Università degli Studi di Padova
Fondazione Bruno Kessler

MASTER THESIS IN PHYSICS OF DATA

EFFECTS OF TOPOLOGICAL CHANGES IN THE INDIVIDUALS DECISION-MAKING IN RELATION TO TRANSPORTATION METHODS IN A CITY

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INTRODUCTION

URBAN MOBILITY

- **Organization of a city to reduce the travel time**
- Use of sustainable transport methods to reduce the pollution.

CARS

+ Fast transportation
+ Comfort & Status
- Pollution
- Occupy much space
- Congestion

COMMUTING TIME

ACTIVE TRANSPORTS

+ Less Pollution
+ Almost non congestion
+ Accessible
- Slower
- Energetic cost

1) What is the optimal users combination to reduce the commuting time?

2) What happens to this combination if we modify the topology of the city?

DYNAMICS OF MODAL SHARE

1) What is the optimal users combination to reduce the commuting time?

COMMUTING TIME

$$C_i(\vec{x}) = B_i + D_i(\vec{x}) + I_i(\vec{x}), \qquad \vec{C}(\vec{x}) = \vec{B} + \mathcal{M}\vec{x}$$

AVERAGE COMMUTING TIME

$$\mu(\vec{x}) = \frac{1}{N}[\vec{x}^T\vec{B} + \vec{x}^T\mathcal{M}\vec{x}]$$

REPLICATOR EQUATION

$$\dot{\vec{x}}_i = \rho\vec{x}_i(\mu(\vec{x}) - \vec{C}_i)$$

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ORIGINAL RESEARCH
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A Ubiquitous Collective Tragedy in Transport

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A tragedy of the commons is said to occur when individuals act only in their own interest but, in so doing, create a collective state of a group that is less than optimal due to uncoordinated action. Here, we explore the individual decision-making processes of commuters using various forms of transport within a city, forming a modal share which is then built into a dynamical model using travel time as the key variable. From a randomised start in the distribution of the modal share, assuming that some individuals change their commuting method, favouring lower travel times, we show that a stable modal share is reached corresponding to an equilibrium in the model. Considering the average travel time for all commuters within the city, we show that an optimal result is achieved only if the direct and induced factors and the number of users are equal for all transport modes. For asymmetric factors, the equilibrium reached is always sub-optimal, leading to city travel trajectories being "tragic", meaning that individuals choose a faster commuting time but create a slower urban mobility as a collective result. Hence, the city evolves, producing longer average commuting times. It is also shown that if a new mode of transport has a small baseline commuting time but has a high induced impact for other users, then introducing it might result in a counter-intuitive result producing more congestion, rather than less.

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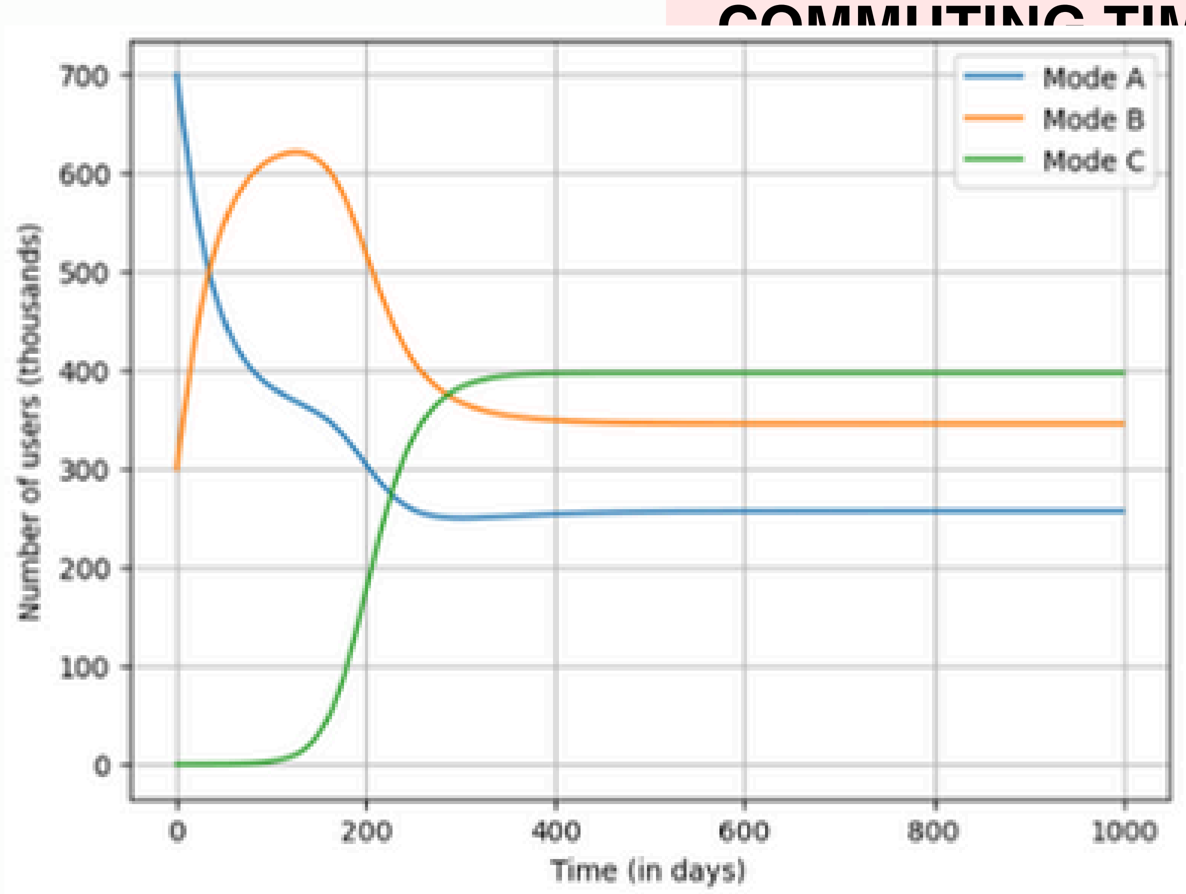
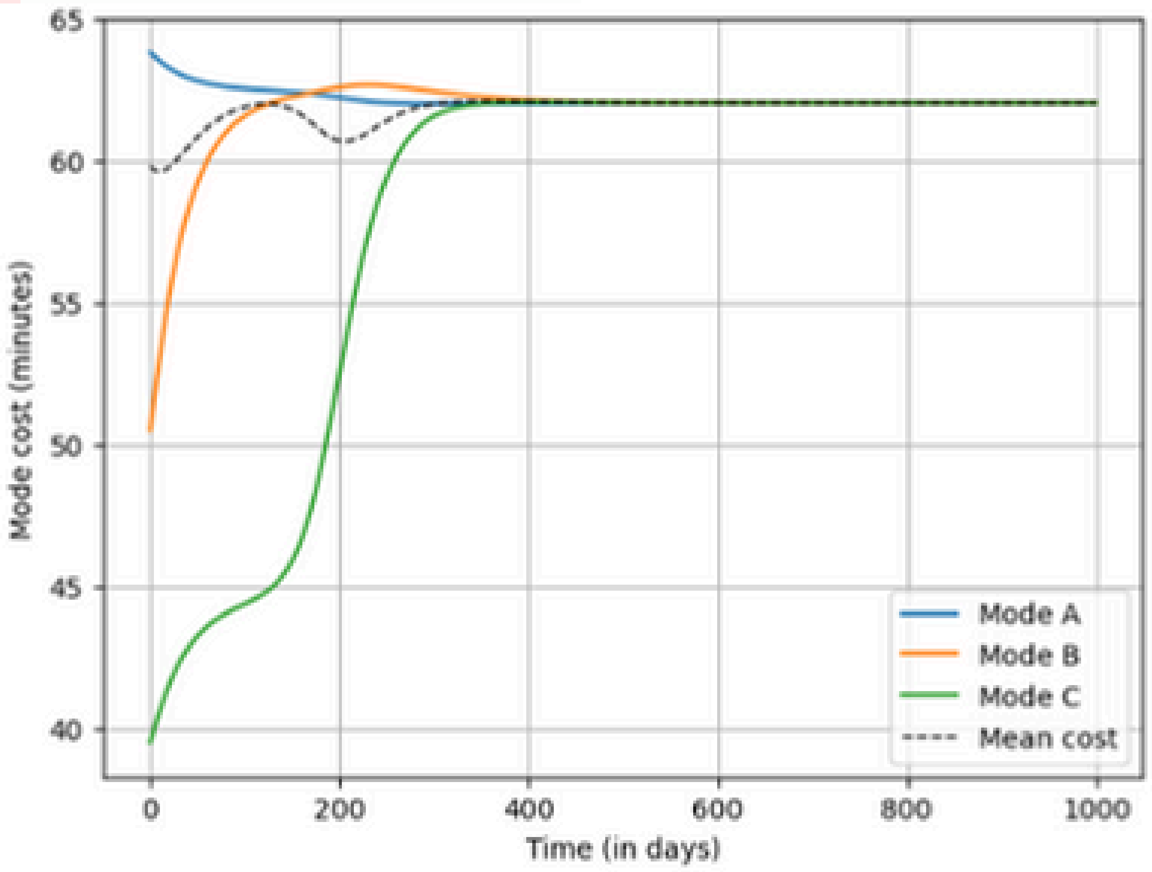
Keywords: tragedy, modes of transport, modal share, public transport, pollution, evolutionary games, dynamical system

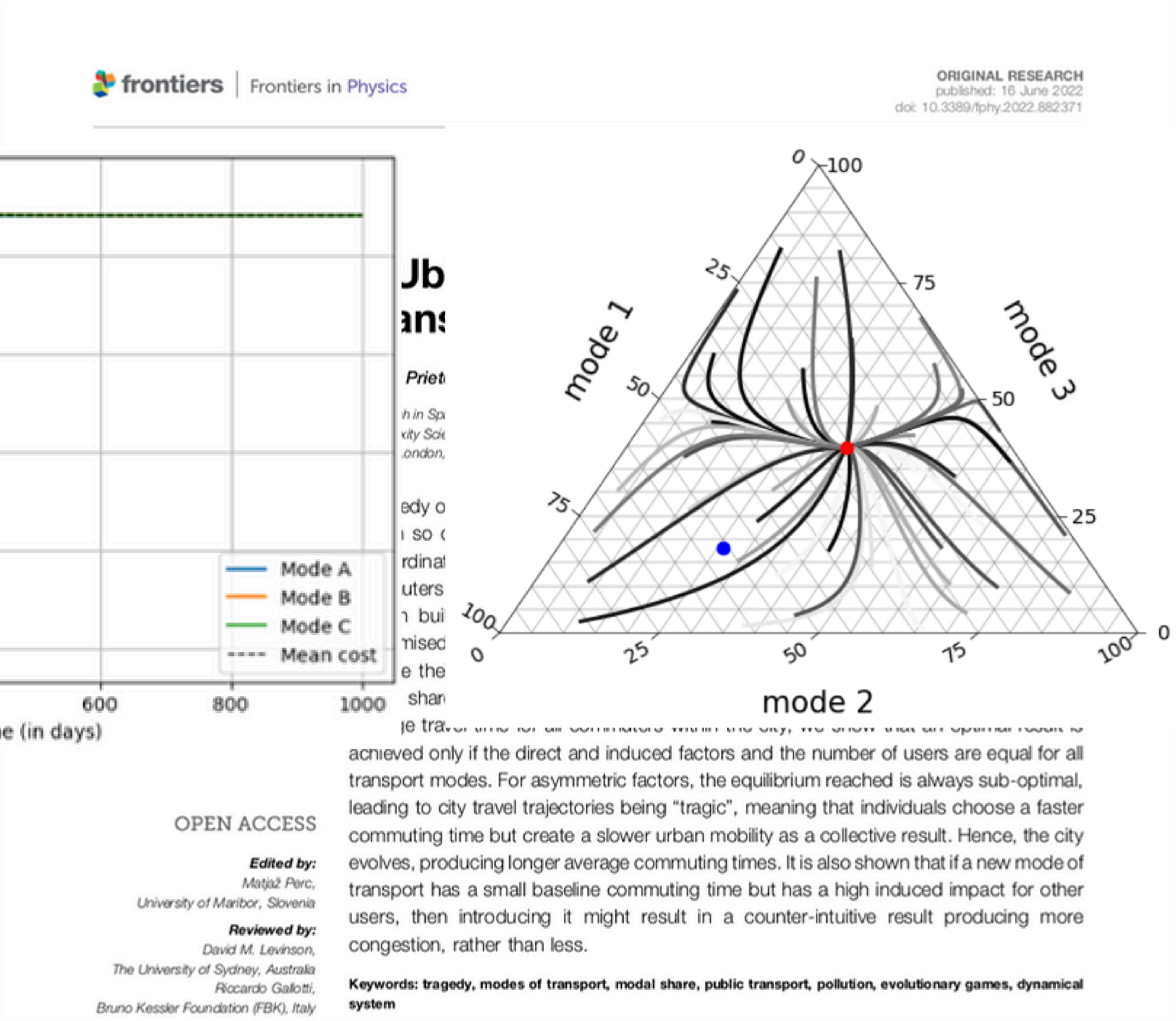
DYNAMICS OF MODAL SHARE

1) What is the optimal users combination to reduce the commuting time?

COMMUTING TIME







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REPLICATOR EQUATION

$$\dot{\vec{x}}_i = \rho \vec{x}_i(\mu(\vec{x}) - \vec{C}_i)$$

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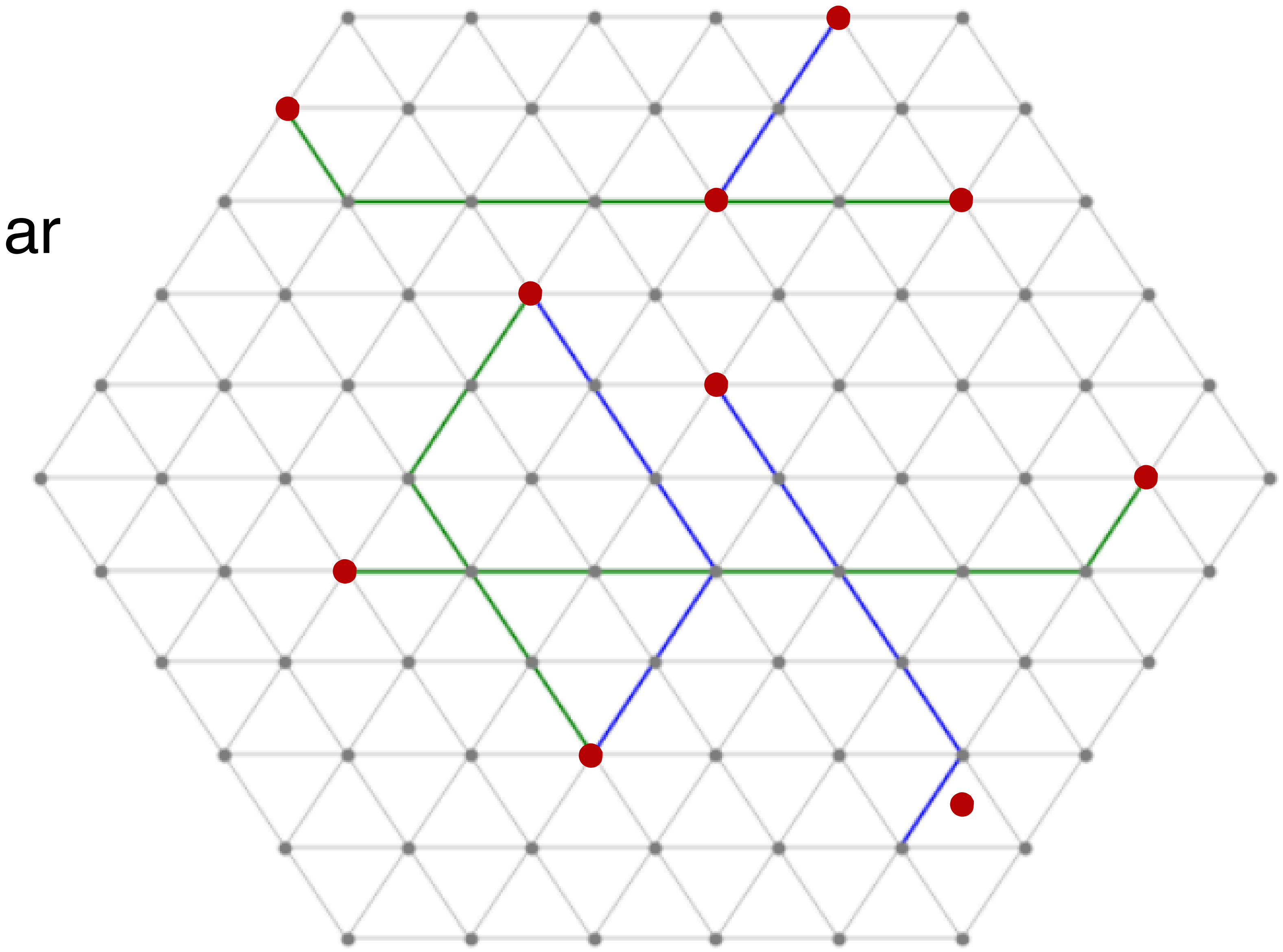
NETWORK MODEL

2) What happens to the modal share if we modify the topology of the city?

G (V, E)

Undirected

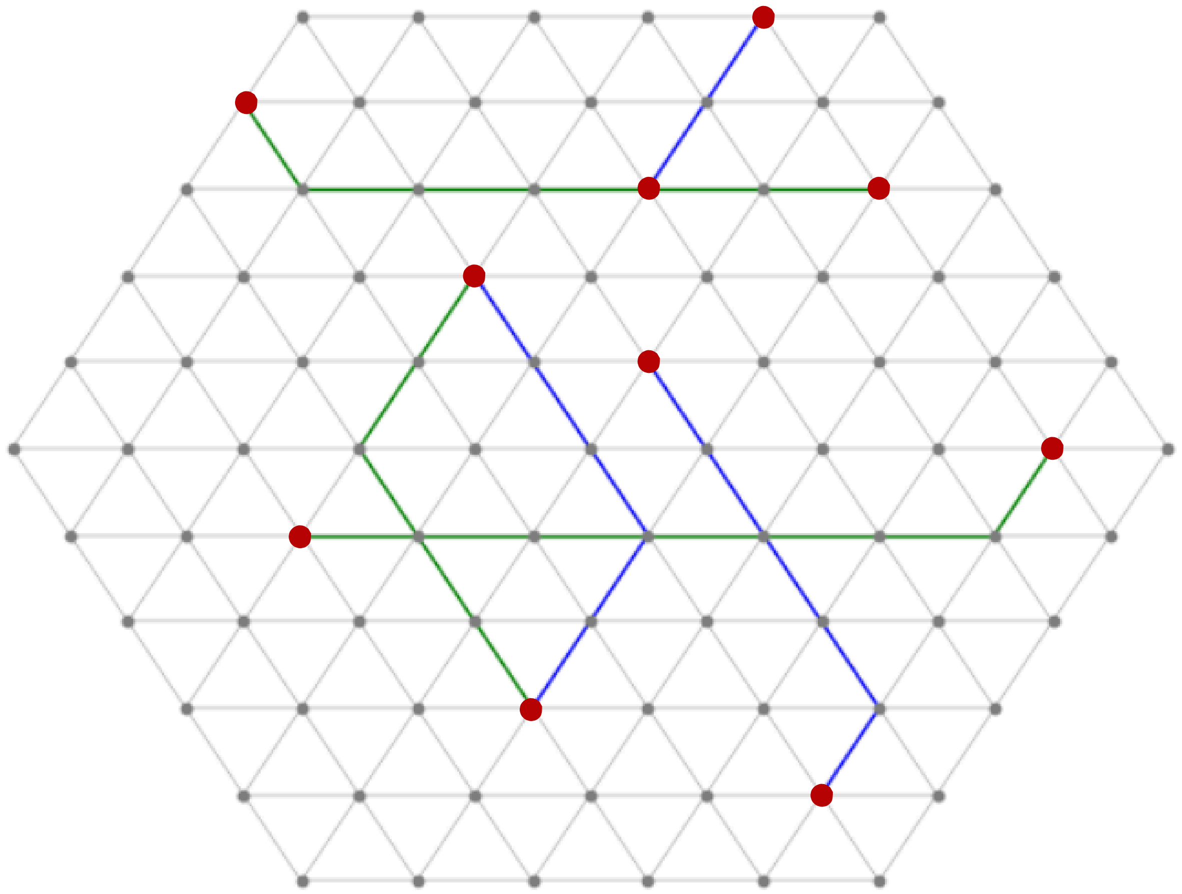
Embedding: Triangular



DIJKSTRA'S ALGORITHM

NETWORK MODEL + TRAFFIC FLOW THEORY

Parameter	Value
Bike free-flow speed	3.34 m/s
Car free-flow speed	8.34 m/s
Edge length	100 m
Bike length	2 m
Car length	5 m
Safe bike distance	2 m
Safe car distance	3 m



CAPACITY

$$c = \left(\frac{L_s}{L_v}\right) \times N_l \times \Delta t$$

VOLUME-OVER-CAPACITY RATIO

$$VoC = \frac{N_v}{c}$$

$$C_i(\vec{x}) = B_i + D_i(\vec{x}) + I_i(\vec{x})$$

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Baseline Commuting Time

$$B_i = \frac{1}{N} \sum_{i=1}^{N} len(i) \times t_E$$

Direct Commuting Time

1. Generate paths
2. Compute the volume-over-capacity ratio on each edge
3. Define a penalty related to the time for crossing an edge
4. For each user we compute the extra time which is given by the multiplication of the penalty and the congestion ratio
5. The direct cost is the average of the extra time of each user

Indirect Commuting Time

1. Generate paths
2. Compute the volume-over-capacity ratio on each edge
3. Define a penalty
4. For each user we compute the extra time which is given by the multiplication of the penalty and the Level of Service (LoS)
5. The indirect cost is the average of the extra time of each user

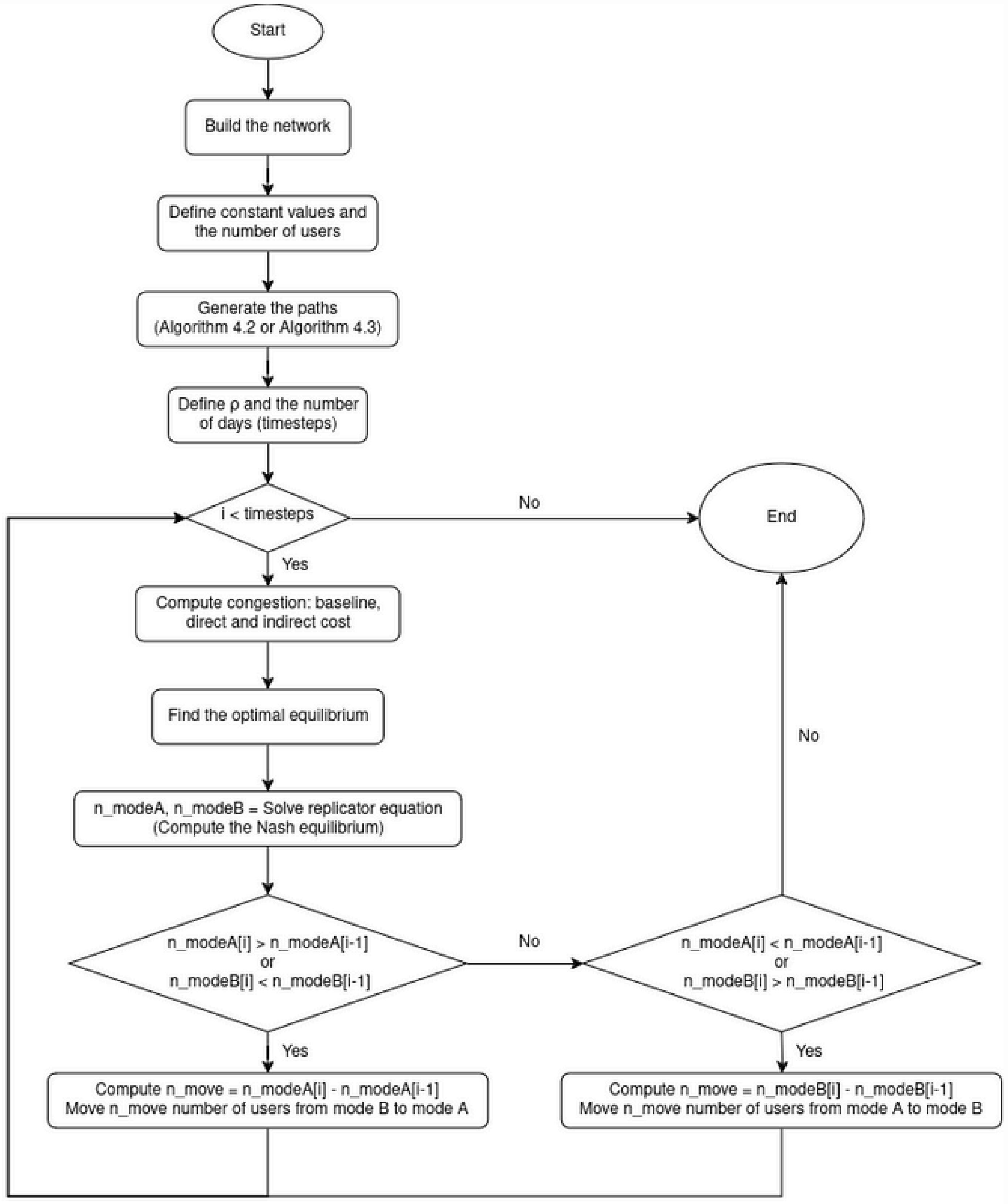
LoS Class	Traffic State and Condition	VoC Ratio
A	Free flow	0.00 - 0.60
B	Stable flow with unaffected speed	0.61 - 0.70
C	Stable flow but speed is affected	0.71 - 0.80
D	High-density but the stable flow	0.81 - 0.90
E	Traffic volume near or at capacity level with low speed	0.91 - 1.00
F	Breakdown flow / jam traffic	> 1.00

COMBINE THE MODELS

<u>TIMESCALE</u> OF MODAL SHARE DYNAMICS

<u>TIMESCALE</u> OF CHARACTERIZED NETWORK

$$C = \left(\frac{L_s}{L_v}\right) \times N_l \times 60$$

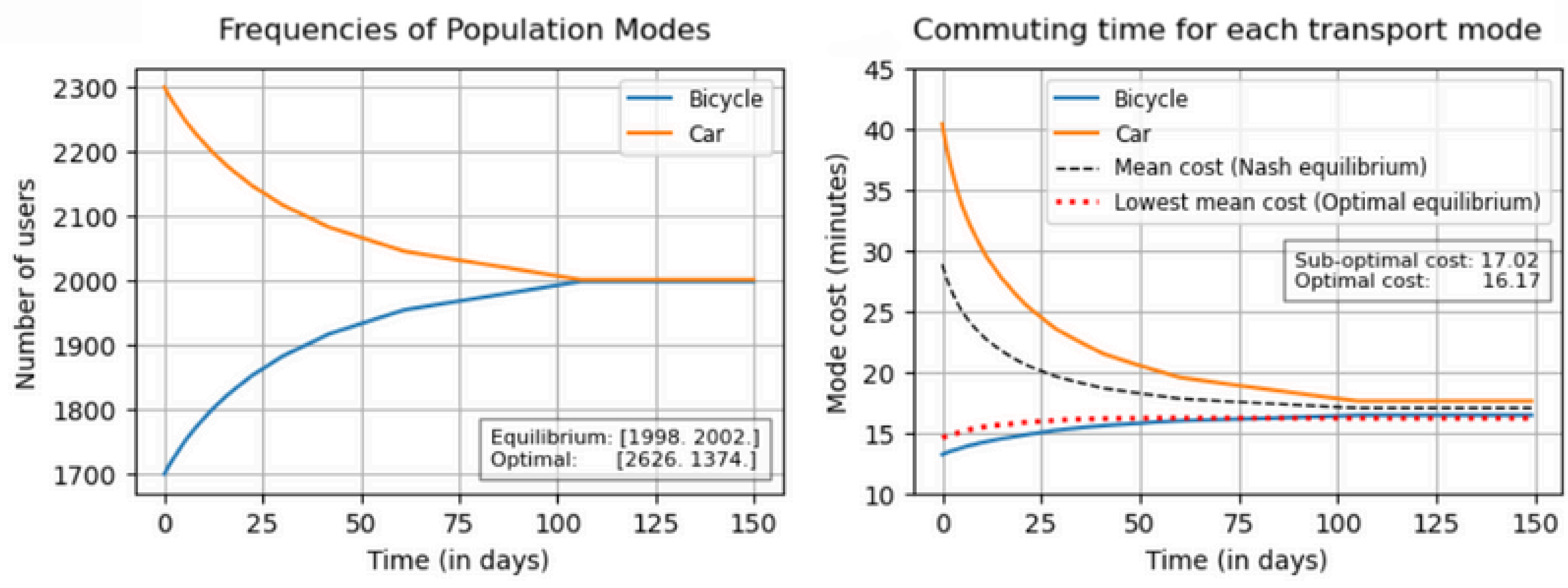


RESULTS

Triangular lattice with random origins and destinations

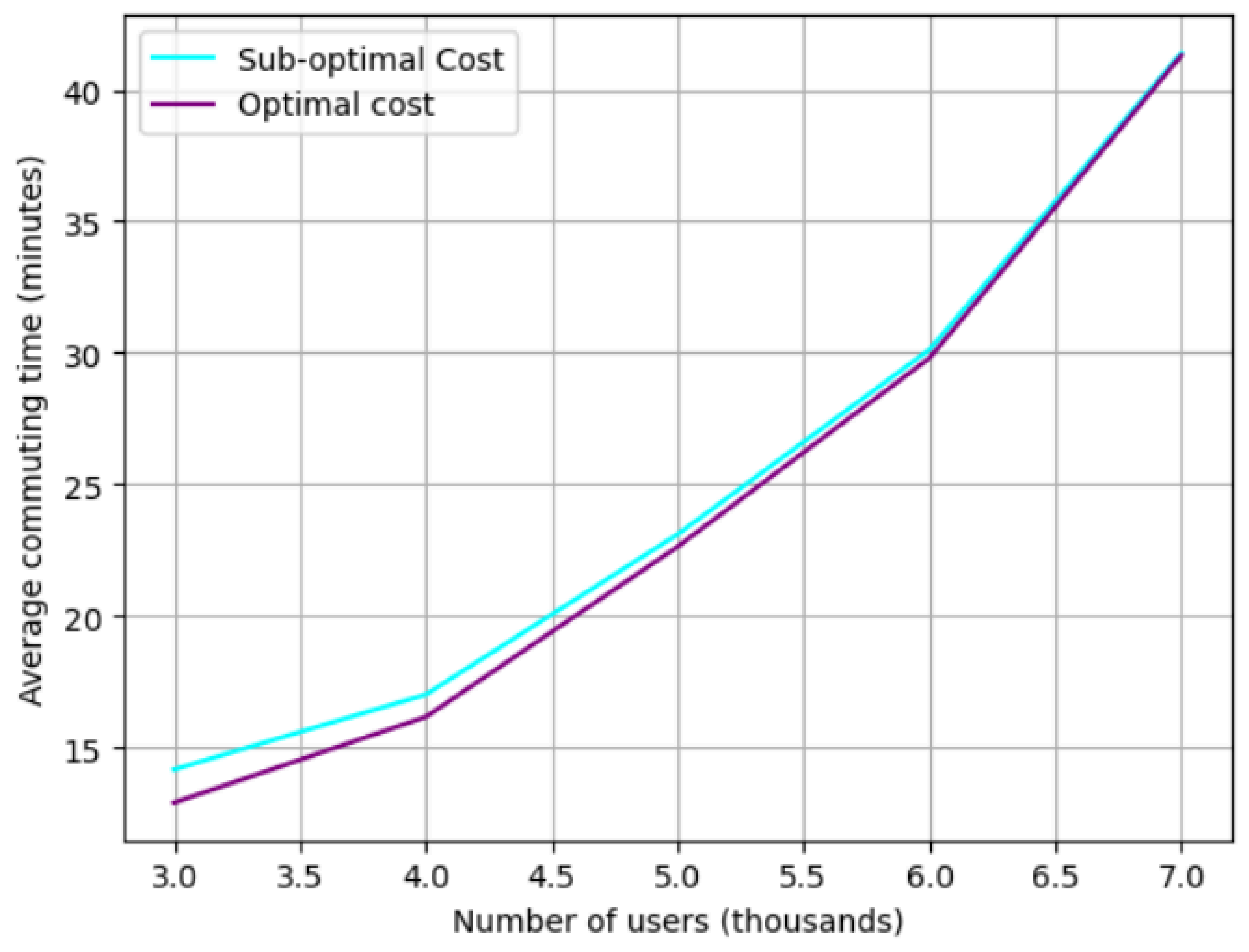
Number of users: bicycles = 1700, cars = 2300

Area of the city = 16.24 km^2



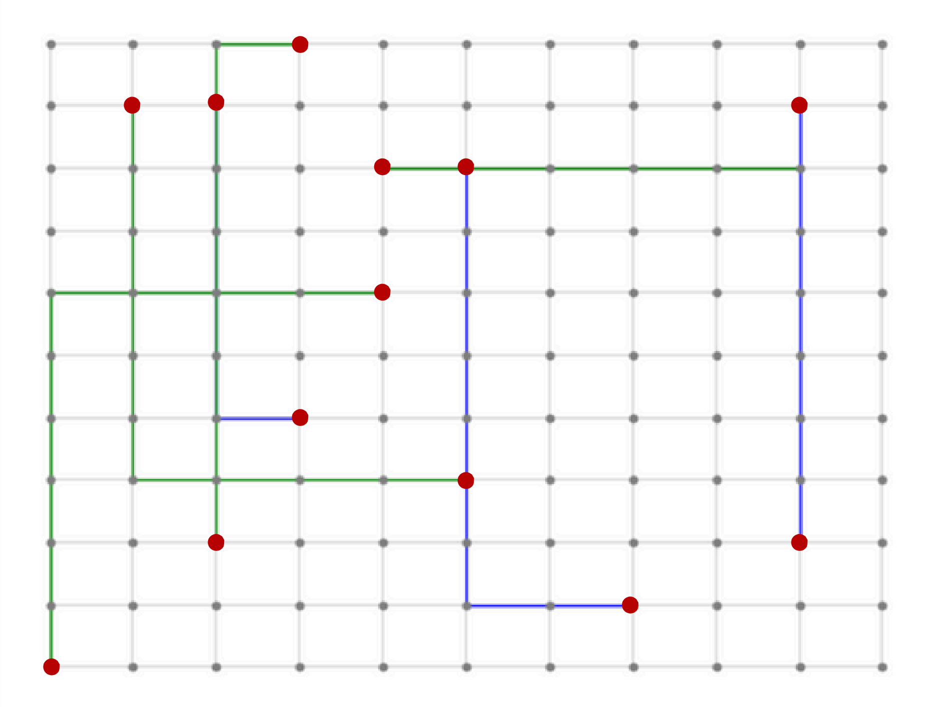
Triangular lattice with random origins and destinations

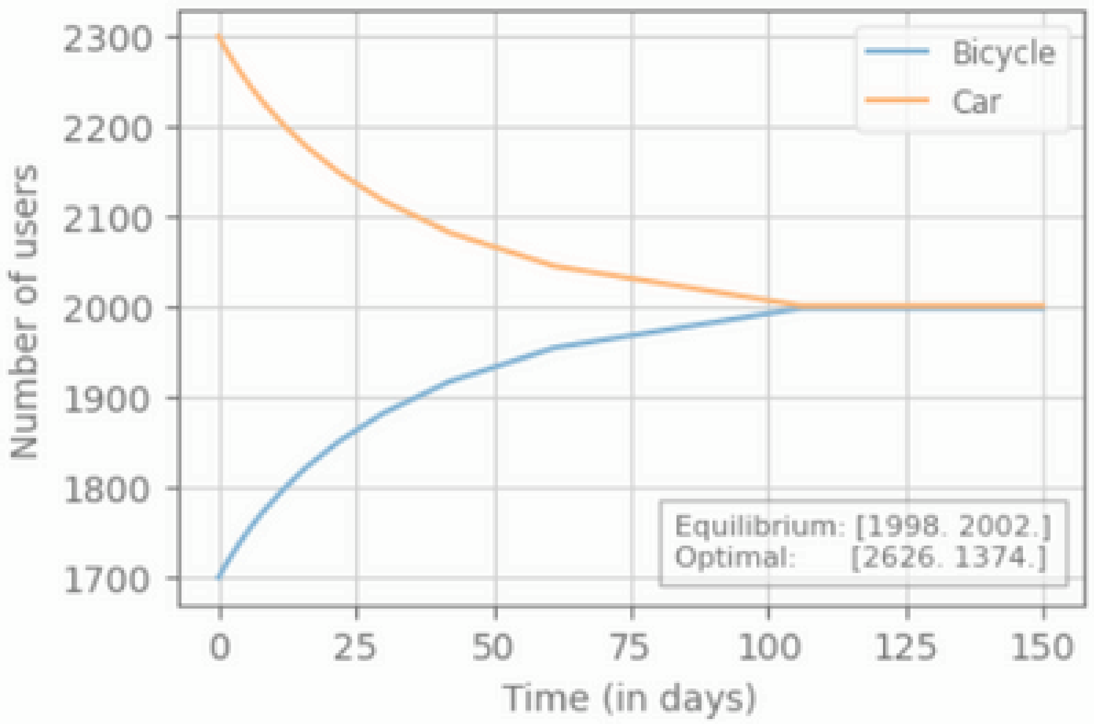
Changing the initial modal share

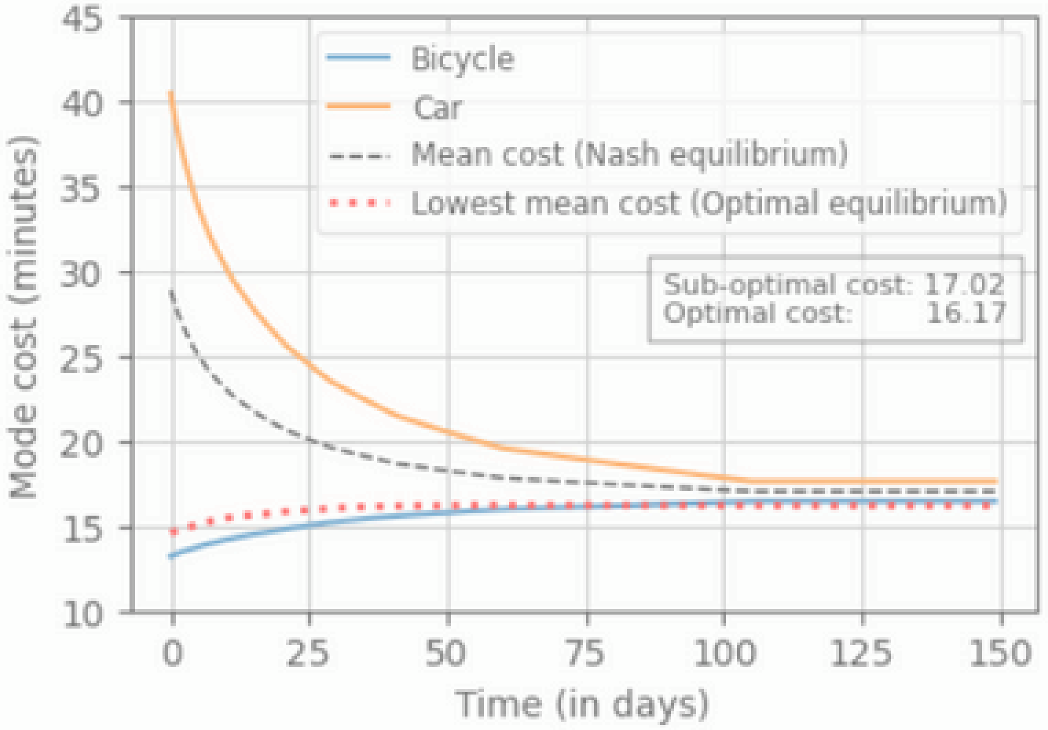


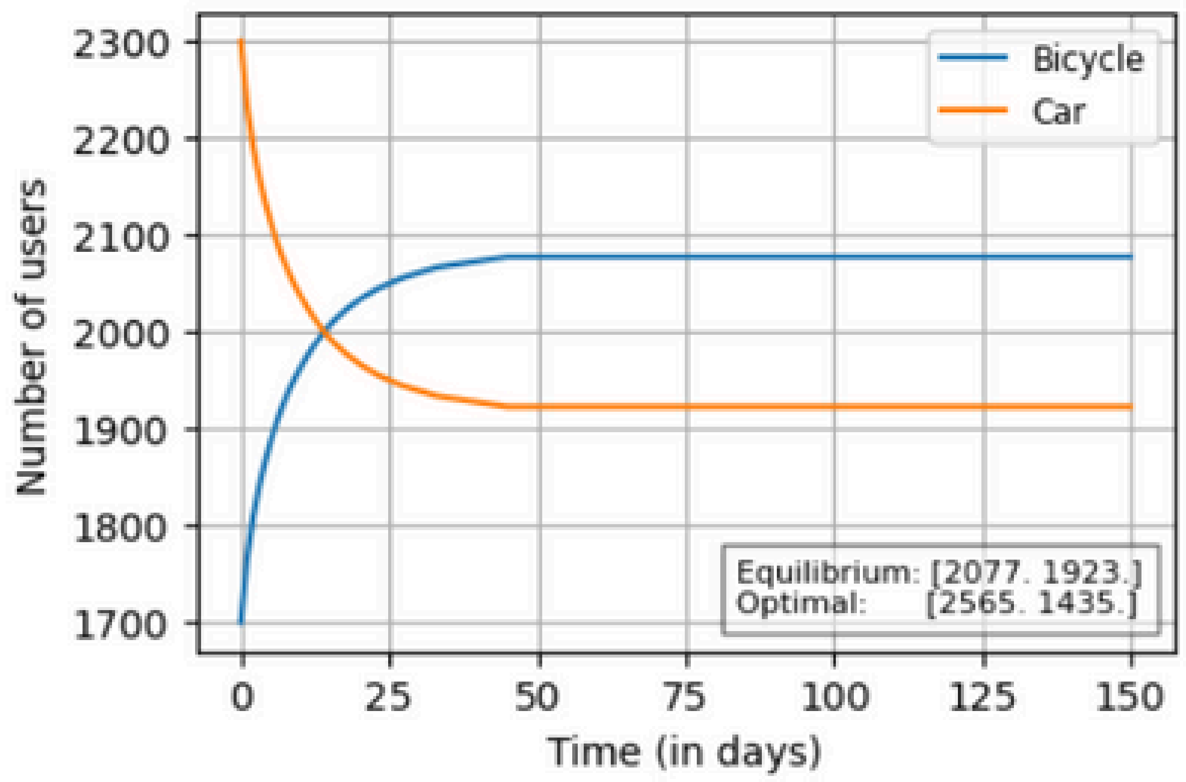
The difference between the optimal and sub-optimal equilibria is smaller as much as the individuals number increase.

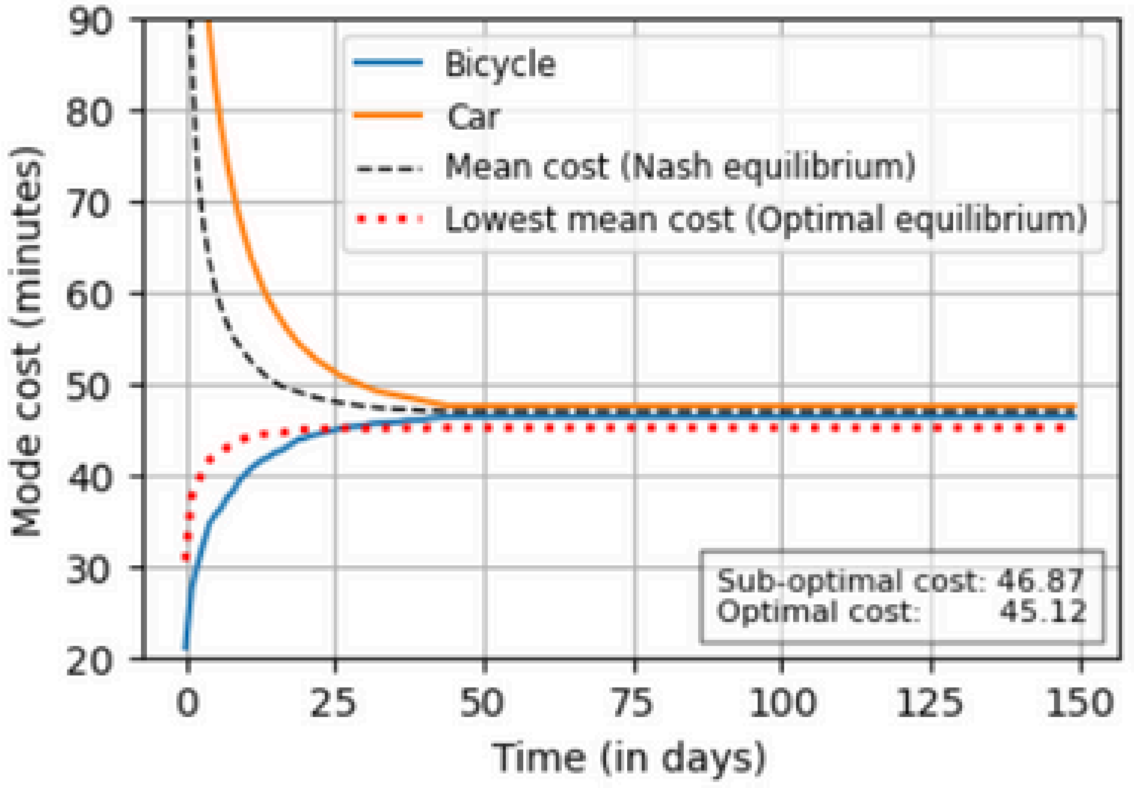
Quadratic lattice









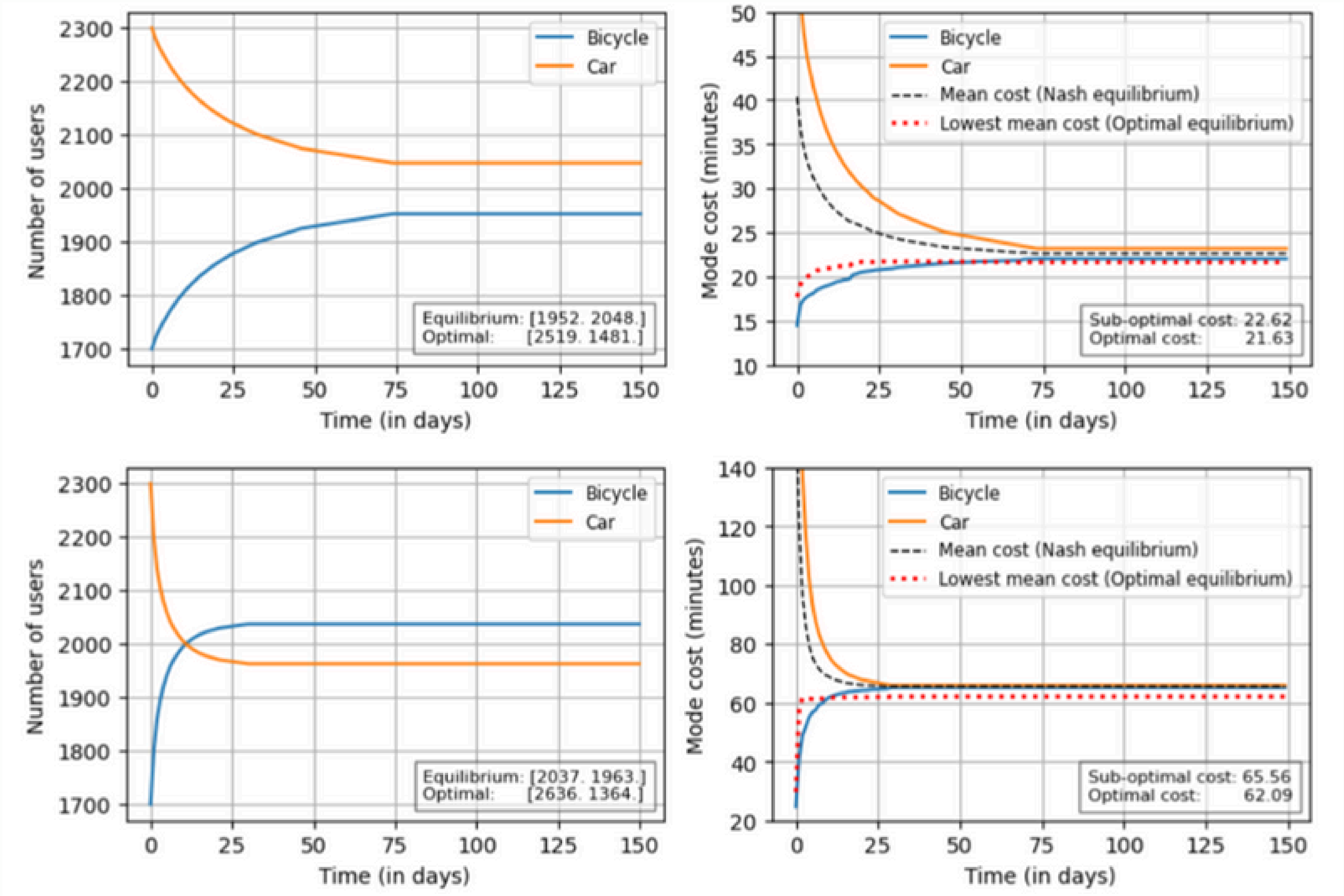


Converge faster, which suggests that this network is more limited and offers less options

Adding hotspots in the city

Triangular lattice

Quadratic lattice



The introduction of hotspots makes the system converge faster.

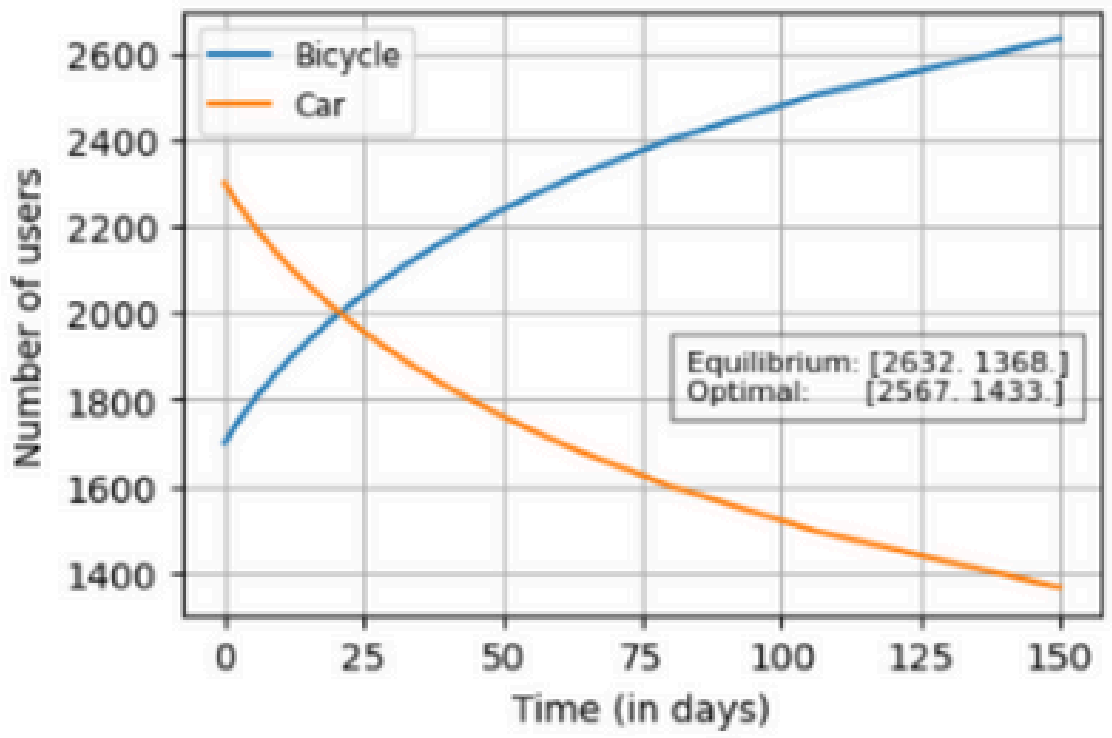
Increases the congestion because there are more individuals using same edges.

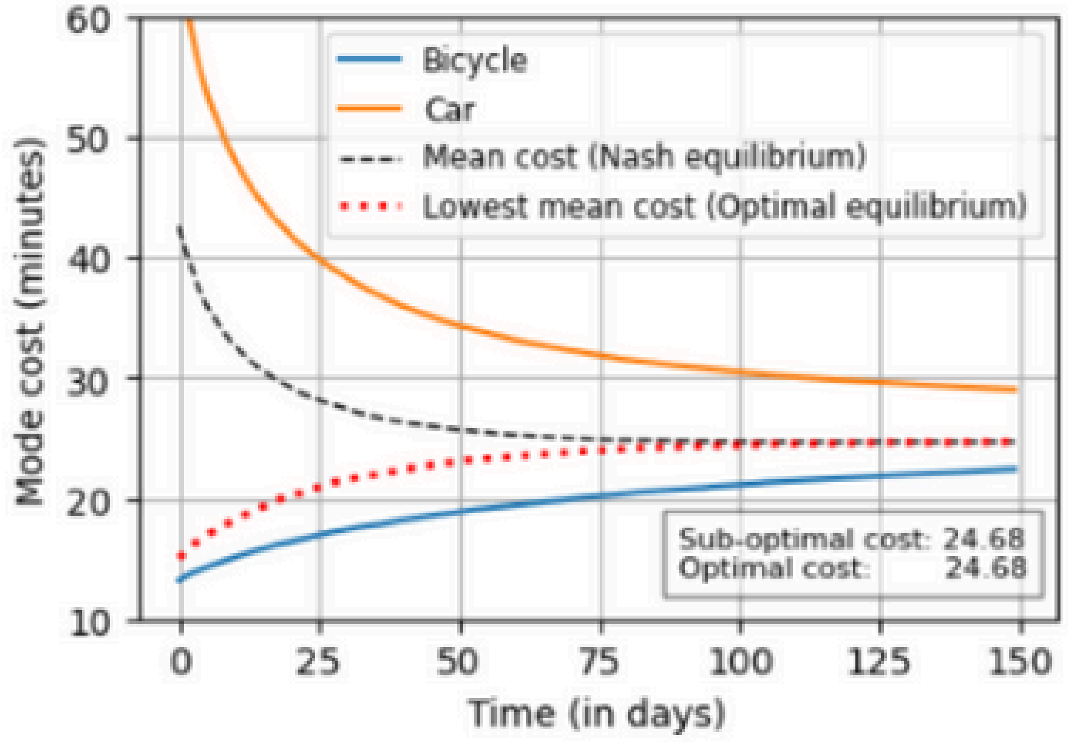
Leading to slower modal switching and longer commuting times.

	TRIANGULAR	QUADRATIC
Random OD	17.02 *mins*	46.87 *mins*
Hotspots OD	22.62 *mins*	65.56 *mins*

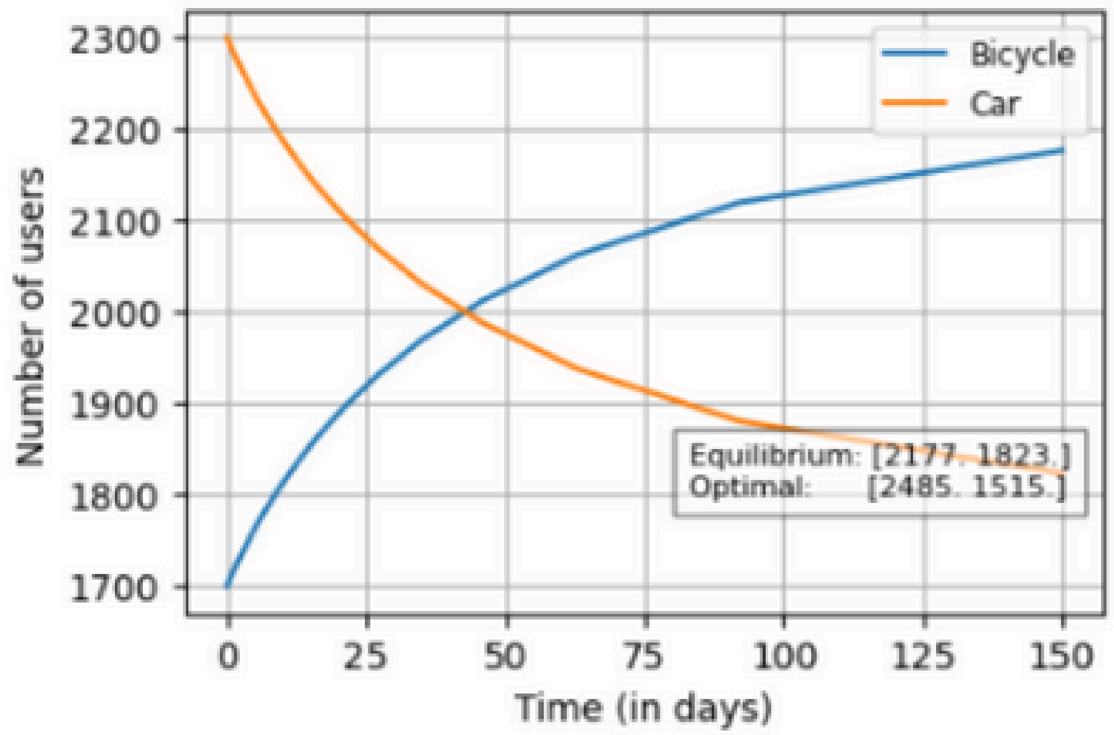
Adding parking spots

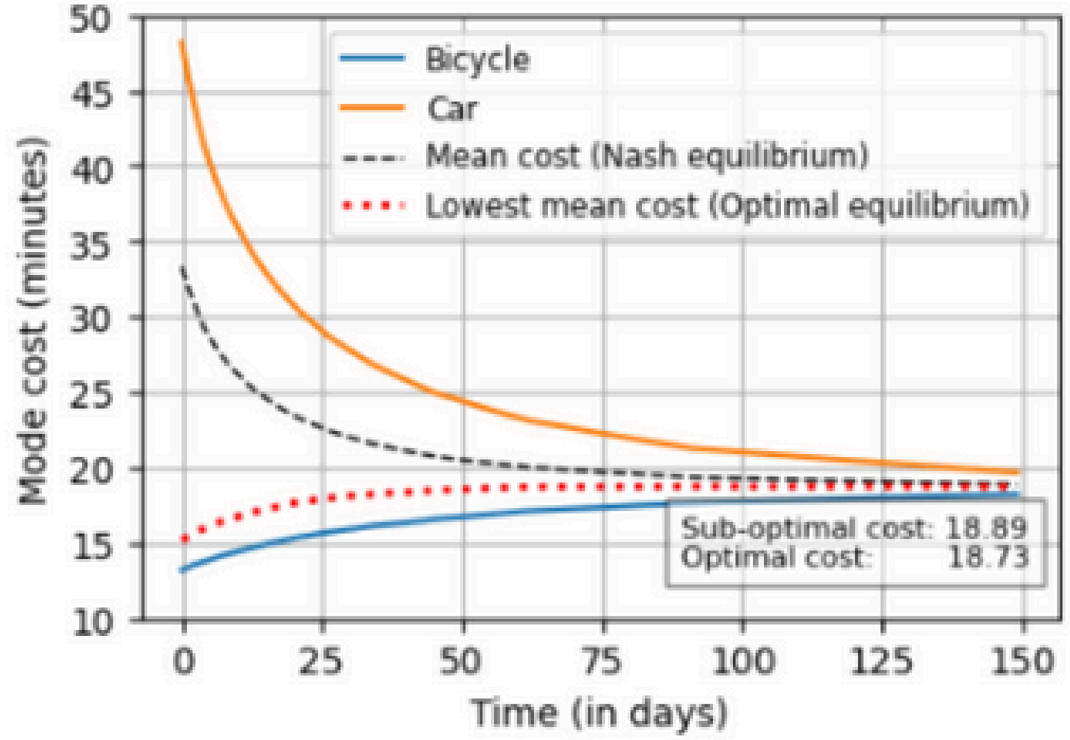
25 parking spots





150 parking spots





CONCLUSION

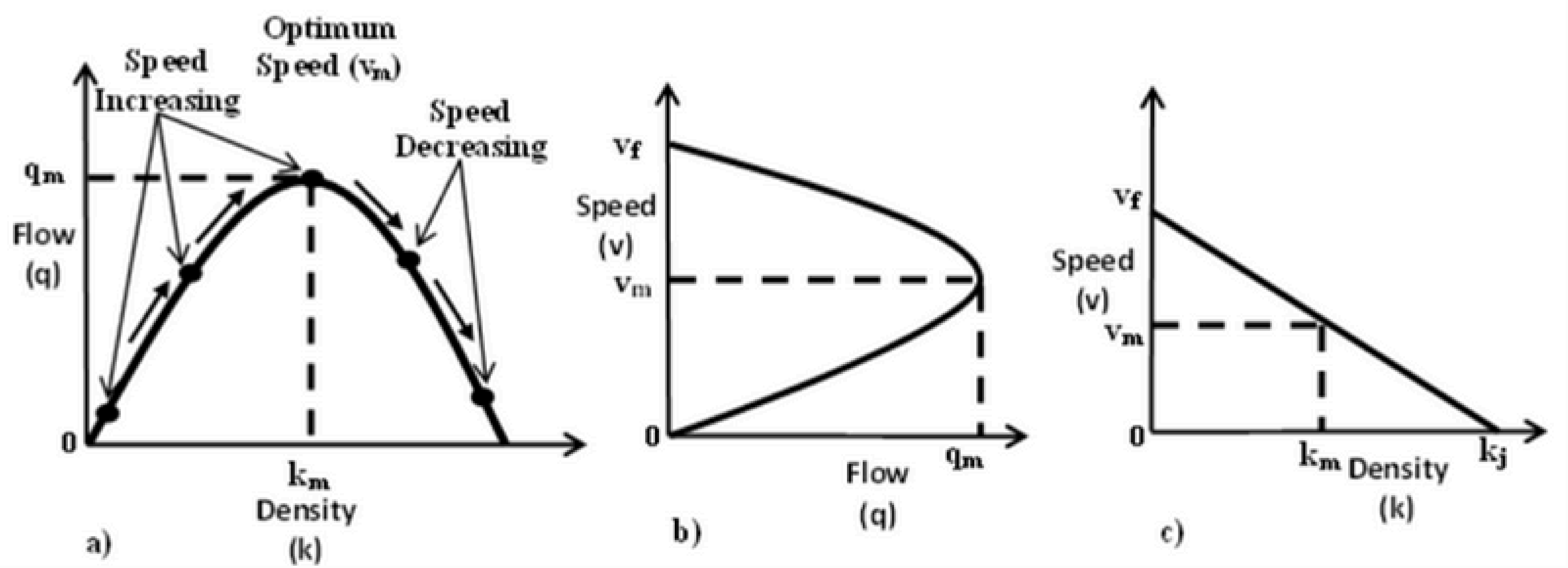
- We developed a theoretical model to investigate the impact of topological variations in spatial networks with respect to the average fitness parameter in the replicator equation, which in this case is the commuting time.
- **Triangular lattice** network with **random origins and destinations** is the arrangement that allows the largest number of users, making the switching between modes of transport feasible.
- A lack of sufficient **parking spaces** caused a sharp decline in car usage.

Incorporating bicycles as a primary method markedly reduces average commuting times in mid-sized cities when competition is limited to cars and bicycles.

FUTURE WORK

- Incorporating real-world data
- Expanding the framework to include other transport modes
- Introducing urban policy considerations, such as congestion pricing or dedicated bike lanes.

TRAFFIC FLOW THEORY



Algorithm 4.1 Dijkstra's algorithm.

Require: *Graph* and *source*
  for *vertex* v in $Graph.Vertices$
    $distance[v] \leftarrow$ INFINITY
    $previous[v] \leftarrow$ UNDEFINED
    add v to Q
  end for
  $distance[source] \leftarrow 0$

  while Q is not empty
    $u \leftarrow$ vertex in Q with *minimum* $distance[u]$
    remove u from Q
    for neighbour v of u still in Q
      $alt \leftarrow distance[u] + Graph.Edges(u, v)$
      if $alt < distance[v]$
        $distance[v] \leftarrow alt$
        $previous[v] \leftarrow u$
      end if
    end for
  end while
  return $distance[]$ and $previous[]$

Algorithm 4.2 Generate shortest paths with random origin and destination points.

Require: N *users* and *network*
  for $user = 1$ to $user = N$
    $origin \leftarrow$ select random node of the *network*
    $destination \leftarrow$ select random node of the *network*
    if $origin = destination$
      $destination \leftarrow$ select random node of the *network*
    end if
    $path \leftarrow$ connect origin and destination points with Dijkstra algorithm
    $paths \leftarrow$ append *path*
  end for
  return *paths*

Algorithm 4.3 Generate shortest paths with some hotspots as origins and destinations.

Require: N *users*, *network*, *hotspots*
  for $user = 1$ to $user = N/2$
    origin ← select a node of *network* following a Poisson distribution around a *hotspots*
    destination ← select a node of *network* following a Poisson distribution around a *hotspots*

    path ← connect origin and destination points with Dijkstra algorithm
    paths ← append *path*
  end for
  for $user = N/2$ to $user = N$
    origin ← select random node of the *network*
    destination ← select random node of the *network*
    Be sure *origin* and *destination* nodes are different
    path ← connect origin and destination points with Dijkstra algorithm/method
    paths ← append *path*
  end for
  return *paths*

Algorithm 4.4 Congestion ratio algorithm

Require: N *paths* and *capacity*
  counts ← Count the number of users in each edge
  for $edge = 1$ to $edge = counts$
    $CongestionRatio \leftarrow list(\frac{edge}{capacity})$
  end for
  return *CongestionRatio*

Algorithm 4.5 Direct commuting time algorithm

Require: $N\,paths$, $CongestionRatio$ and $penalty$
  $DirectCost \leftarrow [\,]$
  for $path = 1$ to $path = N\,paths$
    $ExtraTime \leftarrow 0$
    for $edge = 1$ to $edge = length(path)$
      $ExtraTime \leftarrow ExtraTime + (penalty \times CongestionRatio[edge])$
    end for
    $DirectCost \leftarrow DirectCost + ExtraTime$
  end for
  $Dcost \leftarrow \frac{1}{N}\sum_{1}^{N} DirectCost$
  return $Dcost$

Algorithm 4.6 Indirect commuting time algorithm

Require: $N\,paths$, $CongestionRatio$ and $penalty$
  $IndirectCost \leftarrow [\,]$
  for $path = 1$ to $path = N\,paths$
    $ExtraTime \leftarrow 0$
    for $edge = 1$ to $edge = length(path)$
      if $CongestionRatio[edge] < 0.6$
        $ExtraTime \leftarrow ExtraTime + (0 \times penalty)$
      else if $CongestionRatio[edge] < 0.7$
        $ExtraTime \leftarrow ExtraTime + (1 \times penalty)$
      else if $CongestionRatio[edge] < 0.8$
        $ExtraTime \leftarrow ExtraTime + (2 \times penalty)$
      else if $CongestionRatio[edge] < 0.9$
        $ExtraTime \leftarrow ExtraTime + (3 \times penalty)$
      else if $CongestionRatio[edge] < 1.0$
        $ExtraTime \leftarrow ExtraTime + (4 \times penalty)$
      else if $CongestionRatio[edge] > 1.0$
        $ExtraTime \leftarrow ExtraTime + (5 \times penalty)$
      end if
    end for
    $IndirectCost \leftarrow IndirectCost + ExtraTime$
  end for
  $Icost \leftarrow \frac{1}{N}\sum_{1}^{N} IndirectCost$
  return $Icost$

Algorithm 4.7 Extra time due to parkings algorithm

Require: G, $destinations$ and $parkingNodes$
  $DistToPark \leftarrow [\,]$
  $parkCost \leftarrow 0$
  for $destNode = 1$ to $destNode = destinations$
    for $parkNode = 1$ to $parkNode = parkingNodes$
      if $destNode$ not in $parkingNodes$
        $distance \leftarrow$ compute number of edges between $parkNode$ and $destNode$
        $DistToPark \leftarrow$ append $distance$
      end if
    end for
  end for
  for $d = 1$ to $d = DistToPark$
    $parkingCost \leftarrow$ get the smaller distance of every user d
    $parkCost \leftarrow parkingCost \times 3$
  end for
  $Pcost \leftarrow \frac{1}{N}\sum_{1}^{N} parkCost$
  return $Pcost$