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Using System Dynamics Simulation and Design of Experiments for Planning Sustainable Transportation Systems

Anjali Awasthi, Reza Sayyadi

CIISE, Concordia University

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Sustainable Transportation

- A sustainable transportation is one which meets the needs of the present generation without compromising the ability of future generations to meet their own needs (based on the sustainability definition by World Commission on Environment and Development, 1987).

- It is the result of amalgamation of systems, policies and technologies to positively impact the economic development, environmental integrity, and improvement of social quality of life.

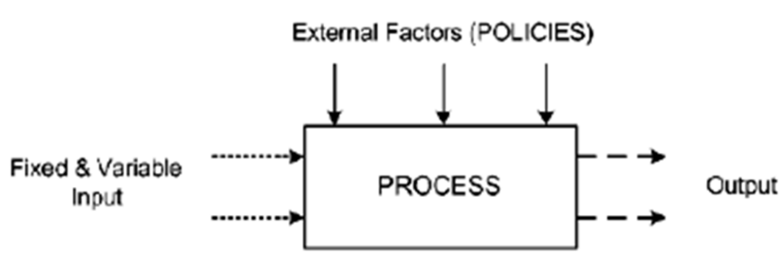
Policies for sustainable transport

- Defining a policy to meet sustainability objective for a transportation system with its numerous socioeconomic environmental factors is not an easy task because:
  - Behavior of the components in the system changes over time.
  - It may be in conflict with interest of different social groups of people who are the main actors affected by the policy.
  - A policy may positively influence one side of the system and be disastrous for the other side.
  - Defining a policy on sustainability is highly dependent on the culture and the view of the Decision Makers (DM).

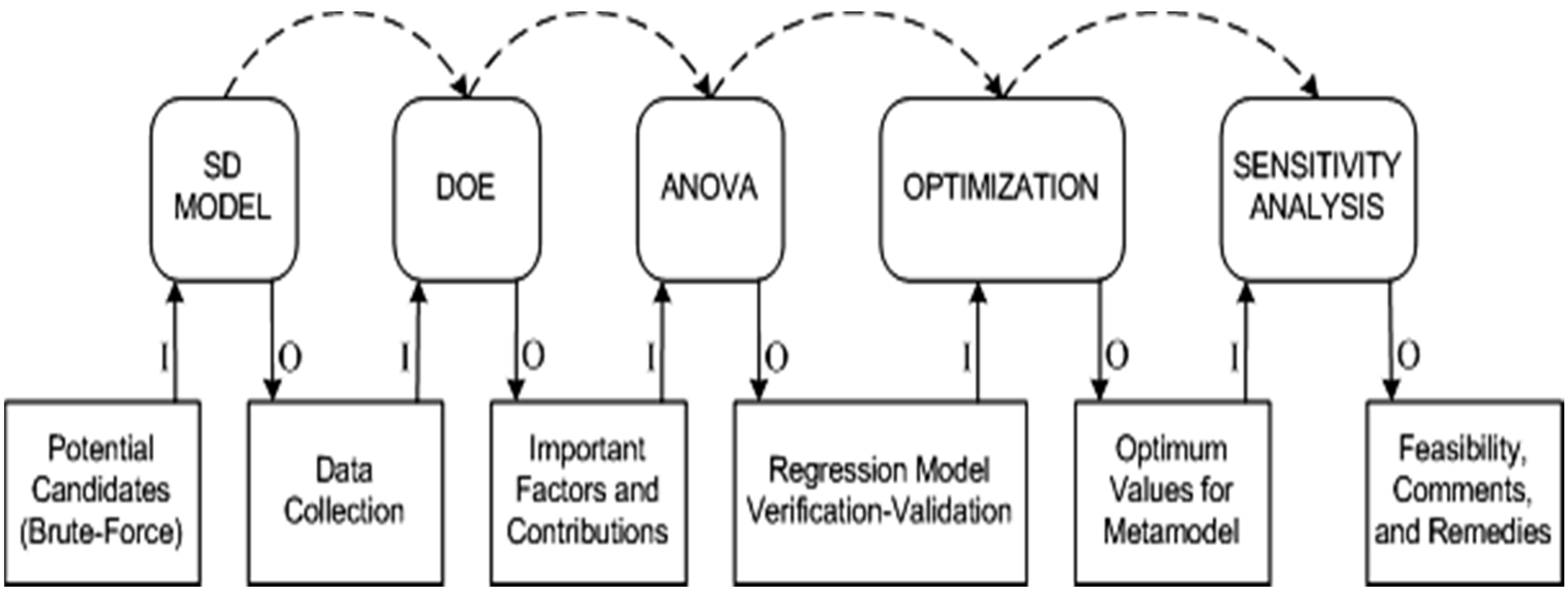
- Examples of few policies are Carsharing, Tripsharing, Usage of Clean Fuels, Environment friendly transport modes, Goods Consolidation, Sharing of public space, Use of public transport, etc.

Objectives

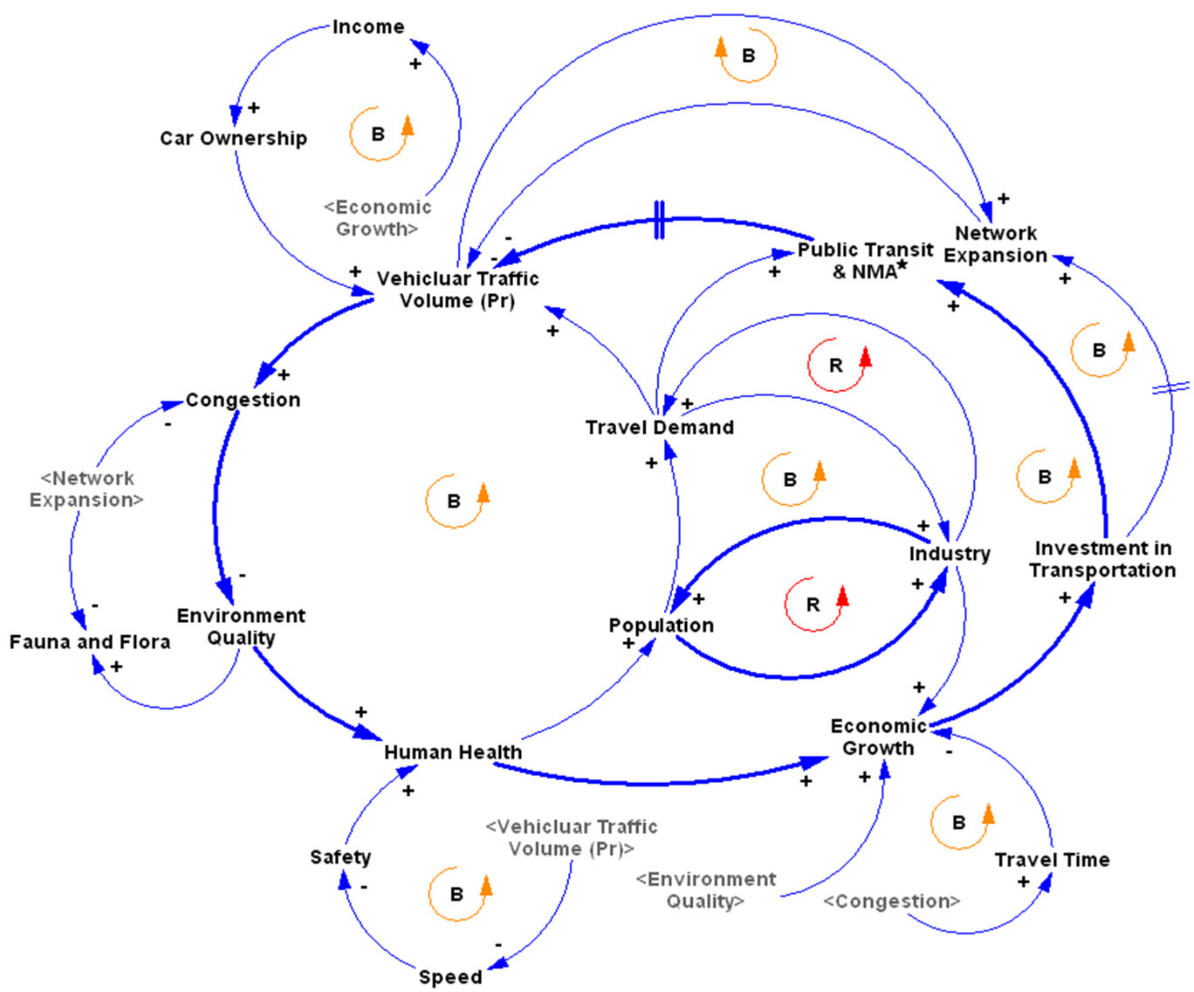
- To achieve such systems, our main objectives are:
  - Development of a conceptual model to understand policies for planning sustainable transportation systems.
  - Development of a methodology to identify critical factors for developing policies to achieve sustainability.
  - Development of an approach to evaluate sustainable transportation policies.



Multi step methodology

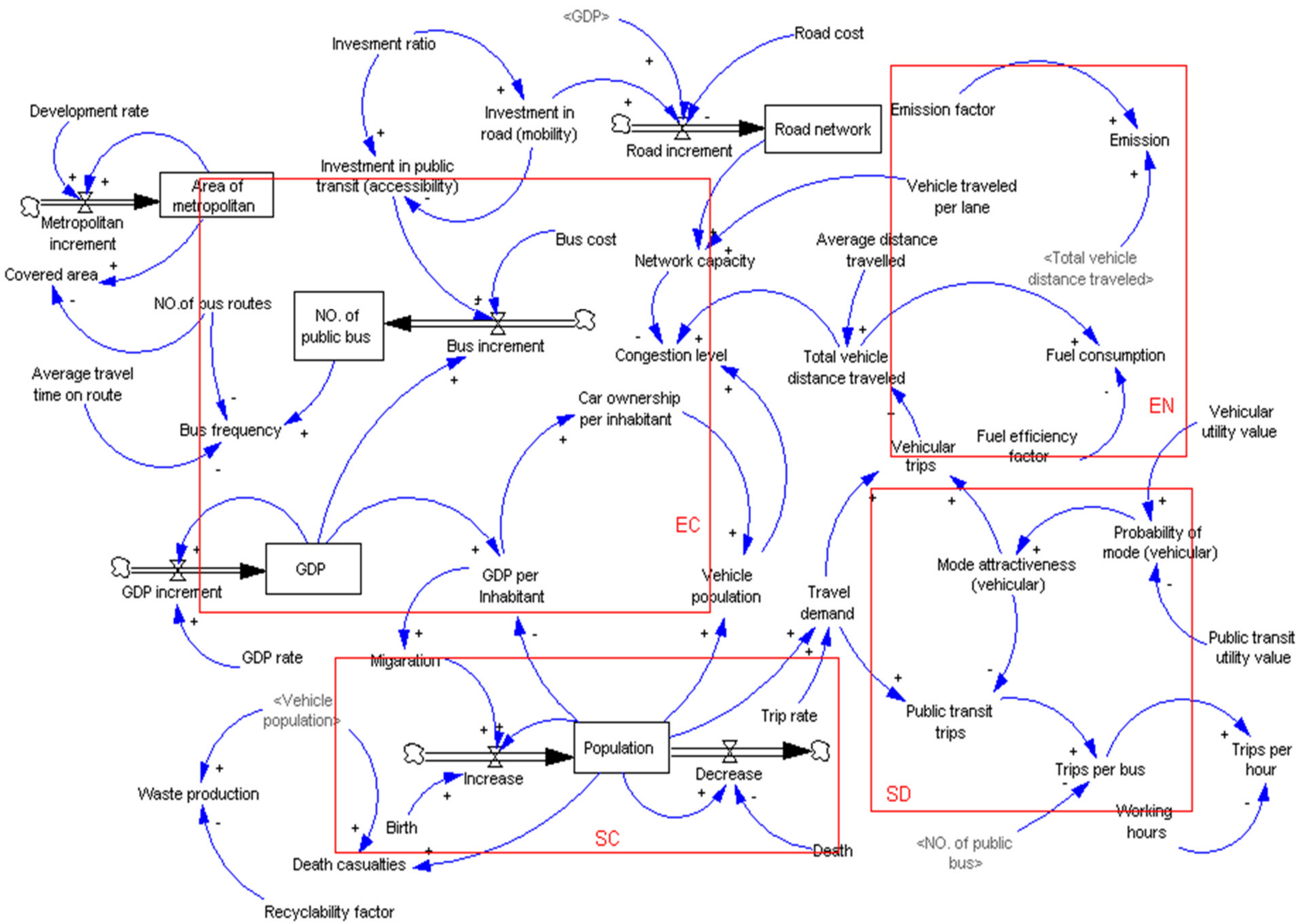


Causal loop diagram

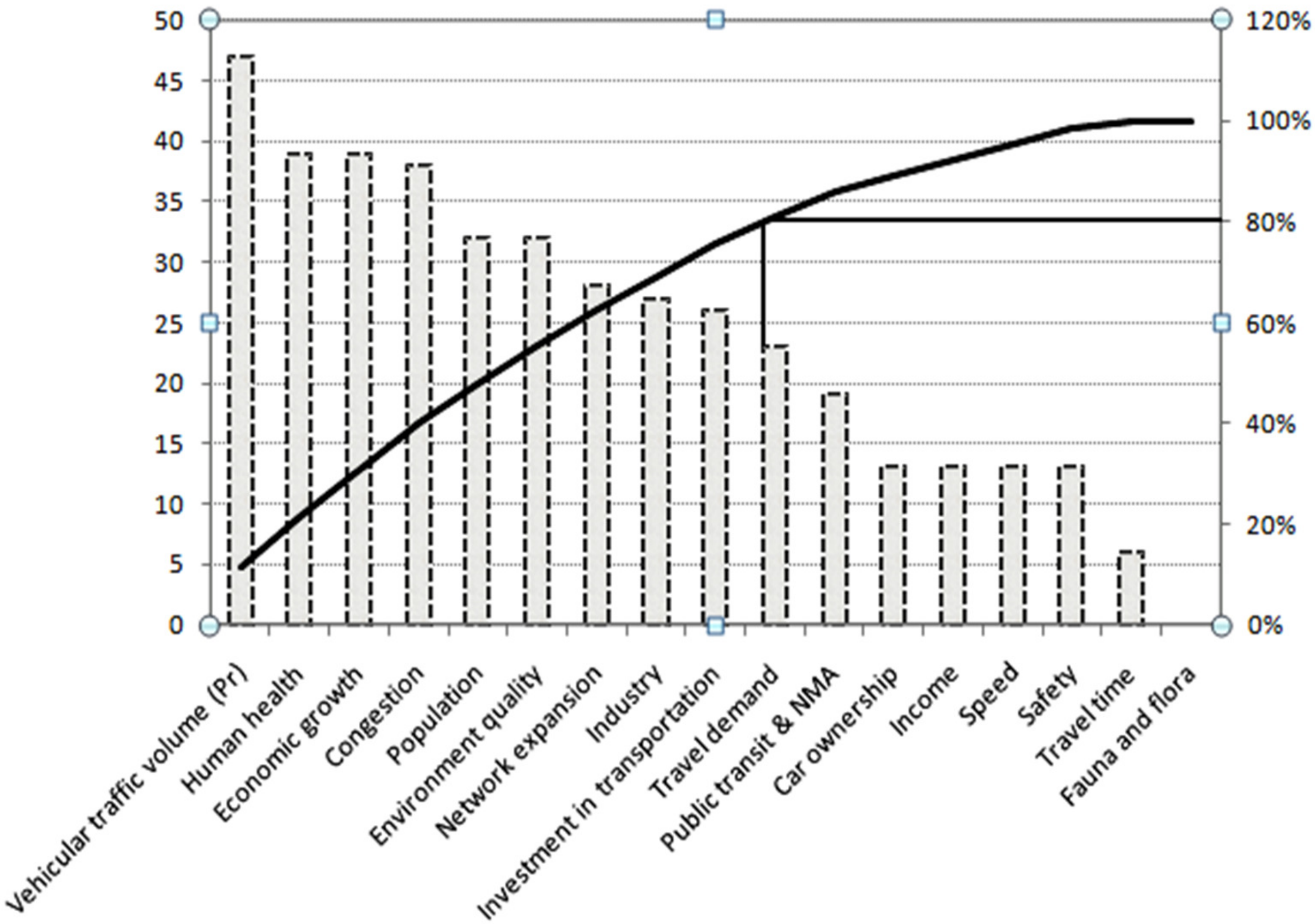


Understanding main factors affecting sustainable transportation

System Dynamics Simulation Model



Pareto diagram



Numerical Illustration

Variable	*Input Value*	*Unit*
Population	4,500,000	NO. (people)
Birth Rate	0.01	-
Death Rate	0.008	-
GDP	25000×4.5e6	$
GDP Rate	0.01	-
Unit cost of bus	500,000	$
Trip Rate	2.8	-
Car ownership rate	64%	No. of car for 100 of people
Vehicle traveled per lane (Wang et al.,2008)	800	VKT
Average Distance Traveled per Capita	8.5	Km
Area of metropolitan	4500	Km^2
Network Length (in lane)	2700	Km
Number of buses	1400	No.
Number of bus routes	190	No.
Average travel time of bus route	60	Minute
Ave. Vehicle emission factor (EPA standards)	0.21	Kg / Km
Fuel Efficiency	0.106	Liter / Km
Working hours	16	Hr

Policy scenarios

Simulated data

Variable	*Year i*	*Year i + 1*	*Year i + 2*	*Year i + 3*	*Year i + 4*	*Year i + 5*
Population (People)	4500000	4542850	4586110	4629780	4673870	4718380
GDP (Dollar)	1.125e11	1.13628e11	1.1476e11	1.1592e11	1.1708e11	1.1825e11
Area (Km^2)	4500	4504.5	4509.01	4513.52	4518.03	4522.55
Veh. pop. (Veh.)	2880000	2907430	2935110	2963060	2991280	3019760

Scenario	*Non Trip sharing percentage (w_1)*	*Non Car ownership percentage (w_2)*
Basic	1	1
First	0.5	1
Second	1	0.9
Third	0.5	0.9

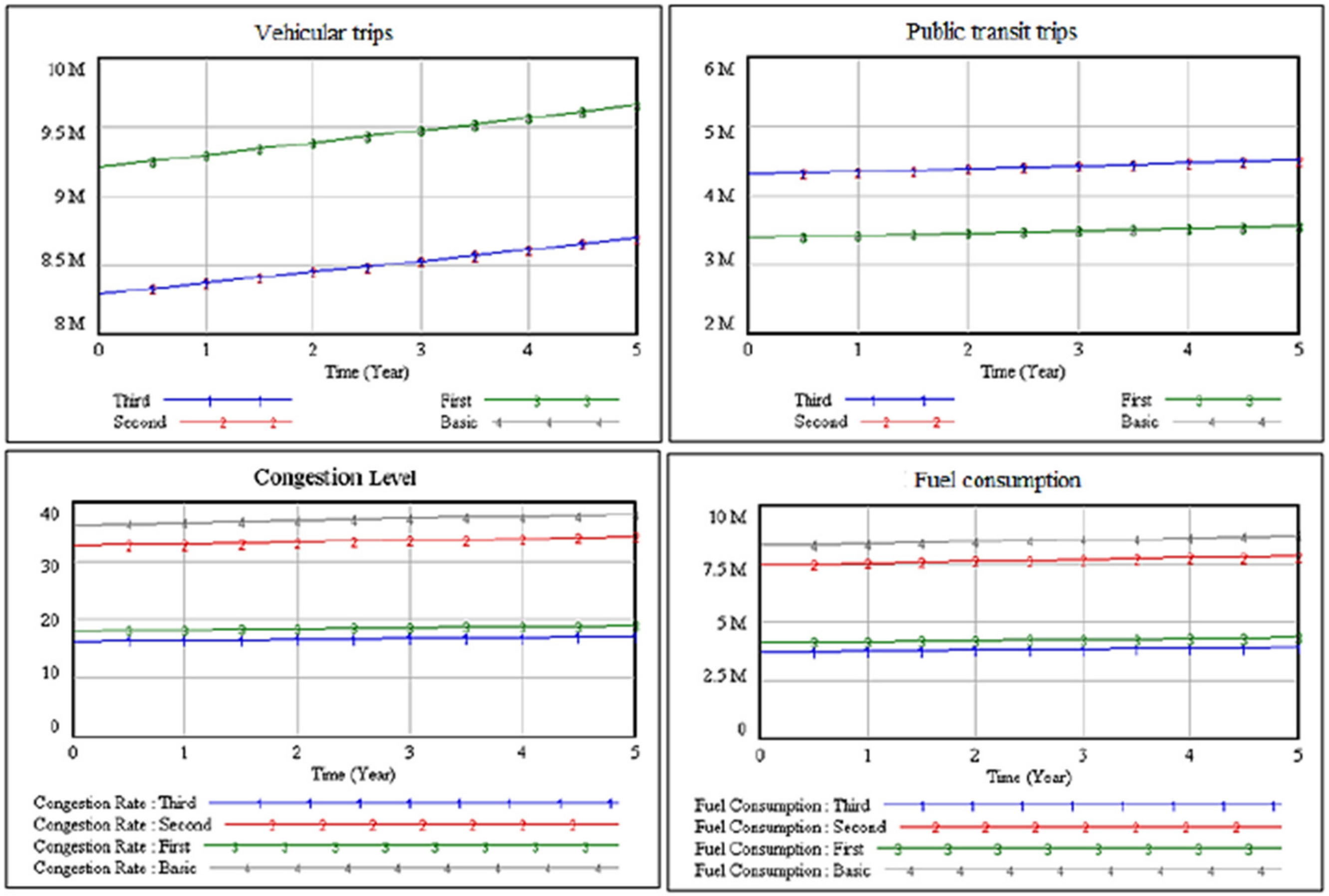
Scenarios (policies)

Scenario analysis results

Scenario	*Vehicular trips (M)*	*Public transit trips(M)*	*Trips per bus*	*Congestion level*	*Fuel consumption (M lit)*	*Emission (M Kg)*
Basic $w_1 = 1$ $w_2 = 1$	9.20-9.66	3.4-3.6	2420-2550	36.25-38.01	8.30-8.70	19.57-20.52
First $w_1 = 0.5$ $w_2 = 1$	9.20-9.65	3.4-3.6	2420-2550	18.12-19.01	4.15-4.35	9.79-10.26
Second $w_1 = 1$ $w_2 = 0.9$	8.30-8.70	4.30-4.55	3100-3250	32.64-34.22	7.47-7.84	17.62-18.48
Third $w_1 = 0.5$ $w_2 = 0.9$	8.30-8.70	4.30-4.55	3100-3250	16.32-17.11	3.74-3.92	8.81-9.24

M- Million, w_1: Non Trip sharing percentage, w_2: Non Car ownership percentage,

Simulation Results



Variables “vehicular and public transit trips”, “congestion”, and “fuel consumption”

Design of Experiments

Alias	*Factor Name*	*Impacts Levels*		*Dependent Factors (Criteria)*			*unit*
		Low (-) $x_{L_i} < L_L < x_{L_j}$	*High (+)* $x_{H_i} < L_H < x_{H_j}$	*CONG*	*FULC*	*EMIS*	
A	TRR	2.1-2.6	3.2-3.8	✓	✓	✓	N/A
B	AKT	4.8-5.8	8.8-9.5	✓	✓	✓	Km
C	LRN	2500-2750	2950-3200	✓			Km la
D	FE	6.5-8.8	8.5-10		✓		$\frac{\text{Lit}}{\text{100Km}}$
E	EF	150-170	180-210			✓	$\frac{\text{gr}}{\text{Km}}$

Factors & Levels

Metamodel - Congestion Level

Considering the terms: y : Congestion Level; x_1 :Trip Rate; x_2 :Average Kilometers Traveled (Km); x_3 :Length of Road Network (Km-lane). The first degree polynomial regression equation is:

$$y = -0.3 - 0.25x_1 + 4.38x_2 + 0.00017x_3 + 1.5x_1x_2 - 0.00153x_2x_3$$

Subject to:

$$y > 0 \quad , \forall \; x_i > 0$$

Metamodel - Fuel Consumption

y: Fuel Consumption (10^8 Liter) daily;

x_1: Trip Rate;

x_2: Average Kilometers Traveled (Km);

x_3: Fuel Efficiency (Lit / 100Km);

The first degree polynomial regression equation of metamodel in x is:

$$y = -5.68 - 0.035x_1 + 0.013x_2 + 0.667x_3 + 0.285x_1x_2$$

Subject to:

$$y > 0 \quad , \forall \ x_i > 0$$

Metamodel - Emissions

y:Emission (10^9g) daily;

x_1: Trip Rate;

x_2: Average Kilometers Traveled (Km);

x_3:Emission Factor (g / Km);

The first degree polynomial regression equation of metamodel in x is:

$$y = 12.4 - 4.31x_1 - 1.72x_2 - 0.0703x_3 + 0.594x_1x_2 + 0.00990x_2x_3 + 0.0239x_1x_3$$

Subject to:

$$y > 0 \quad , \forall \; x_i > 0$$

Metamodel validation

Absolute Relative Error (ARE) test (Kleijnen and Sargent, 2000):

$$ARE\ (SDO, MMO) = \left|\frac{(SDO - MMO)}{SDO}\right|$$

Where, SDO and MMO denote SD Output and metamodel Output respectively

NO.	TR	AKT	LRN	SDO	MMO	ARE
1	3.3	7.52	2663	38.32	38.85	0.0138
2	2.8	6.89	2506	31.66	32.12	0.0145
3	2.5	5.07	2846	18.31	18.70	0.0213
4	2.8	5.64	2909	22.32	22.78	0.0206
5	3.7	8.12	2702	45.72	46.29	0.0125
6	3.3	5.45	2865	25.81	26.32	0.0198
7	2.6	5.53	3171	18.64	18.55	0.0048
8	3.1	9.43	2560	46.96	47.58	0.0132

Sensitivity Analysis

	TRR (x_1)	AKT (x_2)	LRN (x_3)	CONG(y)	Feasibility	Comments and Remedies
1	2.1	4.8	2500	17.38	✗	The large network is not economically sustainable
2	3.8	4.8	2500	29.20	✓	System is doing well, no action is recommended
3	2.1	9.5	2500	34.80	✓	The network is achieving to margin. Needs to reduce AKT, increase LRN
4	3.8	9.5	2500	58.60	✗	Too congested network, AKT and/or TR should be decreased
5	2.1	4.8	3200	12.36	✗	The large network is not economically sustainable.
6	3.8	4.8	3200	24.18	✓	System is doing well, no action is recommended
7	2.1	9.5	3200	24.74	✓	System is doing well, no action is recommended
8	3.8	9.5	3200	48.54	✗	Too congested network, AKT and/or TR should be decreased

Optimization Model

$$\min \quad y = -0.3 - 0.25x_1 + 4.38x_2 + 0.00017x_3 + 1.5x_1x_2 - 0.00153x_2x_3$$

s.t.

$$2.1 \leq x_1 \leq 3.8$$

$$4.8 \leq x_2 \leq 9.5$$

$$2500 \leq x_3 \leq 3200$$

Assume that the congestion level is maintained on a Level of Service C with 25 <=y<=30 vehicles/km of lane. The above metamodel provides the optimal combination x1= 2.81, x2= 5.35 and x3= 2500.

This means for a network with 2500 km lane, if the trip rate is 2.81 therefore the distance traveled by people should not be more than 5.35 km if we intend to observe LOS C.

Roadmap towards sustainable systems