

Macroscopic Modeling and Scenario Evaluation of Internal Traffic Circulation at a Large University Campus

Remus - Andrei DOBRINOIU*

National University of Science and Technology Politehnica Bucharest, Bucharest, Romania

**Corresponding author, remus.dobrinou@upb.ro*

Augustin SEMENESCU

National University of Science and Technology Politehnica Bucharest, Bucharest, Romania

augustin.semenescu@upb.ro

Ionuț - Cosmin CHIVA

National University of Science and Technology Politehnica Bucharest, Bucharest, Romania

ionut_cosmin.chiva@upb.ro

George Gabriel VOLINTIRU

National University of Science and Technology Politehnica Bucharest, Bucharest, Romania

gabriel.volintiru@stud.mec.upb.ro

Abstract. Universities are complex spatial systems where the interaction of mobility demand, land-use patterns and internal circulation networks takes place. In recent decades, the increased motorization and pressures of urban development have transformed traffic on campus, resulting in conflicts between motorized and non-motorized users and undermining traditional circulation designs. The paper presents an evaluation of the internal road network of the Politehnica Bucharest Campus, in order to assess the circulation efficiency and the possibilities to organize it, considering the increasing traffic demand. The study is based on multi-tiered modelling and empirical traffic data. The traffic demand is estimated by a synthetic gravity-based origin-destination model linking access points to the main functional zones of the campus. Graph theory is used to structure the internal road network for scenario partitioning. The analysis of dynamic traffic behavior uses a macroscopic simulation model that focuses on the network-level density, speed and flow relationships, a Greenshields-type speed-density formulation, and deterministic parking search and transit cohorts. Simulation results show that the internal network is underutilized at the existing demand levels, with low densities and insignificant delays. Simulations show that moderate growth in demand can cause increases in density and degradation of performance due to delays. These improvements are obtained thanks to structural and organizational interventions, such as network permeability and one-way circulation systems, which overcome the heavy demand. Some ways of managing traffic flow that don't involve building new infrastructure can reduce congestion, the study says.

Keywords: traffic simulation, transport networks, macroscopic traffic modeling, sustainable mobility, campus mobility.

Introduction

Over the past several decades, socio-economic activities, land-use patterns and travel behaviours have changed dramatically and have substantially reconfigured urban mobility networks. Large

university campuses are a special urban context with high population densities, multiple functions and significant temporal variations in the demand for mobility. The design of internal circulation networks is of utmost importance in such cases, in order to provide access, safety and sustainable development of the campus (Timar, 2010; Terdalkar, 2017; Subedi et al., 2021).

The National University of Science and Technology Politehnica Bucharest campus was originally planned as a predominantly pedestrian area, with public transport as the main access mode and sporadic vehicle circulation inside the campus. The explosion of private car ownership and the associated urban sprawl has greatly increased the amount of motorized traffic coming to the university. This leads to the gradual design of interior roadways for vehicular movement and parking, which reduces pedestrian safety and changes the functional nature of the campus environment (Timar, 2010; Terdalkar, 2017; Subedi et al., 2021; Xie et al., 2013; Chai et al., 2021; Boitor, 2020).

These situations create confrontations between motorized and non-motorized users, particularly at peak times associated with coordinated academic activity. Campus environments if not properly legislated or infrastructured can exhibit similar congestion trends as metropolitan areas that affect safety, environmental conditions, and the general status of mobility (Terdalkar, 2017; Subedi et al., 2021; Xie et al., 2013; Chai et al., 2021).

Politehnica Bucharest is looking for traffic management solutions that will improve traffic flow while keeping the academic and pedestrian-friendly character of the campus. The study provides a quantitative assessment of current and future traffic conditions and examines different organizational variants for internal motorized movement.

Campus is examined as an integrated system of two interconnected subsystems: the physical configuration of activities (education, research, administration and recreation) and the internal road system that facilitates daily mobility. The travel demand depends on the intensity of land use, the accessibility and the behavior of users are influenced by the network layout and the rules of circulation (Nagi et al., 2018; Bîrsănuc et al., 2019; Cappai et al., 2019).

The research aims to pursue four main objectives: (i) analyze the existing road infrastructure and the circulation regulations to identify structural limitations; (ii) evaluate the capacity of the network using empirical traffic and parking data; (iii) evaluate its capability to accommodate the future demand growth; and (iv) test the strategies of circulation reorganization (link openings and one-way systems) designed to improve the network performance (Xie et al., 2013; Chai et al., 2021; Boitor, 2020).

To accomplish these objectives, the study integrates a number of transportation planning methodologies. The gravity model is used to estimate the flows between origins and destinations, while graph theory deals with the structure and connectivity of networks (Raicu, 2007). The traffic dynamics are modeled by a macroscopic model based on the Macroscopic Fundamental Diagram and the Greenshields speed-density function, which allows to evaluate the congestion dynamics under different scenarios (Nagel, 1998; Geroliminis & Sun, 2011; Weng, 2010; Lehe, 2016; Piyapong et al., 2020).

Literature review

Mobility systems in complex spatial contexts are a central theme in transportation planning and urban studies. University campuses are a particular form of the city with multiple functions, strong variations in demand in time and complex interactions between land uses and internal circulation networks.

There is a large body of literature that discusses the strong relationship between land use and transport systems. In this regard, the spatial distribution and density of activities are the main drivers of travel demand (Bîrsănuș et al., 2019; Cappai et al., 2019; Drober, 2020). Urban land use is the distribution of land to certain activities such as education, employment, research, administration and recreation which are related to different movement behaviours (Drober, 2020). Empirical research shows that the educational and occupational activities produce the largest demand in peak hours, due to the synchronisation of schedules and spatial concentration (Damian, 2023; Damian & Ioniță, 2021; Ebrahim, 2021; Kaplan, 2015). This is a phenomenon very visible in university campuses where many students and staff use common facilities in limited time frames (Timar, 2010; Damian, 2023). However, recreational and green spaces tend to create less and more dispersed traffic levels (Morar, 2013; Tonnelat, 2010; Dinca, 2025). Research demonstrates that the demand for campus mobility is not restricted to external access trips but includes innumerable short internal trips between buildings and often using different modes of transportation (Timar, 2010; Terdalkar, 2017; Subedi et al., 2021). If the circulation systems do not adequately respond to these patterns, conflicts may arise between the walkers, bicycles and motorized vehicles affecting the safety and the spatial quality. Therefore, land-use-transport interaction models are increasingly applied to study campus mobility (Nagi et al., 2018; Bîrsănuș et al., 2019; Cappai et al., 2019).

Research often utilize zoning methodologies to establish such linkages, which divide the study area into spatial units with relatively similar land-use characteristics (Morar, 2013; Tonnelat, 2010; Dinca, 2025; The University of Chicago, 1984; Miltiadis & Visvizi, 2018). Transportation models associate the demand for activity to particular activity groupings. The centroid locations of zones are used as the origins and destinations.

Graph theory is often used to study the network structure. Transport systems are represented as nodes and links. This allows to evaluate connectivity, accessibility and possible bottlenecks (Raicu 2007). These methods work best in campus settings where the area is relatively small geographically and where there are alternative routes. In campus applications, origin points are generally represented by access points and destination points by buildings or functional zones, where the attraction potential is given by the number of employees, students or parking capacity (Subedi et al., 2021; Xie et al., 2013; Chai et al., 2021).

Finally, the flow theory provides the analytical basis for analyzing the interrelationships between flow, velocity and density. The Greenshields speed-density relationship and macroscopic fundamental diagram are often used to analyze congestion dynamics and to evaluate circulation scenarios at network level. (Treiber, 2014; Kesting et al., 2007; Knorr et al., 2014; Dobrinoiu et al., 2025a, b).

Modeling the spatial configuration of the Politehnica Bucharest Campus

Functional framework & demarcation of activity

In the analysis of the traffic flows in the Politehnica Bucharest Campus, the spatial structure was formalized by identifying and characterizing the main categories of activities generating and attracting the mobility demand. The campus is a mixed-use environment for educational, research, administrative, recreational and dissemination activities, whose spatial arrangement has a direct impact on the internal circulation patterns.

Activities were grouped into six functional categories which correspond to the main role on campus: educational and university research activities involving students, advanced research activities, recreational and green spaces, sports facilities, administrative functions, and dissemination activities including libraries and conference venues. For each activity category, the

level and temporal pattern of mobility demand are associated with the built area, number of students and employees, and parking availability.

The classification allows a systematic representation of land use intensity and further assessment of travel demand. The strongest peak-period demand for educational and research activities is due to the synchronized schedules and the spatial concentration of these activities, while administrative and dissemination functions cause moderate but constant flows.

Origin-Destination framework and access points

For estimating the internal traffic demand, a synthetic gravity model was used to generate the origin-destination (OD) matrix of the motorized trips within the campus. Origins include the three major access points to the campus and destinations include consolidated zones related to important building clusters and functional areas (Stewart, 1990).

We use the standard formulation of the gravity model:

$$T_{ij} = G_i \cdot A_j \cdot f(d_{ij})$$

where:

- T_{ij} is the number of vehicle trips from origin zone i to destination zone j ;
- G_i refers to the generation potential of origin i , estimated from observed traffic counts;
- A_j attractiveness potential of the destination j , calculated based on the number of employees and students associated with each building group;
- $f(d_{ij})$ is the impedance function, dependent on the distance d_{ij} between zones i and j .

For campus-scale applications and long-term planning considerations, the impedance function is expressed as a function of distance only:

$$f(d_{ij}) = d_{ij}^{-\beta}$$

where β is the distance decay exponent. A preliminary value of $\beta=2$ was used, based on values frequently found in the literature for short distance trips related to work and education (Raicu, 2007; Stewart, 1990).

Table 1. Distance matrix (m)

	O1 (Entrance Splaiul Independenței Bvd.)	O2 (Entrance Doina Cornea Bvd.)	O3 (Entrance Iuliu Maniu Bvd.)
R (rectorat building)	650	400	1100
AN (AN wing)	850	500	900
BN (BN wing)	600	550	1300
CI (FILS bulding)	1300	1000	1300
C2 (FIIR, FIMM, FSA buildings)	1200	800	1100
D (ISB building)	1300	950	900
E1 (FIE building)	1000	700	750
E2(ACC building)	1500	1100	300
E3(FIE building)	1600	1200	190
F(CET building)	1300	1000	650
J1(SIM building)	550	500	1500
J2(Transporturi bulding)	750	270	1400
CMP(Campus building)	1800	1400	220

	O1 (Entrance Splaiul Independenței Bvd.)	O2 (Entrance Doina Cornea Bvd.)	O3 (Entrance Iuliu Maniu Bvd.)
PRC(Precis building)	1500	1100	400
L(L wing)	600	400	1600
BRL(Library building)	1300	1000	1300
AUL(Aula Magna building)	1200	850	1200
SPP(School bulding)	1500	1200	500
O1	-	1000	1700
O2	1000	-	1400
O3	1700	1400	-

Source: Authors' own research.

The generation potentials G_i were calibrated against the average traffic volumes during the morning peak period (07:30-09:30) when the inbound demand is highest. Attraction potentials A_j were calculated as the weighted sum of employees and enrolled students associated with each destination zone (Subedi et al., 2021; Xie et al., 2013; Chai et al., 2021; Stewart, 1990).

Table 2. The source areas generation potential

Zone	G_{0i} [veh/h]
O1	63
O2	122
O3	233

Source: Authors' own research.

Table 3. The attraction power of destination areas

Zone	Parking spots	Employes	Students	Potential for attraction
R	83	650	0	650
AN	40	25	0	25
BN	26	213	1350	1563
C1	78	25	900	925
C2	118	263	2803	3066
D	26	75	900	975
E1	57	138	1800	1938
E2	39	263	1800	2063
E3	20	138	900	1038
F	6	25	0	25
J1	59	75	900	975
J2	65	100	1800	1900

Zone	Parking spots	Employees	Students	Potential for attraction
CMP	93	25	0	25
PRC	76	25	0	25
L	14	25	0	25
BBL	44	100	0	100
AUL	0	20	0	30
SPP	50	40	430	125

Source: Authors' own research.

The resulting OD matrix was corrected by factors so as to correspond to the observed parking occupancy rates and the physical capacity of parking facilities associated with each building group (Ceapoiu, 1968).

Table 4. OD matrix

	O1	O2	O3	Total
R	3	9	2	14
AN	3	8	4	15
BN	4	6	2	12
Cl	2	4	2	8
C2	2	6	4	12
D	2	4	4	10
E1	2	5	5	12
E2	2	4	16	22
E3	2	5	34	41
F	2	5	6	13
J1	4	8	3	15
J2	3	14	3	20
CMP	2	4	21	27
PRC	2	4	16	22
L	4	10	3	17
BBL	1	4	3	8
AUL	0	0	0	0
SPP	56	10	35	61
O1	0	0	66	66
O2	0	0	4	4
O3	7	12	0	19
Total	113	122	233	418

Source: Authors' own research.

The role of spatial modelling in scenario assessment

The above framework for spatial modeling constitutes the structural basis for all subsequent analyses. The uniform demand generation, flow distribution and circulation performance are unified by functional classification, zoning and network representation.

The framework allows for a clear distinction of the structural effects and the behavioral assumptions and an evaluation of the effect of changes in the network configuration on the macroscopic traffic performance assuming constant demand. Thus, spatial modelling is needed to enable scenario-based analysis and evidence-based decision making on campus circulation organization.

Review of existing campus circulation conditions

Internal road system attributes and configuration

The internal circulation network of the Politehnica Bucharest Campus is made up of approx. 6 km of motorized roadways, mostly two-way alleys, one lane for each direction, with an average width of the carriageway of approx. 6 m. This geometric configuration allows the movement of all types of vehicles including passenger cars and light commercial vehicles, while heavy freight traffic is almost non-existent (Figure 1).

A small number of segments, of the order of 700 m (some 12% of the total network length) are operated under one-way traffic systems. Most of these segments are located near campus entrances and major administrative and educational buildings. The campus has 30 km/h speed limits everywhere, in line with its mixed use and pedestrian-friendly character.



Figure 1. Circulation network in the Politehnica Bucharest campus

Source: Authors' own research.

Time request distribution and traffic quantification

The empirical traffic data were collected during one full observation day, from 07:30 to 19:30, at the three main access points of the campus. The recorded data shows that 2424 vehicles entered the campus during the observation period.

The biggest part of traffic is passenger cars in the amount of 2346 units. This is about 97% of all entrances. Light commercial vehicles (1,5 - 3,5 t) 78 units (around 3%). No heavy goods vehicles are recorded. This composition reemphasizes the dominance of private motorized mobility and provides support for the hypothesis of modelling that traffic dynamics are mainly dictated by passenger vehicles.

The spatial distribution of the access flows shows a clear hierarchy between the entry points:

- Iuliu Maniu Bvd.: 1.172 vehicles (around 48%),
- Doina Cornea Bvd.: 774 vehicles (approx. 32%)
- Splaiul Independenței Bvd. – 478 vehicles (some 20%).

Temporal analysis shows significant peaks during morning (07:30 - 08:30) and afternoon (15:30 - 16:30) periods, which is in line with the synchronized arrival and departure of students and staff. The average hourly entry rate across the whole day is about 202 vehicles/hour with the peak hourly volume of 353 vehicles/hour during the morning rush.

Table 5. Total vehicles entering the campus

Time period	Cars	Light commercial vehicles (1.5-3.5 tons)
07:30 - 08:30	347	6
08.30 - 09:30	330	4
09:30 - 10:30	341	7
10:30 - 11:30	202	12
11.30 - 12.30	214	13
12.30 - 13.30	154	6
13.30 - 14:30	190	5
14:30 - 15:30	136	11
15:30 - 16:30	155	5
16:30 - 17:30	129	5
17:30 - 18:30	111	1
18:30 - 19:30	37	3

Source: Authors' own research.

Network Load, Density and Capacity Utilization

The empirical traffic counts were converted into macroscopic indicators of network congestion using a total internal network length of approximately 6 km. The average network density during peak times is estimated to be between 5 and 5,8 vehicles per kilometer, while off-peak values are below 3 vehicles per kilometer.

The traffic flow computed at the network level varies from 60 vehicles/hour at low demand periods to about 165 vehicles/hour at peak load periods. These numbers are well under the theoretical capacity of an average single urban lane, which is conservatively estimated to be approximately 900 vehicles per hour.

These observations prove that the internal road network is under-utilized volumetrically, and is functioning below its theoretical capacity

Table 6. Density and traffic flow of the network

Time interval	Entries [veh/h]	Density [veh/km]	Traffic flow [veh/h]
07:30–08:30	353	5,322	152,6
08:30–09:30	330	4,974	143
09:30–10:30	349	5,262	150,9
10:30–11:30	202	3,039	88,9
11:30–12:30	214	3,22	94
12:30–13:30	154	2,315	68,1
13:30–14:30	190	2,858	83,7
14:30–15:30	136	2,044	60,3
15:30–16:30	158	5,759	164,5
16:30–17:30	133	5,369	153,9
17:30–18:30	112	5,042	144,9
18:30–19:30	40	3,924	113,9

Source: Authors' own research.

Relationship between circulation and parking occupancy

Many zones are fully or almost fully occupied, especially around the Rectorate and the educational institutions. There are local shortages and an increase in traffic to look for parking. On the other hand, other areas show a significant number of empty spaces during the same period.

In some places the mismatch between demand for parking and supply of parking gives rise to informal or irregular parking practices that further reduce the effective width of roadways and increase the friction of interaction. The dynamics lead to long vehicle dwell times in the network, despite low overall traffic volumes.

Table 7. Occupied parking spaces between 7:30 - 8:30

	O1	O2	O3	Flow	Parking spaces	Available parking spaces
R	6	14	4	24	83	59
AN	6	10	8	24	40	16
BN	8	8	4	20	26	8
C1	4	4	4	12	78	66
C2	4	6	8	32	118	86
D	4	4	8	16	26	10
E1	4	6	10	20	57	37
E2	4	4	32	39	39	0
E3	4	6	68	20	20	0
F	4	4	12	6	6	0
J1	8	12	6	40	59	19
J2	6	24	6	36	65	29
CMP	4	4	42	93	93	0
PRC	4	4	32	56	76	20
L	8	14	6	14	14	0

	O1	O2	O3	Flow	Parking spaces	Available parking spaces
BBL	2	4	6	12	44	32
AUL	0	0	0	0	0	0
SPP	3	2	10	15	30	15

Source: Authors' own research.

Motorized traffic simulation on the campus

Network representations and circulation models

The internal road network of the campus is represented as a graph $G = (V, E)$ where the nodes V are intersections and access points and the edges E are road segments. This representation allows for the formal assessment of the network structure and provides a means to compare different circulation configurations (Chai et al, 2021; Popa, 2020).

Based on these structural variations, four traffic scenarios were defined:

- I1 (reference) – current circulation regulations and current demand;
- I2 (increased demand) – traffic demand increased up to 30% compared to the reference year;
- I3 (improved permeability) – increased demand and the re-connection of internal links;
- I4 (optimized circulation) - I3 conditions and the introduction of one-way circulation systems on selected arteries (Figure 2.).

These scenarios provide the basis for the dynamic simulation of traffic flows at network level.

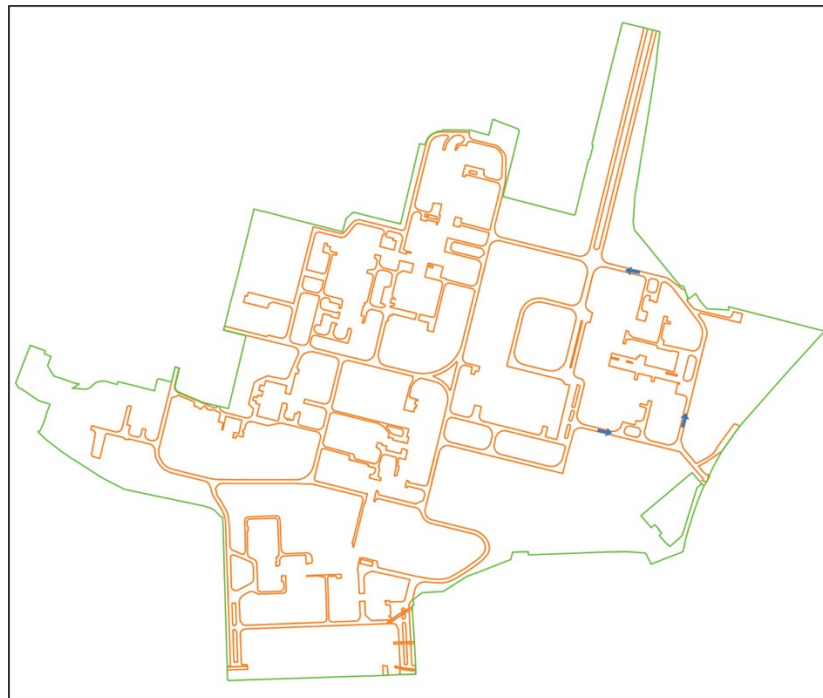


Figure 2. Making one-way streets

Source: Authors' own research.

General simulation model formulation

The simulation of the motorized traffic in the Campus of Politehnica Bucharest is based on a macroscopic representation of the internal road network, where the traffic dynamics are described using aggregate state variables that evolve in discrete time steps (Xie et al., 2013; Nagel, 1998; Geroliminis & Sun, 2011; Weng, 2010; Lehe, 2016; Piyapong et al., 2020). The analysis is done with a one minute resolution for the period $t = 0, 1, \dots, 719$, corresponding to the interval 07:30-19:29.

The state of the system at each time step t is described by the total number of vehicles active in the internal network (Daganzo & Geroliminis, 2008):

$$N(t) = N_p(t) + N_t(t) + N_e(t)$$

where:

- $N_p(t)$ represents vehicles looking for parking,
- $N_t(t)$ represents cars in the street,
- $N_e(t)$ denotes vehicles leaving parking facilities after the release time.

The corresponding spatial density:

$$k(t) = \frac{N(t)}{L}$$

where L is the total length of the internal road network.

This formulation ensures the vehicle conservation at the network level and offers the foundation for the computation of macroscopic performance indicators.

Speed-density relationship and macroscopic flow

The network-level traffic speed is given by the classical Greenshields macroscopic relationship in its aggregated form (Xie et al., 2013; Nagel, 1998; Geroliminis & Sun, 2011; Weng, 2010; Lehe, 2016; Piyapong et al., 2020):

$$v(t) = v_f \left(1 - \frac{k(t)}{k_j} \right)$$

where:

- v_f is the free-flow speed,
- k_j is the jam density.

Hence, the speed is limited to the range:

$$v(t) \in [v_{\min}, v_f]$$

The macroscopic minute traffic flow is derived from:

$$Q(t) = k(t) \cdot v(t)$$

Such a formulation captures the nonlinear dependency of traffic performance on density variations, which is the main building block of the simulation framework .

Modeling behavioral cohorts and entry flows

At each minute t the number of vehicles entering the network, $q_{\text{in}}(t)$, is known from empirical traffic counts. Incoming vehicles are grouped into two behavioral cohorts (Geroliminis & Sun, 2011; Fulman & Benenson, 2018):

$$q_p(t) = \alpha \cdot q_{\text{in}}(t), \quad q_t(t) = (1 - \alpha) \cdot q_{\text{in}}(t)$$

where:

- $q_p(t)$ represents parking seekers,
- $q_t(t)$ represents transit vehicles,
- $\alpha = 0,8$ is the fraction of parking seekers obtained from the observed parking occupancy.

Parking seekers remain in the network for a deterministic search time τ_p , and after that they are considered parked and thus removed from circulation.

Transit vehicles travel an average distance d_t and leave the network when this distance has been covered at the current macroscopic speed (t).

Dynamic evolution of vehicle cohorts

Parking search dynamics

Let $F_p(t)$ be the number of vehicles completing the parking search at time t . The evolution of parking seekers for deterministic search times is given by (Treiber, 2014; Kesting et al., 2007; Knorr et al. 2014):

$$N_p(t+1) = N_p(t) + q_p(t) - F_p(t)$$

where $F_p(t)$ is the flow of vehicles which entered the network at time $t - \tau_p$.

Transit dynamics

Transit vehicles move forward in proportion to the distance travelled per time step:

$$\Delta d(t) = \frac{v(t)}{60}$$

If $F_t(t)$ is the number of transit vehicles ending their trip at time t , then:

$$N_t(t+1) = N_t(t) + q_t(t) - F_t(t)$$

Exit flows after the release time

From release time t_r (corresponding to 15:30) vehicles that were parked start to go out of the network. Total parked vehicle after the release:

$$N_{\text{parked}}(t_r) = \sum_{t < t_r} F_p(t)$$

A release function $g(t)$ specifies the distribution of the exit flows over time and yields:

$$N_e(t+1) = N_e(t) + g(t) - F_e(t)$$

where $F_e(t)$ is the vehicles finishing their exit distance d_e .

This ensures the worldwide preservation of the vehicles:

$$\sum_t q_{\text{in}}(t) = \sum_t [F_p(t) + F_t(t) + F_e(t)] + N(719)$$

Specific parameterization of I1-I4 Scenarios

The four simulated scenarios are characterized by different changes in demand and effective network capacity:

- I1 (reference):

$$q_{\text{in}}(t) = q_{\text{obs}}(t), k_j = k_{j,\text{ref}}$$

- I2 (more demand):

$$q_{\text{in}}(t) = (1 + \delta) \cdot q_{\text{obs}}(t), \delta \leq 0.3$$

- I3 (increased permeability):

$$k_j = k_{j,\text{ref}} + \Delta k_j$$

- I4 (optimized flow):

$$k_j = k_{j,\text{ref}} + \Delta k_j + \Delta k_j^{(1w)}$$

To isolate the effects of demand growth and circulation organization, all behavioral parameters are set to a constant value (α, τ_p, d_t, d_e).

Measures of macroscopic performance

At each time step, we calculate the following indicators (Xie et al., 2013; Nagel, 1998; Geroliminis & Sun, 2011; Weng, 2010; Lehe, 2016; Piyapong et al., 2020):

- Density:

$$k(t) = \frac{N(t)}{L}$$

- Speed:

$$v(t)$$

- Flow:

$$Q(t) = k(t) \cdot v(t)$$

- Specific delay with respect to free-flow:

$$\Delta(t) = \frac{1}{v(t)} - \frac{1}{v_f}$$

The flow-weighted averages of the aggregated indicators over an interval $[t_1, t_2]$ are calculated by:

$$\bar{v} = \frac{\sum_{t=t_1}^{t_2} Q(t)v(t)}{\sum_{t=t_1}^{t_2} Q(t)}, \quad \bar{\Delta} = \frac{\sum_{t=t_1}^{t_2} Q(t)\Delta(t)}{\sum_{t=t_1}^{t_2} Q(t)}$$

The average performance is thus proportionally affected by traffic periods with greater traffic volumes (Dobrinou et al., 2025a, b).

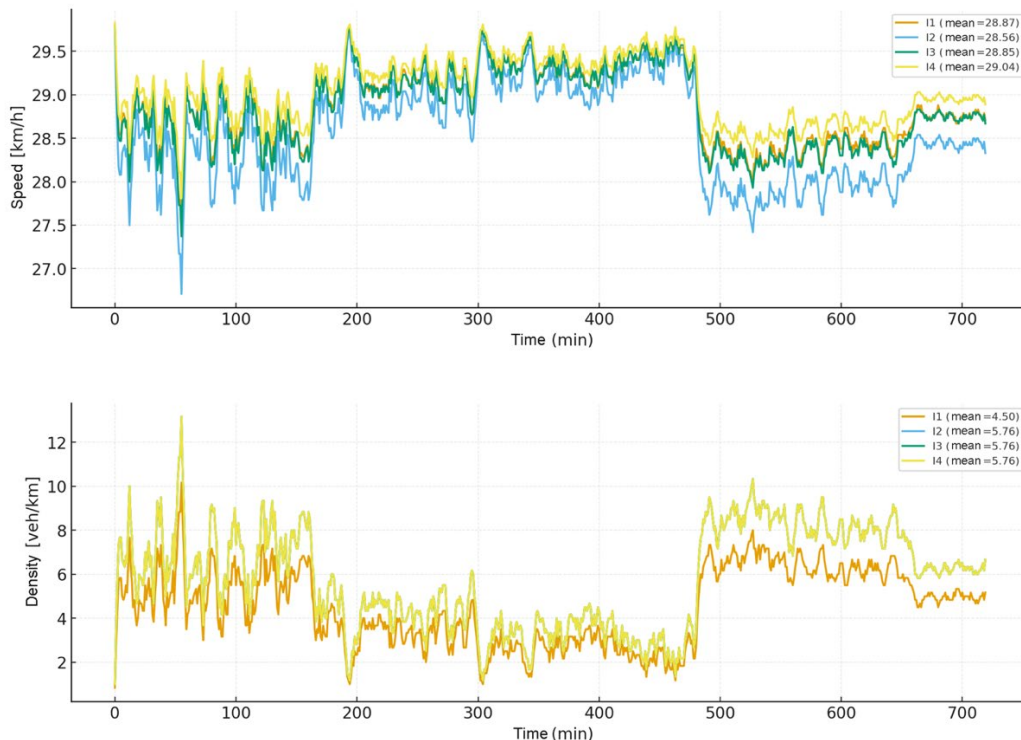


Figure 3. Daily traffic analysis – Speed and Density (I1-I4)

Source: Authors' own research.

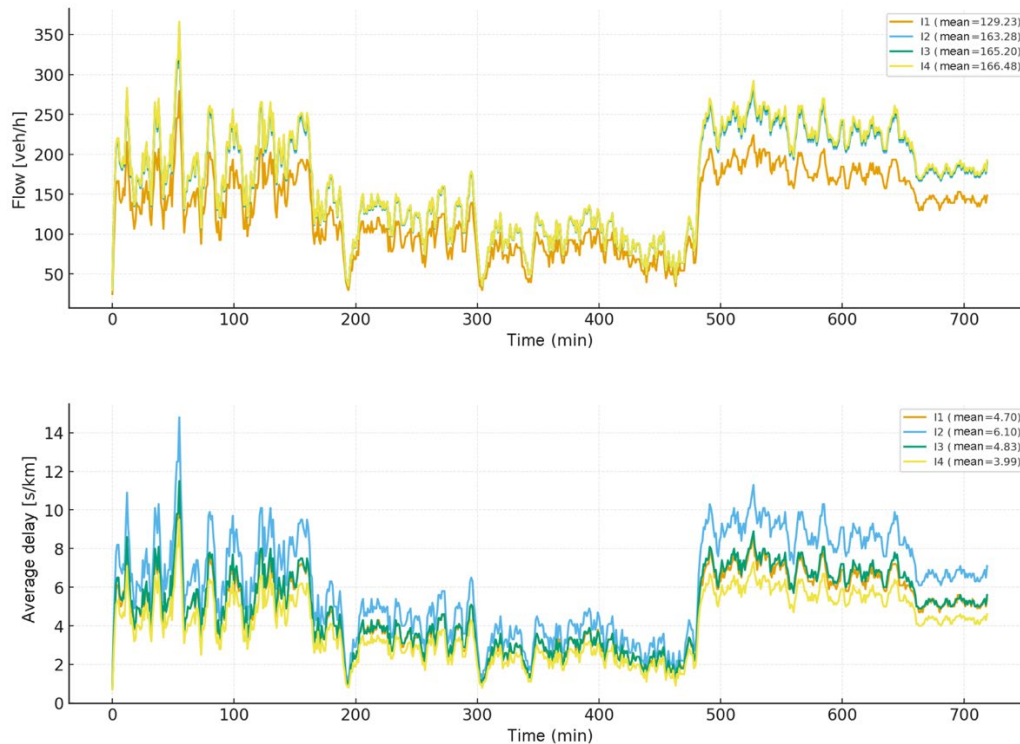


Figure 4. Analysis of daily traffic – Flow and Average delay (I1-I4)

Source: Authors' own research.

Tabel 8. Traffic parameters in simulation

	I1	I2	I3	I4
Mean delay [s/km]	4,7	6,1	4,83	3,99
Mean density [veh/km]	4,5	5,76	5,76	5,76
Mean flow [veh/h]	129,23	163,28	165,2	166,48
Queue length [veh]	0,01	0,01	0,01	0,01
Mean speed [km/h]	28,87	28,56	28,85	29,04
Stop duration [s/km]	1,55	2,01	1,59	1,32

Source: Authors' own research.

The internal circulation system does not work on signalized intersections but on a continuous internal network, which is treated in a standard way for congested areas. The queue length, Q [veh], is given as follows (Dobrinou, 2025):

$$Q = \max(0, (k - k_c) \cdot L)$$

where:

- k - traffic density [veh/km];
- k_c - the critical density, approximately given by:

$$k_c \approx \frac{q_{\max}}{v_f}$$

The Highway Capacity Manual(2010) defines stop delay (D_{stop} [s/km]) as the difference between total delay and running (in-motion) delay.

$$D_{\text{stop}} = \alpha \cdot D_{\text{total}}$$

where:

- D_{total} - the average total delay [s/km];
- α is a proportional coefficient calculated on the basis of the HCM recommendations for internal networks with conflicts with pedestrians and parking search behaviour.

According to the HCM(2010) guidelines for university campus environments, the coefficient α is usually in the interval:

$$\alpha \in [0,25; 0,40]$$

For normal applications the recommended value is:

$$\alpha = 0,33$$

Then the stop delay is calculated as:

$$D_{\text{stop}} = 0,33 \cdot D_{\text{total}}$$

Discussion

Beyond the specific case of the Politehnica Bucharest campus, the research offers a number of methodological and empirical insights for the mobility planning of large university campuses and other "micro-city" contexts.

The study shows that perceived congestion in campus environments is not necessarily caused by lack of network capacity. The case presented shows that the internal road network is operated under a significant extent of its theoretical capacity. The local failures are mainly caused by the spatial structure, the unequal distribution of parking spaces and the parking search behavior. This study shows that campus mobility problems are often organizational rather than infrastructural.

The modeling framework developed in this study is reproducible for other campus environments with few data requirements. The methodology is composed of three analytical parts: (i) a gravity based origin-destination estimation from campus access points to functional zones, (ii) a graph theoretical representation of the internal circulation network, and (iii) a macroscopic traffic simulation based on the Greenshields speed-density relationship and the Macroscopic Fundamental Diagram. The methodology can be applied in the absence of specific microscopic traffic data as it is based on aggregate indicators such as traffic counts, network length and activity-based attraction potentials.

Simulation of the scenario demonstrated the effectiveness of organizational changes (improved network permeability, one-way circulation system). These strategies are effective at increasing circulation efficiency but do not require large increases in infrastructure, which is critical in campus environments where the constraints of geography, culture, and pedestrian priorities limit the ability to construct large roads.

The modeling approach assumes a fairly uniform composition of vehicles, low traffic volumes and a minimal presence of heavy vehicles, which is typical for university campuses but may be different in mixed urban areas. The simulation excludes complex dynamics of intersections and pedestrian-vehicle interactions. In the future these interactions may be studied by means of hybrid or microscopic modelling.

The results show that the campus mobility planning should focus on circulation organization, parking management and network connectivity improvement before a capacity

expansion. The analytical paradigm of the present study may aid evidence-based decision-making for universities facing the challenge of increasing motorization while still maintaining the pedestrian-oriented character of academic environments.

Conclusion

The detailed evaluation of the internal road infrastructure, traffic behavior and simulation scenarios for the Politehnica University of Bucharest campus highlights several key factors that influence the efficiency and safety of mobility. The research is based on a structural evaluation of the internal network and detailed macroscopic simulations based on empirical data. The Macroscopic Fundamental Diagram and the Greenshields speed-density relation are applied.

The empirical observations show that the high prevalence of private automobiles (96 - 98% of the incoming vehicles are private automobiles) and the peak periods are between 07:30 - 08:30 and 15:30 - 16:30. Peak morning entry volumes were over 350 vehicles per hour but the internal network is operating well below optimal capacity. Furthermore, congestion is not systemic but localized, mainly due to the uneven distribution of flows, conflicts between vehicles and pedestrians, illegal parking and poor geometric design in some areas, especially in the AN–BN–Rectorate zone, where deficiencies of parking create chronic operational and safety problems.

The whole operational day was simulated with a macroscopic model that allowed the evaluation of four different scenarios. In the present configuration (I1), the network operates in stable conditions, with low average delays (around 4,7 s/km) and local disruptions. Demand increase (I2) of 30% leads to substantial growth in density and increases delays, hence increasing the vulnerability of the system with overall operability preserved. The scenarios with higher internal permeability (I3) present significant improvements in performance, with delays near reference levels even in higher demand situations. The optimized solution with the combination of new links and one-way circulation (I4) always performs better and the delay is the least and the average speed is the highest and the stability is better in both morning and afternoon peak hours.

In all cases, the network density is always below critical levels, rarely exceeding 8-10 vehicles/km, and average speeds are stable at around 30 km/h, confirming the suitability for campus environments. The results indicate that the current network is constrained by organization of circulation, safety and spatial efficiency, not by capacity.

To conclude, the scenario I4 is the best compromise between performance, safety and sustainability. Better parking management and a more efficient traffic and parking demand monitoring, combined with the optimization of the one-way systems and the selective reopening of the internal links, will contribute to the evolution of the Politehnica University of Bucharest campus into a more efficient, safer and sustainable mobility system, capable of responding to the modern needs of academic and urban environments.

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