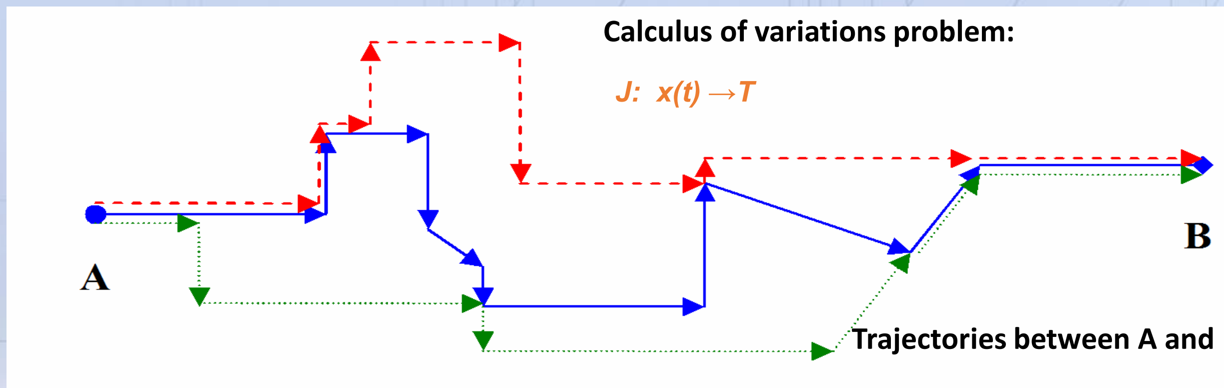
$$\frac{\partial V}{\partial t} = L \cdot < L >^{-1} [K_{11}(x)\, x + K_{12}(x, s)\, s]$$



Control: $\sum \mathbf{F}_{\mathbf{input}} \leq \sum \mathbf{F}_{\mathbf{output}}$

Fig.12.

Control (optimal trajectories)



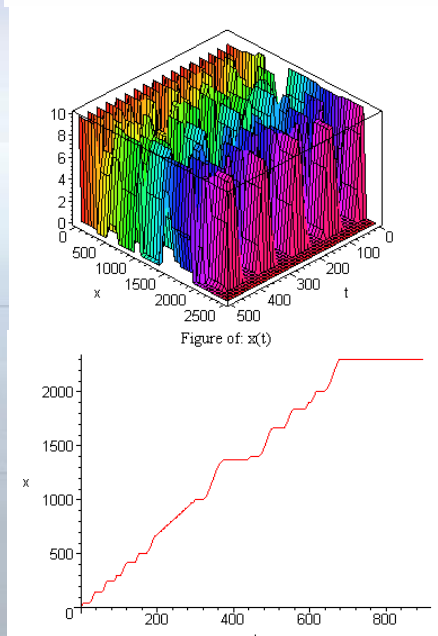


Fig.13.

$$x(t) = \int_{t_0}^{t} V(\tau, x(\tau))\, d\tau \qquad (10)$$

Equivalent non-linear differential equation $x(t_0)=x_0$:

$$\frac{\partial}{\partial t} x(t) = V(t, x(t)) \qquad (11)$$

Győr: road traffic model

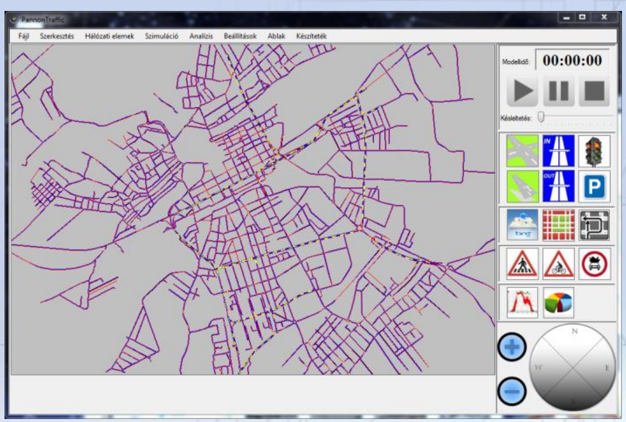
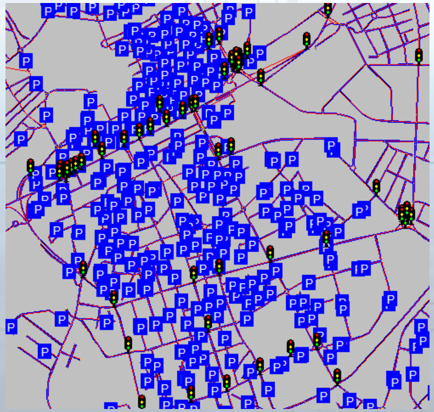


Fig. 14. Modelled network of Győr in our software

This 175 km^2 sized network is executed in only some minutes, which would be possible without our development in weeks. This network consists 4600 road sections (this is only the skeleton network) approaching 500 km of total length. This basic network has to be expanded by several lanes, bicycle roads (about 36 km) and parking places.



20 000 vehicles on approximately

650 spots

Fig. 15. Parking places and traffic lights in the example model

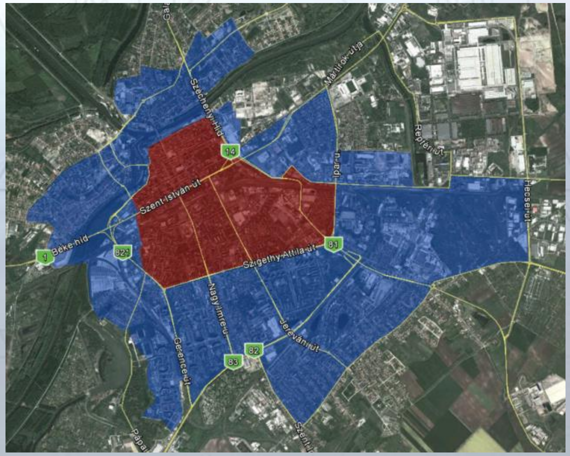


Fig. 16. A two-level domain control for the city of Győr

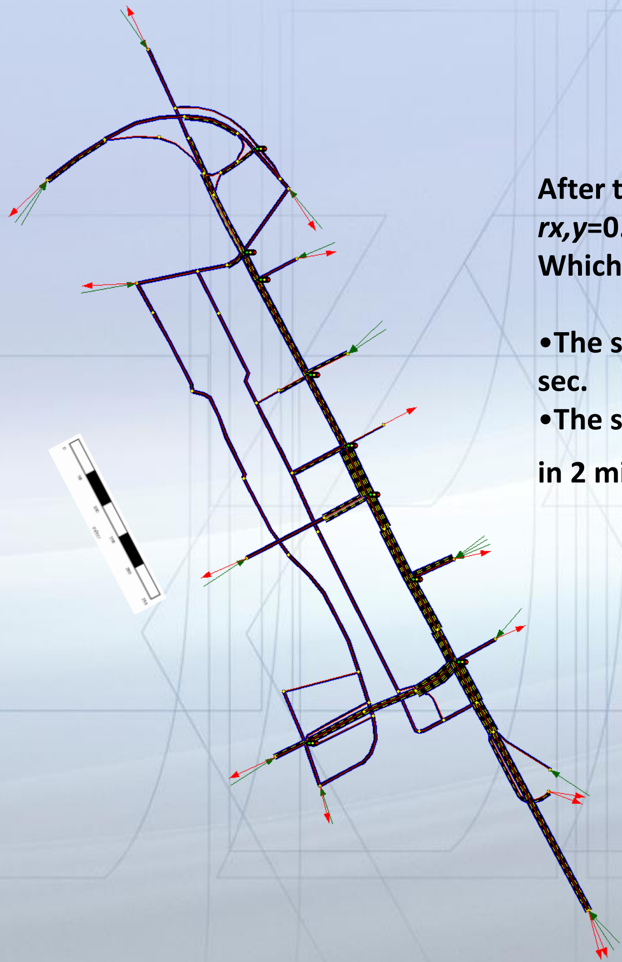
Győr: road traffic model

- **Győr: Szent István Street represents the trunk of the network**
- PannonTraffic software was used for modeling and simulation. The introduced model is an important sub-domain of the traffic network of Győr including Szent István Street. The validation of the model is carried out with the measured cross-sectional traffic data and the result of velocity measurements by GPS equipped cars.
- **The characteristics of the network**
- 228 roads
- 9 intersections controlled by traffic lights
- 38 other intersections
- 18 input sections
- 15 output sections

Inputs:13 points 18 lanes		***Outputs:13 points 15 lanes***	
1.	Benczur u.,	1.	Benczur u.,
2.	821. u. 2 db. sáv	2.	821. u.,
3.	Béke híd,	3.	Béke híd,
4.	Újlak u.,	4.	Újlak u.,
5.	Munkácsi M. u.	5.	Munkácsi M u.,
6.	Jókai u. 2. db. sáv	6.	Aradi Vértanuk u.,
7.	Baross Gábor Híd,	7.	Baross Gábor Híd,
8.	Teleki László u. 3 db. sáv	8.	Teleki László u.,
9.	Gárdonyi G.,	9.	Gárdonyi G.
10.	Tihanyi Árpád u.,	10.	Tihanyi Árpád u.,
11.	Mészáros Lőrinc u.,	11.	Mészáros Lőrinc u.,
12.	Körforgalomból bevezető út.	12.	Kivezető jobbra 2 db. sáv
13.	Bissinger József Híd 2 db. sáv	13.	Bissinger József Híd 2 db. sáv

Fig.17. Inputs & Outputs

Győr: road traffic model



After the evaluation, the correlation coefficient is:
***rx,y*=0.9925070033**
Which can be regarded as 100% correlation practically.

- **The simulation for the given interval (7:15 - 8:15) was executed in 6 sec.**
- **The simulation regarding to the 24 hour time interval was executed in 2 minutes 14 seconds**

Fig. 18. Szent István Street represents the trunk of the network

Győr: road traffic model and validation

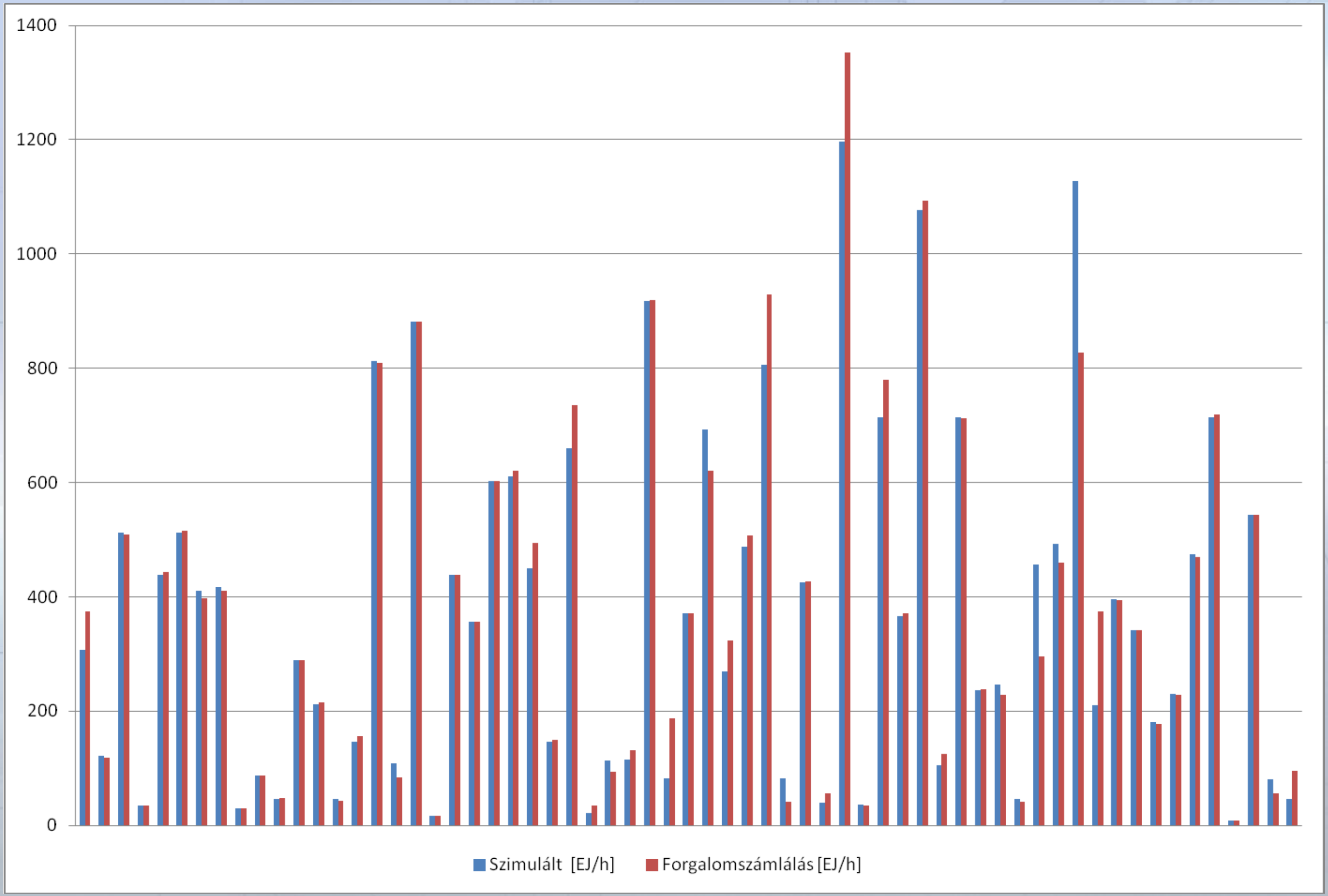
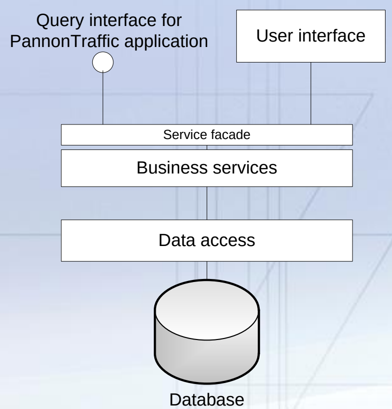
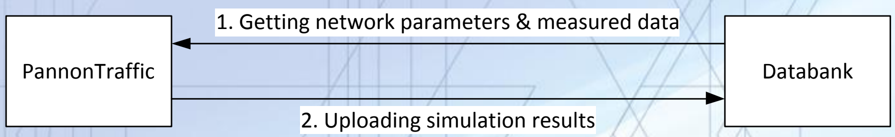
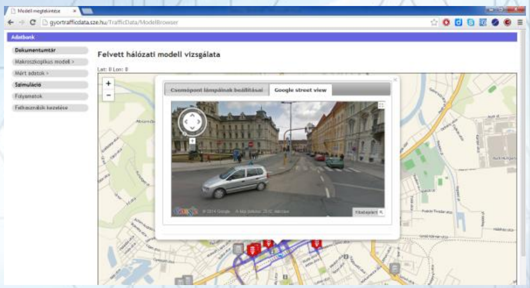


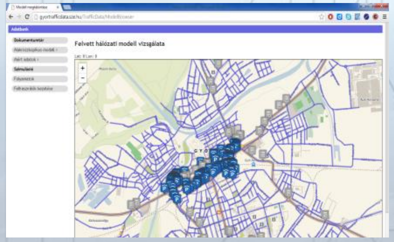
Fig. 19. The measured and simulated traffic correlate very well

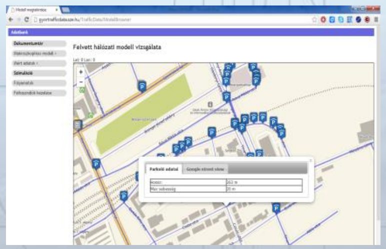
The road traffic modelling and design of the traffic database of Győr in project Smarter Transport

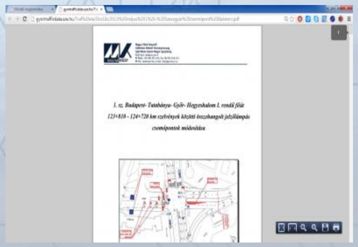


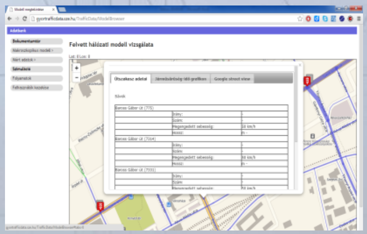












Motor Vehicle Analysis and validation

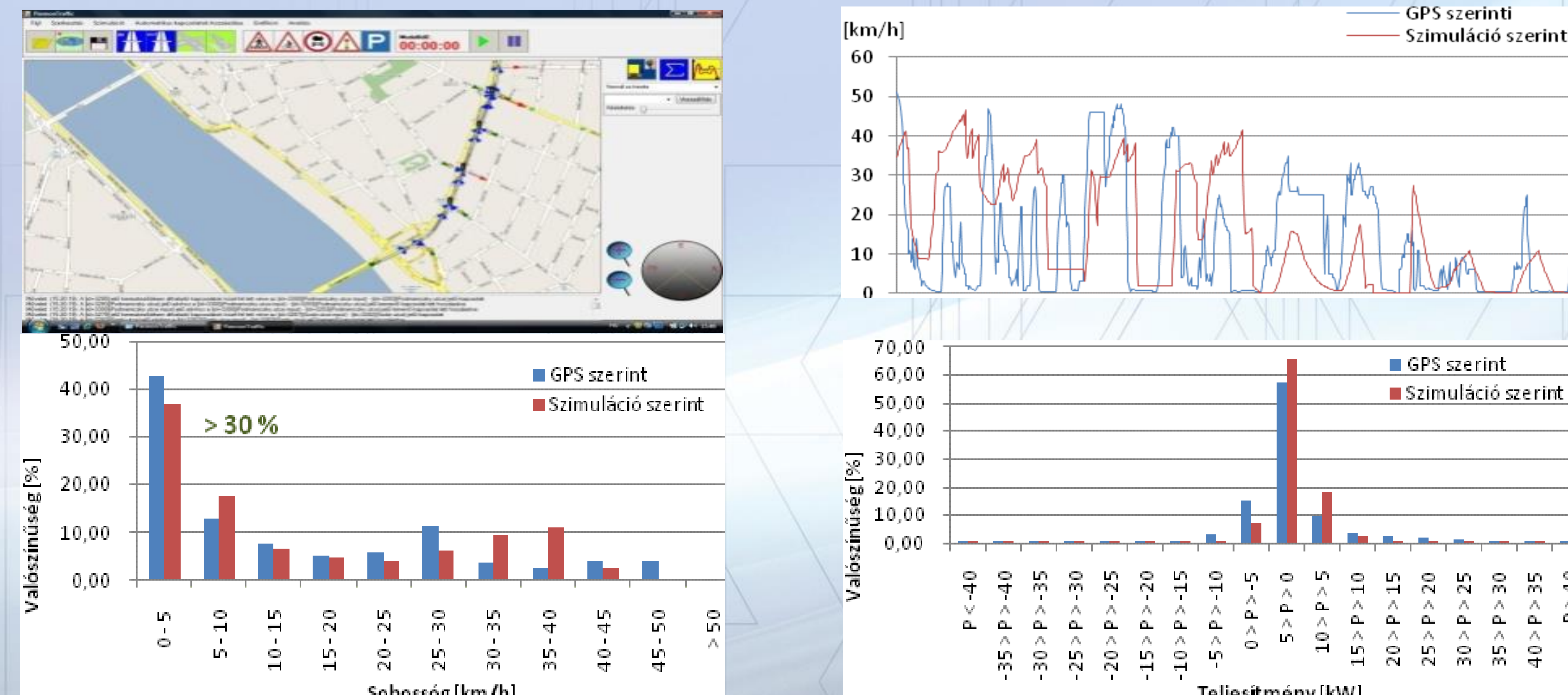


Fig.20.

Motor Vehicle Analysis and validation

Non-parametric statistical tests (homogeneity test)
Level: 95%

$$Eqv := \chi^2 = N\,M \left(\sum_{k=1}^{r} \frac{\left(\frac{v_k}{N} - \frac{u_k}{M} \right)^2}{v_k + u_k} \right) \qquad (12)$$

Velocity distribution(r=11), **GPS & simulation:** — **χ_{r-1}^2 table**

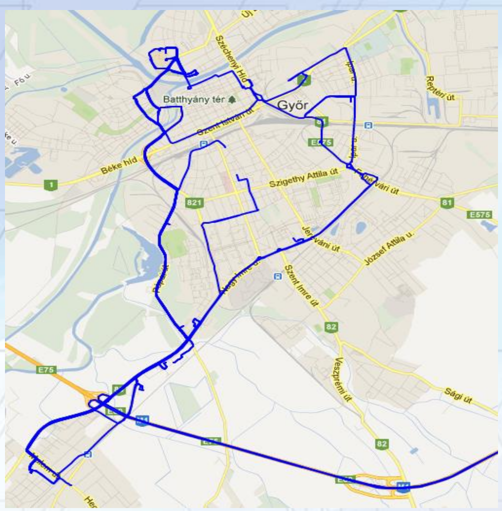
$$\chi^2 = 14{,}2747 \quad < \quad \chi_{10}^2 = 18{,}3$$

Engine power distribution (r=18), **GPS & simulation:**

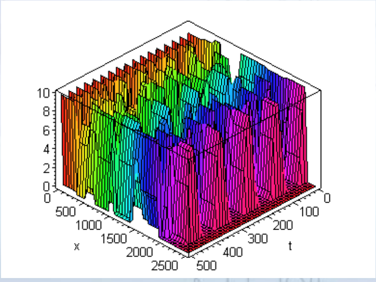
$$\chi^2 = 6{,}0976 \quad < \quad \chi_{17}^2 = 27{,}6$$

<u>Both are considered to be homogenous, level of: 95%!</u>

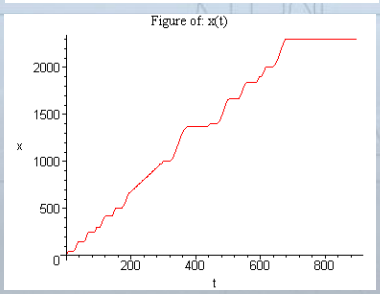
Examination of complex traffic dynamic systems



$$\dot{x} = \langle L \rangle^{-1} [K_{11}(x,s)x + K_{12}(x,s)s]$$

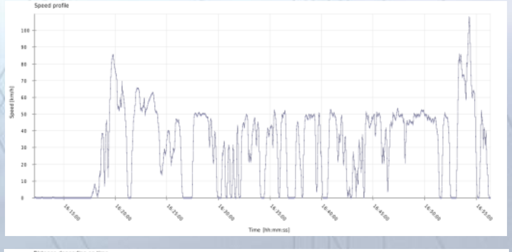


$$v(t) = f(x(t)) = \begin{bmatrix} f_1(x_1) \\ f_2(x_2) \\ .... \\ f_n(x_n) \end{bmatrix} \qquad (13)$$



$$\dot{v}_i(t) = a(t) = \frac{df_i(x_i(t))}{dx_i} \cdot \dot{x}_i(t) = f_i' \cdot \dot{x}_i \qquad (14)$$

$$a(t) = \langle f_i' \rangle \cdot \dot{x} = \left\langle \frac{f_i'}{l_i} \right\rangle \cdot [K_{11}(x,s)x + K_{12}(x,s)s]$$



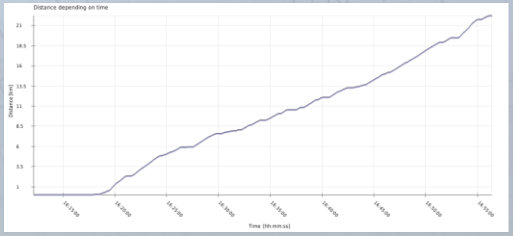
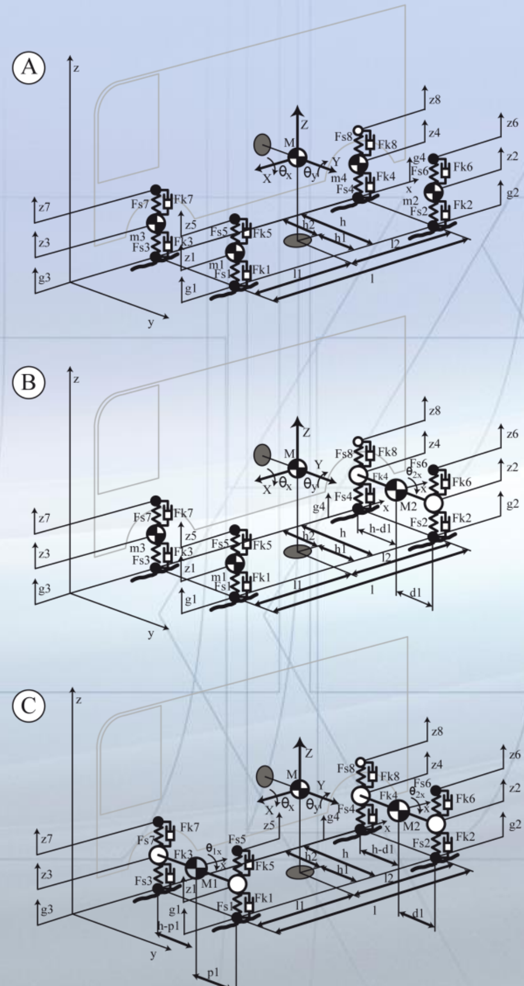


Fig.21.

Examination of complex traffic dynamic systems



$$M_v \cdot \ddot{z} + F_K + F_S + F_{K1stab} + F_{K2stab} + F_{S1stab} + F_{S2stab} + FA_x + FA_y = 0 \qquad (15)$$

$$FA_x := \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \dfrac{a_x(t)\, M\, H \left(-1 + \dfrac{h_1}{h}\right)}{l_1} \\ 0 \\ -\dfrac{a_x(t)\, M\, H\, h_1}{l_1\, h} \end{bmatrix} \qquad FA_y := \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \dfrac{a_y(t)\, M\, H \left(-1 + \dfrac{l_1}{l}\right)}{h_1} \\ -\dfrac{a_y(t)\, M\, H\, l_1}{h_1\, l} \\ 0 \end{bmatrix} \qquad (16)$$

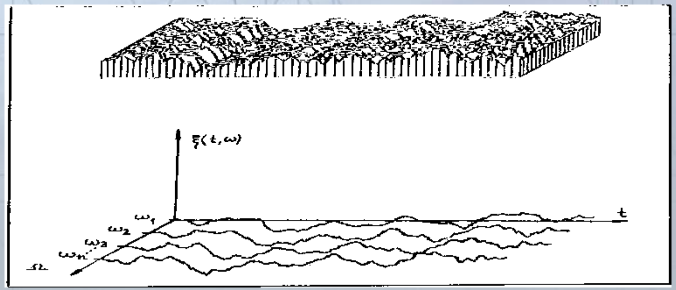


Fig.22.

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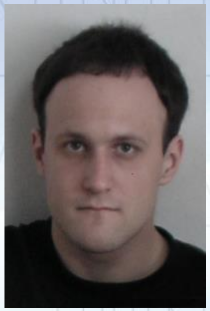
Further work planned: HORIZON 2020

Győr City Management

The team

Thank you for your contribution

Bede Zsuzsanna



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THANK YOU FOR YOUR ATTENTION.

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