Journal of Research and Innovation for Sustainable Society (JRISS)
Volume 7, Issue 2, 2025
ISSN: 2668-0416
Thoth Publishing House

DOI: 10.33727/JRISS.2025.2.5:39-55

Traffic congestion a negative component of sustainable development of modern road transport system

Gheorghe Neamțu[1], Marinela Inţă[2], Ioan Ţincu[3]

[1] ”Lucian Blaga” University of Sibiu, 10 Victoriei Street, Sibiu, Romania, ORCID 0000-0001-9043-9962
[2] ”Lucian Blaga” University of Sibiu, 10 Victoriei Street, Sibiu, Romania, ORCID 0000-0003-0117-7652
[3] ”Lucian Blaga” University of Sibiu, 10 Victoriei Street, Sibiu, Romania, ORCID 0000-0003-3462-704X

E-mail: geluneamtu@yahoo.com, marinela.inta@ulbsibiu.ro, ioan.tincu@ulbsibiu.ro

Abstract. Traffic congestion in major cities continues to deteriorate as a consequence of the continued development of the economy, resulting in lost time in traffic, increased risk of accidents, pollution and many other negative externalities for urban and non-urban residents. For those involved in traffic, traffic congestion is an irritating phenomenon, as it causes them stress by disrupting their daily activities. The scientific work presents in a concrete and elegant manner a research carried out by the authors with the aim of highlighting congestion in contemporary road traffic. In this way, those interested can get acquainted with a concrete analysis of congestion in road traffic, sensitive areas where congestion in road traffic occurs, influencing factors of road traffic congestion, techniques and relations of measuring congestion in road traffic, calculation relations for combating congestion in road traffic and paradoxes of road traffic congestion - case study. At the end of the scientific article, the conclusions in the addressed area are presented.

Keywords: c*ongestion, road/street, traffic, vehicle, road intersection, zipper rule, paradox*

Introduction

Congestion in road traffic is the phenomenon of reducing the speed of a flow of road vehicles on a road, until they stop moving, due to so-called *"sensitive areas"* that occur on a route or a travel itinerary. The phenomenon is characteristic of densely populated urban areas with a high ratio of car ownership to the number of inhabitants, where people travel on foot, by public or personal transport, to schools, schools, work, work, leisure, recreation, etc. The problem first appeared in the mid 1920s in the USA and was due to the massive development and acquisition of cars. Today the problem is a common one and has become critical in large urban agglomerations, whether a country is economically, socially or industrially underdeveloped or highly developed. In Romania after the revolution of December '89, with the liberalization of the movement of goods and people from/beyond the country's borders, the influx of road vehicles, especially second-hand vehicles, has increased, clogging up road traffic in the major cities. Over the last decade, the situation in our country has become critical, due to the large number of registered road vehicles, but also to the road infrastructure developed on an old infrastructure specific to the 50s and 60s, totally inadequate to the requirements of today's traffic, especially in urban areas and on the main axes in the extra-urban area. The most recent study carried out in the USA in this area revealed the negative characteristics of road traffic congestion, with half the number of traffic jams on extra-urban freeways causing delays of 4 seconds/km, while traffic jams on other types of road cause a delay of 1.2 minutes/km. The values presented were calculated for an average annual mileage of 16,000 km/vehicle. The results of the study also show that delays to vehicles immobilized in congested road traffic cause an average loss of 640 USD per vehicle per year. The total losses caused by traffic congestion are much higher if one also considers losses due to work, delays in delivering goods to shops or businesses, plus social costs which are high but difficult to accurately estimate. Solving the problems related to this phenomenon is not simple because the measures that should be imposed are either unpopular, too expensive or ineffective after a short period of time after their implementation [1, p. 1]. Sustainable development seeks and tries to find a stable theoretical framework for decision-making in any situation where there is a human-environment relationship, be it environmental, economic or social. The concept of sustainable development is not just a set of measures taken to protect the environment. In this context, sustainable development means all those actions, taken as a whole, taken to build, to develop in a sustainable and viable way the necessary conditions for day-to-day activities. For example, mankind's need for mobility has led to the development of the automobile and communication routes, objectives which are still pursued today through technology and the modern network of roads and highways [2, p. 43].

1. Literature review

Road traffic congestion is approached in different ways in the literature and defined in terms as follows [3, p. 61], [4]:

- the infrastructure development strategy manager is interested in ensuring that infrastructure elements capture the standardized flows for which they were designed;
- the infrastructure user has an interest in not being hindered in his travel by other traffic participants on the same infrastructure; slowing down below the speed achieved on the freeway is interpreted as the beginning of congestion;
- the traffic engineer, congestion occurs much later, i.e. only when the traffic intensity reaches a threshold in the vicinity of the capacity of a road;
- the transport beneficiary only highlights congestion to the extent that his or her expectations of travel time, as assumed by the carrier, have not been met;

transportation economists conceive of congestion as an externality that forces those who are not the beneficiaries of a particular travel activity to pay the costs of the effects produced by infrastructure users.

In the literature, the following definitions, terms and interpretations of road traffic congestion are also identified:

- *Road traffic congestion,* is a condition where the volume of vehicles on a given road network exceeds the capacity of that network, leading to a significant decrease in travel speed and traffic efficiency. Congestion can generally be said to occur when the supply of road infrastructure cannot meet the demand of vehicles [5];
- *Roadblock,* is an extreme form of congestion in which vehicles are slow moving or even completely blocked. In such situations, travel time becomes extremely uncertain [3, p. 61];
- *Road traffic slowdown,* this interpretation refers to the decrease in vehicle travel speed on a given stretch of road resulting from overloading of that road infrastructure. The average vehicle speed is significantly reduced compared to the average speed during periods without congestion [3, p. 61];
- *Time lost in road traffic,* refers to the additional time required to travel a given distance in congested conditions. It can be calculated by comparing the travel time in congested periods with the time needed for the same distance in non-congested periods [3, p. 62].

2. Road traffic congestion analysis

Road transport is the backbone of today's economy and society. Underpinning it is mobility characterized by its vitality for the internal market and for the quality of life of citizens, as they enjoy the privilege of travel. Road congestion is a major concern, in particular in the road sector and air space, compromising accessibility [6].

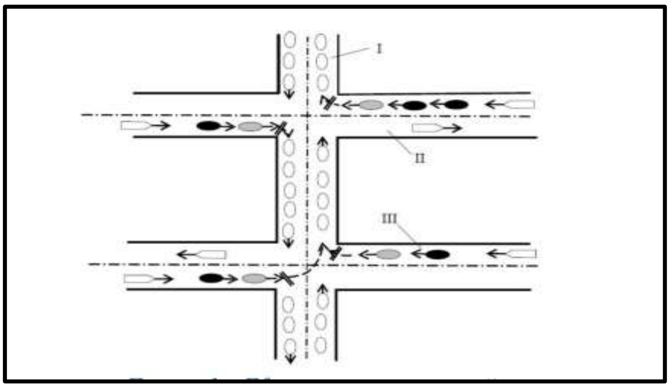

Figure 1. Effects of road congestion at a sequence of two intersections [7].

Overall, congestion is interpreted as the level of demand for an area of road infrastructure for which road traffic has significant queues. Short queues, formed occasionally but not persisting over time, as well as temporary traffic peaks that do not exceed the capacity of the section/intersection, are not excluded. Congestion occurs when traffic approaches or exceeds the maximum capacity of the road segment or intersection [7]. According to the data presented in Figure 1, congestion at intersections can be either primary (represented on road section I), caused by the occurrence of vehicle queues at road intersections, or secondary (indirect, represented on road sections II and III), caused by the disruption (inconvenience of vehicle traffic) at other intersections as a result of primary congestion. The evolution of street networks over time reflects the development of human civilization as a result of meeting mobility needs. Figure 2 shows the evolution of the street network of Times Square in the American city of New York in two periods: 1900 and 2020. Analyzing the two images presented (the reality of the two historical periods), we see that the street infrastructure in 2020 has remained almost identical, even slightly reduced in size compared to that of 1900, with the difference that only the building facades have changed completely over time. In 2020 the population, living in the skyscraper blocks, has become more numerous than in 1900, and the number of cars has increased significantly. This phenomenon has spread to most major cities around the globe. As time has passed the vast majority of major cities around the world have become extremely congested and the road infrastructure built at that time is functionally obsolete. Today's road drivers face traffic jams that have become a paradigm of the contemporary world. Dutch multinational developer and creator of localization technology and consumer electronics TomTom [8], presented a study showing that road vehicle users waste on average 100 hours annually for a 30 minute commute to work. For this reason, one wonders why some cities of the same size (identical

Figure 2. Times Square, New York City (USA) comparison for street infrastructure (1900 and 2020) [7].

	City	Country	Index Traffic (%)	Population
2	Hull	USA	32	10455
3	Limerick	Ireland	27	58319
4	Lugano	Switzerland	29	63185

Figure 3. Database with traffic index and number of inhabitants in different cities in the world (2021) [7].

surface areas, streets, population, motorization index and traffic index) have a low congestion index. In order to find an explanation for this problem, we need to analyze the direct dependence between the overcrowding of these cities and the increase in traffic congestion.

Searching the database of the navigation equipment manufacturer mentioned above, we found that there is such a dependency between the two components (traffic congestion and saturation). A total of 136 cities, the most significant in the world, have been selected from which the traffic index, expressed in percentages for the year 2021, has been extracted (Figure 3). This study found that a traffic index of 50% means that the duration of a 30 min journey will be 50% longer in optimal traffic conditions, i.e. 45 minutes.

Together with the traffic index, the population of each city was added and the graph in Figure 4 was realized, showing the cities represented according to the congestion index and population.

The blue points represent the cities that are graphed by traffic index and population. Our analysis shows that, according to the data presented in the image, an acceptable traffic index of 37% is considered (a route that would be traveled in 30 minutes, reaches a travel time of 41 minutes). The orange line representing the acceptable level of congestion divides the graph into two parts: cities with high road traffic and cities with low road traffic. In the red boxes are represented four cases in which a city can be. Thus we have: case 1 - low traffic and population below 4 million; case 2 - high traffic and population below 4 million; case 3 - high traffic and population above 4 million and case 4 - low traffic and population above 4 million.

Implicit covalencies between implicit traffic growth and population growth cannot be made in this case. It can be seen that in case 4 there are overpopulated cities with low road traffic and at the same time there are underpopulated cities with much higher road traffic than large cities. The graph also shows the capital of France, Paris, which is in case 4 and has 11 million inhabitants with a road traffic index of 36%, while Bucharest, the capital of Romania, in case 2, has 2 million inhabitants (a relatively small population in terms of numbers) and a high traffic index (50%).

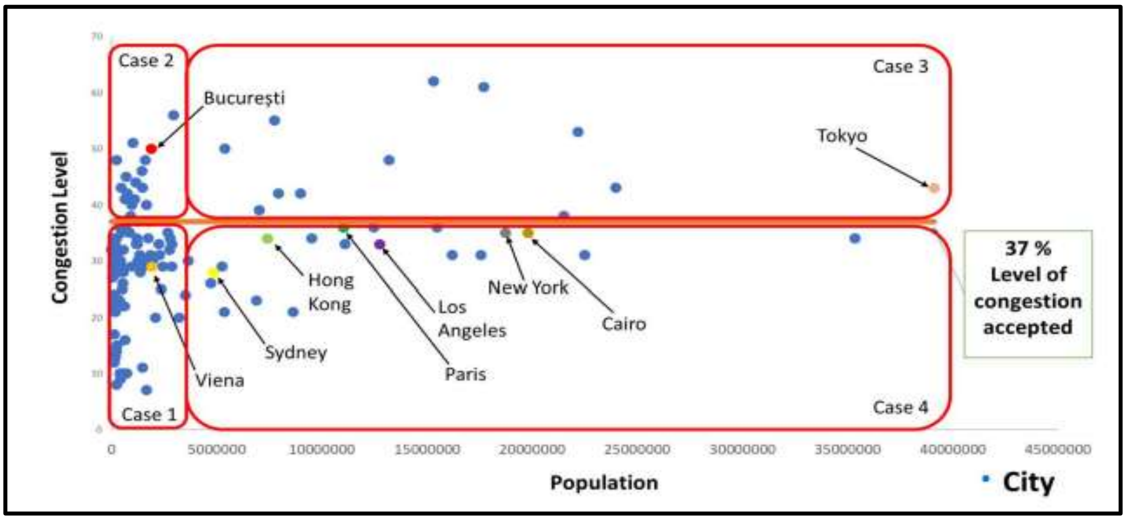

Figure 4. Ranking of cities by traffic and population index on the world (2021) [7].

In order to reduce road congestion and to find solutions to the large congested urban areas shown in the graph in Figure 4, we propose the following improvement methods:

- rethinking and modifying road infrastructure;
- rethinking and improving public/alternative transportation;
- educating the urban population to use alternative means of transport, including public transport instead of private cars;
- road traffic control through smart traffic lights;

Journal of Research and Innovation for Sustainable Society (JRISS)
Volume 7, Issue 2, 2025
ISSN: 2668-0416
Thoth Publishing House

- introduction of roundabouts at intersections where the urban architecture permits this.

Returning to the road traffic in the Romanian capital, Bucharest, the number of vehicles involved in congestion was measured periodically at 15-minute inter vals at certain points on the streets by means of inductive loops (Figure 5). All the results obtained were recorded in a database, which includes the section where the measurements were taken, the direction of travel of the vehicles, the date and time, the number of vehicles recorded in traffic and the average value of the vehicle flow/minute (Figure 6 a and b).

The database contains 72,413 records. Following the calculations based on the number of vehicles involved in the measured traffic, the analysis of the data shows that on average 69 vehicles/minute flow on the streets of the Romanian capital Bucharest.

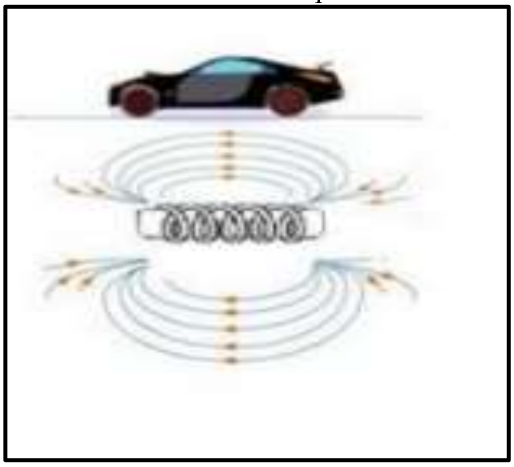

Figure 5. Inductive loops.

Road	SectionNo	From	To	Timestamp	VehicleFlow	Flow/min
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 0:15	156	10.4
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 0:30	132	8.8
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 0:45	228	15.2
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 1:00	192	12.8
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 1:15	180	12
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 1:30	132	8.8
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 1:45	96	6.4
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 2:00	108	7.2
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 2:15	84	5.6
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 2:30	84	5.6
B-dul- Dacia	4.1	Calea Victoriei - B.dul Dacia	Piata Romana	10/23/2008 2:45	84	5.6

a. • • •

Area	Average
Unirii	34
Sos.Kiseleff	35
Dacia - Dorobantilor	37
Carol	53
Str.Halelor	153
Stefan cel mare	84
B-dul Dacia	25
Lascar Catargiu	79
Calea Victoriei	54
Iancu de Hunedoara	47
B-dul Carol	33

b. • • •

Figure 6 a, b. Bucharest traffic database.

3. Sensitive areas causing road traffic congestion

Sensitive areas causing road traffic congestion include:

- *Usual difficulties occurring in an area considered in traffic:*

a) intersections controlled by road signs or traffic lights;

b) the road narrowing at the entrance to a tunnel or when crossing a bridge;

c) educing the speed of traffic at rail level crossings with or without barriers;

d) narrowing of the lanes (arteries) of circulation of vehicles considered from *"nb"* lanes to *"nb-1"*, *"nb-2"*, etc...;

f) entrances from side streets - main arteries or highways, a frequent case in road traffic at peak hours, when the volume of vehicles on a main artery is at its maximum, reaching saturation, and hardly receiving the secondary flow coming from a side street or major artery. The phenomenon is also common in the opposite direction, at ex exits from major roads or highways, at entrances to side or side streets;

g) modernization or maintenance works on roads, sections of roads or road arteries (works requiring more than 48 hours of work), with alternating traffic on one-way traffic.

- *Accidental obstacles:*

a) short-term maintenance work on the road or parts of the roadway;

b) meteorological disturbances or adverse weather conditions;

c) road traffic incidents or events (in vehicle-vehicle collisions, vehicle-vehicle collisions with obstacles on or off the roadway affecting one or more lanes, or vehicle-pedestrian collisions).

4. Factors influencing road traffic congestion

- *Static factors:*
  - capacity of streets or roads: any street or road depending on its design characteristics handles on average between 1,500-2,500 vehicles/hour. The capacity of these roads is variable and is influenced by other factors;
- *Variable factors:*
  - weekend traffic and public holidays;
  - periods in a year or areas of tourist interest;
  - inclement weather (rain, snow, ice, fog, hot weather, etc);
- *One-pointed factors:*
  - work on the carriageway or other elements of the road or streets;
  - road accidents or incidents;
- *Psychological factors:*
  - traffic behavior of vehicle or motor vehicle drivers (frequent lane changing, aggressive driving, failure to keep the prescribed distance from the vehicle in front, failure to apply the zipper rule when narrowing lanes, inattention at the wheel, etc).

5. Rules driver behavior in traffic congestion

In congested road traffic, road vehicles are traveling bumper-to-bumper in a slow-moving speed. For this reason the irritability and desire to escape from the traffic jam increases as the traffic speed slows down or stops.

Below are some essential rules to follow when stuck in a traffic congestion:

- inform yourself before you hit the road and avoid crowded areas;
- use alternative routes during busy periods, especially in areas of recreation, tourism, events, critical hours when children are taken to/from school, or when people are traveling to/from the workplace;
- always keep a safe distance between the vehicle you are driving and the vehicle in front. If your vehicle is stationary, stop the engine to reduce fuel consumption and environmental pollution;
- be careful behind the wheel and anticipate situations that may be created by other road users;
- do not drive in the emergency lane at traffic jams on highways (it is forbidden and punishable according to the road traffic legislation of each European country);
- activate the traffic info function (if the vehicle you are driving has it) and act according to its guidance;
- do not stop at the scene of an accident or traffic incident if first aid teams are on the scene for intervention;
- uses the zipper rule (an unwritten rule), if traffic is moving in two lanes in the same direction and one of the lanes is occupied;
- if you have been caught in a traffic jam (congestion), try as far as possible (if at all possible) to escape from it by using side streets or access roads and use other adjacent, less or not so congested/less congested streets/roads. You need to consider and analyze whether this is an effective and economically and financially efficient option;
- when approaching the tail of the queue reduce your speed to the point of avoiding a hazard, activate the flashing yellow vehicle lights (hazard lights) and keep a reasonable distance from the last vehicle in the queue to avoid possible incidents if the vehicle behind you does not notice the queue of vehicles stopped in the traffic jam (give sufficient room to the vehicle following you);
- leave enough maneuvering room for emergency crews and emergency vehicles in the event of a road accident in case you arrive first on the scene.

6. Techniques and mathematical relationships for measuring road traffic congestion

The primary elements underlying a system for measuring (quantifying) road traffic congestion are [3, p. 61]:

- time required for road vehicles to travel on a section of the route, θ [minute];
- time taken to cover one unit length of a portion of a route (slowing down, slowing down, i.e. the inverse of speed), I [minutes/kilometer];
- absolute size of the average delay per unit length, $A = I_r - I_f$, unde I_r, I_f represents the slowness of the unit-length travel under observed, free-flow conditions;
- relative size of average delay, $a = A/I_f$;
- length of route traveled under congested conditions, L_c;
- congestion effects experienced by drivers, calculated as the product of the number of users (travelers) or vehicles, N_c and the length of the portion of the itinerary, L_c affected by congestion, $C = L_c \ x \ N_c$;
- actual flow provided by that section of the route, $D_c = N_c \ x \ \overline{V}_c$, where $\overline{V}_c$ is the average speed of the flow of vehicles on the analyzed section of the route/itinerary;
- mobility index on a homogeneous portion of an itinerary, $i_m = D_c/D_n$, where D_n is the normalized vehicle flow on that stretch of route/itinerary;

For each of the levels of service of a road, the values of A (absolute measure of delay) and a certain critical value above which traffic is considered congested can be defined [4].

In the framework of road traffic congestion measurements we have defined the following terms [4]:

a) Absolute delay meter $A = I_r - I_f$;

b) Relative delay meter $A = I_r / I_f - 1$;

c) Daily congestion indicator in the system. It highlights the temporal nature of congestion. If on an element j of length $l_{c,j}$ daily congestion duration is $t_{c,j}$ then for an artery or area of the network as a whole, the daily congestion indicator is:

$$S = \sum l_{c,j} \ x \ t_{c,j} \qquad \text{[minutes congestion x kilometer/day]} \qquad (1)$$

d) the aggregate congestion index of an urban network. They provide the possibility to evaluate congestion on a scale of 0,...,1 for a whole urban network consisting of heterogeneous arterials in terms of the transit capacities of the components.

Measuring road traffic congestion can also be achieved by [3, p. 62]:

- *Average speed,* this indicator measures the average speed of vehicles traveling on certain stretches of road during periods of congestion and compares it with the average speed during periods without congestion. A significant decrease in average speed indicates congestion.
- *Congestion index*, there are different indices used to quantify the level of congestion on specific stretches of road or in specific geographical areas. The Congested Traffic Index (CTI) is an example of such an index which combines several parameters, such as travel speed, traffic density and travel time, to assess the level of congestion.

The relationship used to quantify the *Congestion Traffic Index (CTI)* is:

$$CTI = [(V_f - V) / V_f] \ x \ 100 \qquad (2)$$

where,

V is the average speed observed on the road segment during congestion;

V_f – free-flow speed or average vehicle speed in free flow conditions on the same road segment.

Specification: at the higher of the CTI, we have the higher the congestion level. This is an indicator for assessing the level of congestion on a given stretch of road or in a geographical area. The socio-economic influences of traffic congestion concern additional costs to the economy resulting from longer travel times and even significant losses in the case of delays caused by delays in public passenger transport. Other costs include increased fuel consumption and associated costs, additional expenditure for road infrastructure maintenance. The impact of congestion on the environment is

Journal of Research and Innovation for Sustainable Society (JRISS)
Volume 7, Issue 2, 2025
ISSN: 2668-0416
Thoth Publishing House

increased greenhouse gas emissions and air pollution. Long idling of vehicles in traffic leads to the release of pollutants into the atmosphere with negative effects on air quality and human health. Traffic congestion affects people's quality of life, causing stress and frustration. Time lost in traffic can reduce the time available for personal activities, relaxation or social interaction, having a negative impact on individuals' general well-being. Time lost in traffic is calculated by comparing actual travel time *(T_c)* during periods of congestion with estimated duration *(T_f)* for the same distance in periods without congestion [3, p. 62].
In the final, the relationship for calculating *time lost (used) in road traffic (T_{lrt}),* becomes:

$$T_{lrt} = T_c - T_f \tag{3}$$

The result is the extra time needed in congestion to travel an equal distance on a stretch of road.
Table 1 shows the congestion situation in 2022 in the top 10 urban metropolitan areas in the world. Travel times for a distance of 10 km are given.

Table 1. Travel time required to cover a distance of 10 km in the world's top 10 urban metropolitan areas in 2022 [3, p. 62], [8].

Congestion ranking	**City**	**Average travel time per 10 km**	**The situation compared to 2021**	**Duration in peak hour per year [h]**	**Average speed during rush hour [km/h]**
1	United Kingdom **London**	36 min 20 s	+ 1 min 50 s	325	14
2	India **Bengaluru**	29 min 10 s	+40 s	260	18
3	Irleland **Dublin**	28 min 30 s	+1 min 40 s	277	17
4	Japan **Sapporo**	27 min 40 s	+ 50 s	240	19
5	Italy **Milan**	27 min 30 s	-20 s	259	18
6	India **Pune**	27 min 20 s	+1 min 10 s	249	19
7	Romania **Bucharest**	27 min 20 s	-10	277	17
8	Peru **Lima**	27 min 10 s	+2 min	254	18
9	Filippines **Manila**	27 min	+40 s	241	20
10	Colombia **Bogota**	26 min 20 s	+50 s	249	19

Analyzing the data presented in Table 1, Bucharest, the capital of Romania, ranks second in Europe in terms of time lost in road traffic congestion. Commuting in urban areas took an additional 143 hours annually due to traffic. Commuters working in Bucharest spent 277 hours commuting at peak hours. The advantage felt by drivers in Romania's capital city for a typical 10 km journey in terms of travel time required improved by 10 seconds compared to 2021, while in Dublin, travel time required worsened by almost 2 minutes. Bucharest ranks 7th in the top 10 most congested cities worldwide with an average travel time of about 27 minutes resulting in 63 numerous economic losses and environmental pollution. The day with the highest average travel time in the year 2022 was 35 minutes and 10 seconds, having significant monetary and scarcity costs. The costs on fuel consumption being about 3,500 lei of which 950 lei due to congestion, and CO_2 emissions being about 1,032 kg of which 295 kg due to congestion. [3, p. 62].

7. Calculation relationships to combat road traffic congestion

Until recently, congestion was reduced by developing the capacity of road infrastructure without taking into account the fact that this is a limited resource, as with any technical system.The capacity of a road is determined on the basis of the traffic capacity of a lane under ideal traffic conditions [9] (flow of cars only, traffic at equal intervals, no overtaking, no intersections at the same level with other roads or thoroughfares, specified roadway widths and shoulders, etc.), which is then reduced according to the degree of non-compliance with the ideal conditions [3, p. 63].

The traffic capacity of a lane under ideal conditions is:

$$C = 3{,}600/t \quad \text{[standard vehicles/hour]} \tag{4}$$

where,

t is the time interval in which the minimum following distance *(d)* between vehicles is covered. The minimum following distance between the vehicles can be determined by equating the kinetic energy resulting at the start of the braking procedure with the mechanical work done during the braking procedure, to which a safe distance between the vehicles can be added. One known expression for d is [3, p. 63]:

$$d = 0{,}003\ v^2 + 0{,}2\ v + s_0 \tag{5}$$

where,

s_0 is the safety space between vehicles.

In this case, the expression of *t* is solved with the relation:

$$t = \frac{0{,}003v^2 + 0{,}2v + s_0}{v} \cdot 3{,}6 \quad s \tag{6}$$

And the maximum capacity value is determined from the mathematical relation:

$$dC/dv = 0, \text{ where we can get} \tag{7}$$

$$-3v^2 + 10^3\ s_0 = 0 \tag{8}$$

But substituting the value of the velocity into the mathematical relation of *d* gives:

$$d = 2\ s_0 + 1{,}83\sqrt{s_0}\ . \tag{9}$$

And for the maximum value of the capacity we obtain the mathematical relation [3, p. 63]:

$$C = \frac{9150\sqrt{s_0}}{s_0 + 1{,}83\sqrt{s_0}}, \tag{10}$$

where $s_0 = 7.5$ *meters* gives:

At a speed of 50 km/h, C = 2,000 standard vehicles per hour. (11)

For speeds above 50 km/h, the traffic capacity of road vehicles shows a slow, approximate decrease. *Note:* The maximum value of road vehicle capacity can only be achieved under ideal conditions, but ideal conditions can never be achieved. For practical calculations we consider about 850...950 standard vehicles/hour, a value which is highly dependent on the speed estimated.

8. Fluidizing road traffic congestion with the zipper rule

On all European roads, drivers are experiencing increasingly visible congestion. In urban areas in particular, because of narrow roads and the sheer number of vehicles on them, users and beneficiaries of the road transport system spend hours in their vehicles.

The zipper rule is an effective method of decongesting road traffic, as it ensures a reasonable flow of traffic and reduces the risk of accidents, increasing the predictability of drivers. Although in Romania it is not regulated by road tra ffic laws and regulations, in countries such as Germany, Sweden, Belgium or England, the zipper rule has been legislated by regulation, thus becoming a basic rule for decongesting and fluidizing road trafficIt's a rule that comes from defensive driving. In Romania this rule is considered contrary to traffic rules. Because the rule in the Highway Code says that when you have to change from two lanes to one lane or from two streets to one street, some have priority, some don't. Those who don't have priority should stay there for 3-4-5 hours until the priority lane clears [10].

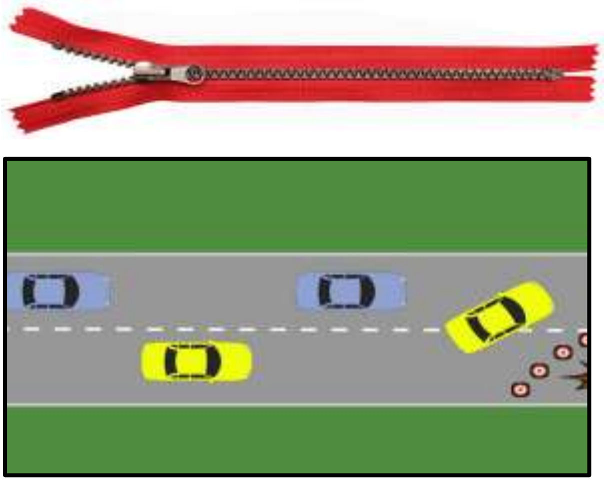

Figure 7. The zipper rule [11].

In Romania, nobody knows it, nobody teaches it and nobody pays attention to it. That is why we sit in traffic and block each other when we have to move from two lanes into one lane or into an intersection where some have priority and others do not. According to the traffic rules, those who have the right of way should keep going and the others should stay there for 3 hours, 5 hours, until they clear. But there's a common sense rule coming in called the *"zipper rule"* which says that when you have to move from two lanes into a lane, you don't take the priority rule into account, but one from the left, one from the right. Which means imaginary traffic routing, Titi Aur told GSP Live [11].

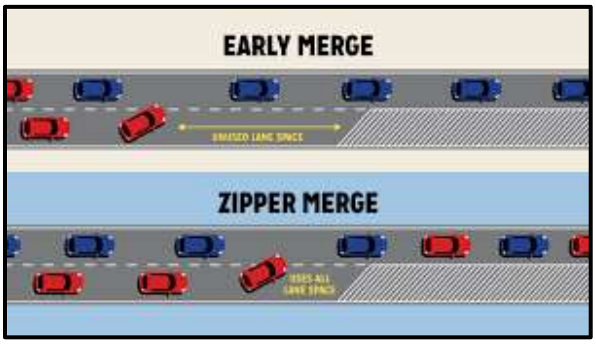

Figure 8. The early merge and zipper merge [12].

But here is how this law is applied: in the traffic regulations of European countries, the priority of road vehicles is regulated by law. In practice, situations arise where we have to respect these rules. The zipper rule, a rule that we have already mentioned that in most European countries is not regulated by law, i.e. it is an unwritten law that drivers apply in traffic when their lane of traffic narrows due to an obstacle, according to this defensive driving rule, they must enter the flow of vehicles that has the unobstructed lane, one vehicle from the left and another from the right, alternately (Figure 7). In this way, road traffic can flow and congestion is reduced in an efficient and elegant way.

The zipper merge is based on the same mechanics as a zipper you'd find on a jacket. Just as the teeth of that zipper smoothly come together, a zipper merge methodica lly brings together vehicles from two or more lanes. Here is how it works: you're driving on a busy highway in a construction zone, and you see a sign indicating a lane closure ahead. If you follow the zipper merge method, you should stay in your lane up to the final merge point (instead of an early merge as soon as you see the warning sign). Then, take turns with drivers in the other lane to safely and smoothly ease into the remaining lane (Figure 8) [12].
Zipper merges work exactly as they sound – like a zipper. As drivers see *"lane closed ahead"* signs, they should stay in their current lane up to the designated merge point. Then drivers should take turns moving into the open lane. This practice is much safer than merging early, which causes congestion and more significant changes in speed (Figure 9).
Early Merge versus Zipper Merge: most drivers tend to merge at the first sight of a *"lane closed ahead"* sign, however many slow too quickly, which can lead to unexpected lane switches, serious crashes and road rage. Zipper merges provide several benefits to the traveling public. Risks decrease when motorists use both lanes until reaching the defined merge area and then alternate or take turns moving to the open lane in a zipper-like fashion [13].

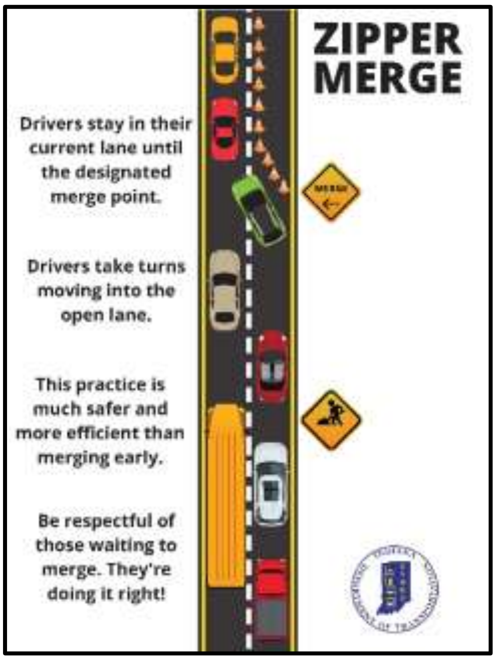

Figure 9. The zipper merge [13]**.**

The benefits of the zipper rule are as follows:
- creates a sense of fairness and equity that all lanes are moving at the same rate;
- reduces queue length by up to 40%;
- reduces speed differences between two lanes;
- brings order to the merging process;
- reduces congestion and keeps traffic moving smoothly.

9. Road congestion paradoxes. Case Study
The research carried out in this field has revealed the mechanism of congestion formation in road traffic, the parameters of which are determined by traffic delays, the number of vehicles on the waiting wires, the length of these wires, the reabsorption times, etc., thus highlighting three major paradoxes, situations in which the most widely used and known method, that of developing the network of roads or streets between two points of destination or major interest, becomes inefficient or totally unproductive. A major cause of these paradoxes is *"slow demand"*, or in other words, potential users of these new road links who are not taken into account when resizing the road network. They normally use detour routes, travel at off-peak times or use public transport. In this case it can be said that, whenever an attempt is made to reduce road congestion on a stretch of road by extending the road network, other road users will not be encouraged to use the route at times and to destinations they would otherwise avoid. The result immediately becomes paradoxical, as the decongested section of road will become congested again in a short time. Another reason why expanding the carrying capacity of a road section does not substantially change the congestion problem is that the time lost in traffic is of no value to most road users, and is taken into account from the outset in trip planning as part of the time budget allocated to the trip [1, p. 2]. In this way, the time wasted by a road traffic participant becomes detrimental to those who are caught in this congestion trap, or rarely or even casually pass through the area. Combined, these two tendencies can lead to the opposite of the

expected results in the case of an expansion of transportation capacity on a given area of an artery exposed to this phenomenon.

A) Paradox no.1 of road traffic congestion is called the ***"Pigou - Knight - Dows Paradox"*** (Figure 10), which explains and advances why the expansion of transportation capacity between two areas produces new demands that cannot be solved. Analyzing the practical example in Figure 1, we assume that between the two zones of interest (*A* and *B*), $q_1 = 1{,}000$ vehicles/hour travel between the two zones at peak hours, whose drivers can choose to travel on a short road over the bridge *P*, or they can use a longer road, a less busy and less congested detour. The first travel route/route T_1 can be covered in 10 minutes in low traffic conditions. Time t_1 traveling the section increases linearly with the ratio:

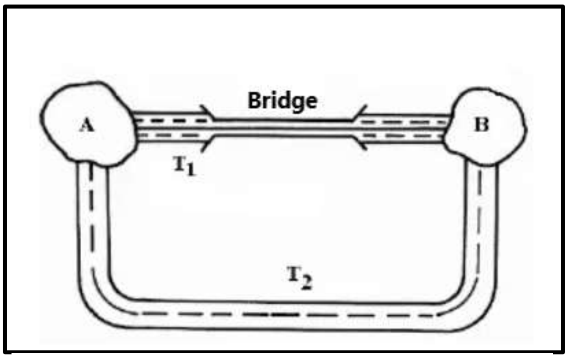

Figure 10. The Pigou- Knight-Downs paradox [1, p. 3].

$$t_1 = \frac{q1}{C1} \tag{12}$$

where,

q_1 represents road traffic flow;
C_1 – bridge crossing capacity *P*.

The size C_1 is conventional and is set based on pragmatic data, it defines the maximum flow over the bridge at half the legal traffic speed on that stretch of road when it is not congested. The section T_1 can be traveled in time $t_1=10$ minutes as an uncongested section and can be calculated with relation (2) in case of congestion as follows:

$$t1 = 10\ min. + 10 * \frac{q1}{C1} \tag{13}$$

The second term in the presented relation defines the additional time needed to travel the road section due to congestion on bridge *P*. Road section T_2 is the detour and takes 15 minutes to travel, assuming that all drivers of road vehicles traveling on it will always choose the fastest possible route.
Two situations arise in this case:

- *situation no. 1:* the bridge crossing capacity $P(C_1)$ is greater than 2,000 vehicles/hour *(C_1>2,000 vehicles/hour)*, in this case the 1,000 vehicles can cover the road section T_1 in less than 15 minutes. Being at the limit, C_1 = *2,000 vehicles/hour*, t_1 will have the value according to the calculation of the relation:

$$t1 = 10 + 10 * \frac{1{,}000}{2{,}000} = 15\ minutes \tag{14}$$

According to the created situation the travel time on road T_1 is equal to the travel time on road T_2, where all drivers choose road T_1.

- *situation no. 2*: the crossing capacity of the bridge $P(C_1)$ is less than 2,000 vehicles/hour *(C1<2,000 vehicles/hour)*, taking into account a number of 1,500 vehicles/hour, we obtain the following result :

$$t1 = 10 + 10 * \frac{1{,}000}{1{,}500} = 16.6\ minutes \tag{15}$$

Analyzing the result obtained from the relation (4) we observe that the time t1 is greater than the maximum allowed limit of 15 minutes, in which case the traffic is divided on the two road sections in such a way that $t_1 = t_2 = 15$ *minutes*. In Figure 11 we plot the variation of the parameter t1 with respect to the values of P_1 for the variation law (1).

From the analysis of the data shown in Figure 11, it can be seen that the paradox occurs when the bridge crossing capacity is $C_1<2{,}000$ *vehicles/hour*. In this case, as specified above, the crossing time *t = constant* and *equal to 15 minutes*, as the road traffic is divided on the two road sections. Consequently, any bridge crossing capacity in the range [0 – 2,000 vehicles/hour] will not bring any benefit on the travel time. We observe that, as the C_1's wavecapacity increases, the more drivers who will be on the road section T_1, will travel it in the same time, which is equal to 15 minutes. As long as there is traffic on T_2, it will cancel out any attempt to improve traffic on T_1. This cancellation will occur as long as the bridge crossing capacity does not reach the critical value C_1 = *2,000 vehicles/hour*, at which point all drivers will use road T_1. If this threshold is exceeded, as the bridge capacity increases, there will be a slight decrease in the travel time on road T_1 below the critical value of 15 minutes. Following a value of C_1 = *3,0000 vehicles/hour*, i.e. an increase of 50%, the time t_1 will be reduced by 11.4%.

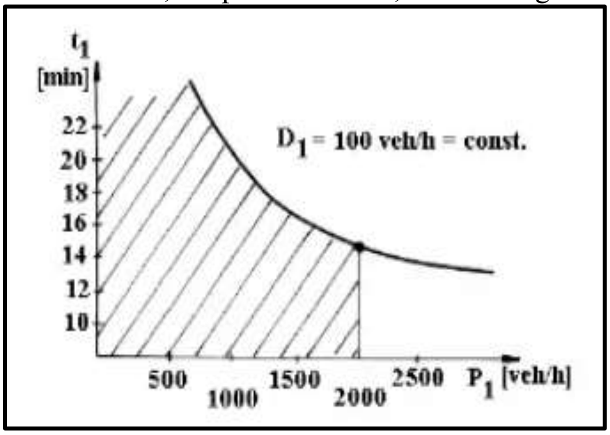

Figure 11. Law of variation of parameter t_1 as a function of C_1 [1, p. 3].

As a result of this paradox, road traffic optimization calculations have to take into account the latent demand of potential users, a parameter which is very difficult to quantify [1].

B) Paradox no. 2 of road called congestion which is called the ***"Downs-Thompson Paradox"*** (Figure 12), has even more astonishing effects than paradox 1. Using the previous computational data, but assuming that the T_2 section is served by a rail line, the following situation arises: road users are offered the possibility to use the train instead of their private car for travel. Trains run at full capacity and a journey takes 20 minutes. If the demand for train use is at 3,000 passengers the t otal train travel time is reduced by 10 minutes by increasing the frequency of train movements. If we consider the number of passengers to be D_c and the time of one train trip to be T_2, it has the value calculated with the relation:

$$t2 = 20 - 10 * \left(\frac{Dc}{3{,}000} \right) \qquad (16)$$

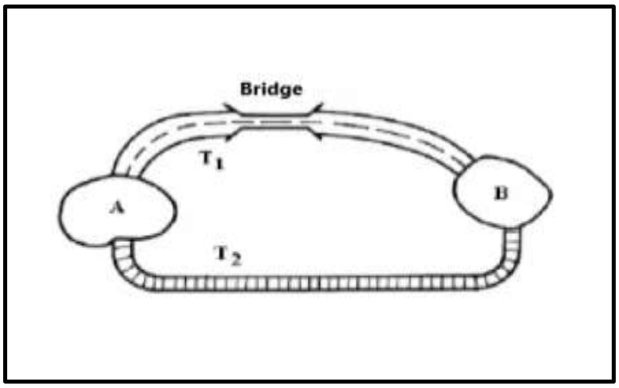

Figure 12. The Downs -Thompson paradox [1, p. 3].

Time t_1 is calculated with expression (1).

As in the previous case, travelers choose the route with the shortest travel time such that $t_1 = t_2$. Considering the case where the bridge capacity $C_1<1{,}000$ *and* $q_1+D_c = 1{,}000$ *travelers*, it follows:

$$q_1 = \frac{C_1}{\left[1{,}5 - \left(\frac{C_1}{2000}\right)\right]} \tag{16}$$

$$10 + 10 * \left(\frac{q1}{C1}\right) = 20 - 10 * \left[1{,}000 - \left(\frac{q1}{3{,}000}\right)\right], \text{ and} \tag{17}$$

By substitution in relation (17) we obtain:

$$t_1 = 10 + \frac{10}{\left[1{,}5 - \left(\frac{P_1}{200}\right)\right]} = t_2 \tag{18}$$

In Table 1 we present the calculated results for different values of parameter P_1.

Table 1. Travel time depending on bridge crossing capacity.

C_1 [veh/hour]	q_1 [veh/hour]	D_c [travelers]	$t_1 = t_2$ [minutes]
250	182	818	17,2
500	400	600	18.0
750	667	333	18.9
1,000	1,000	0	20.0

Analyzing the results presented in Table 1, considering that C_1*>1,000 vehicles/hour*, all travelers use the T_1 route, and the travel time decreases from 20 minutes to the value of 15 minutes for C_1 *= 2,000 vehicles/hour*. The paradox exists in the fact that by using the train, travelers have the following benefit: they arrive at their destination in good time (a much shorter time than by car on the road) thus reducing waiting time for those who depend on their activity.

This is a property that should characterize all public transport. However, for subjective reasons, travelers prefer to travel by car on the road and thus suffer the consequences of delays, extra expenses and reduced efficiency of the activity caused by road congestion. At the limit, it was found that even if rail transport is free of charge, the facts of the problem do not change. The number of those who give up road transport in favor of rail transport, even free of charge, is disarmingly small.

C) Paradox no. 3 of congestion in road traffic is called ***"Barnes' Paradox",*** (Figure 13), after the name of a German researcher who, while studying real problems related to road traffic, also reaches a paradoxical conclusion, namely: a new route between two points of interest, added to existing ones, increases the travel time between these points. In this case it is assumed that the traffic flow between points *A* and *B* is 1,000 vehicles/hour. In this context, the first route has q_1 vehicles/hour and the second route has q_2 vehicles/hour. The road traffic on both routes is congested by bridges C_1 and C_2. Under moderate traffic conditions without congestion, the travel time on the two road sections is equal, i.e. $t_1 = t_2 = 15$ *minutes*. If for every 1,000 extra vehicles that appear in traffic

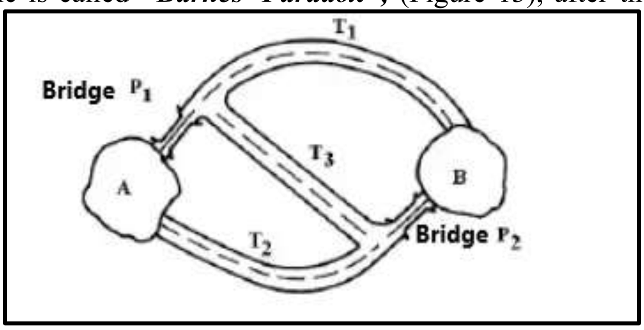

Figure 13. The Barnes paradox [1, p. 3].

the travel time is increased by 10 minutes, the travel time on the two sections will be given by the relations:

$$t1 = 15 + 10\left(\frac{C1}{1{,}000}\right) \qquad [\text{veh/hour}] \qquad (19)$$

$$t1 = 15 + 10\left(\frac{C2}{1{,}000}\right) \qquad [\text{veh/hour}] \qquad (20)$$

For equal travel times the flow rates on the two road sections will be equal. Therefore, for a flow of 1,000 vehicles/hour each route will be loaded with 500 vehicles/hour and the travel times will be $t_1 = t_2 = 20$ *minutes*. In a later phase of development, in order to ease road traffic, section T_3 is built, which shortens the road, providing a direct link between the two bridges. On this section of road, the travel time between points *A* and *B* under traffic-free conditions is $t_3 = 7.5$ *minutes*. In this case, it can be seen that each bridge will take the road traffic for the two road sections, i.e. $P_1(C_1)$ will take the traffic for T_1 and T_3, and $P_2(C_2)$ will take the traffic for T_2 and T_3. By calculation, the travel time in the two cases will be:

$$t1 = 15 + 10 * \left(\frac{C1+C3}{1{,}000}\right) \qquad [\text{min}] \qquad (21)$$

$$t2 = 15 + 10 * \left(\frac{C2+C3}{1{,}000}\right) \qquad [\text{min}] \qquad (22)$$

If up to 1,000 vehicles per hour are added to road traffic at peak hours, they are distributed in such a way that $t_1 = t_2 = t_3$, hence:

$$t1 = 15 + 10 * \left(\frac{C1+C3}{1{,}000}\right) = t2 = 15 + 10 * \left(\frac{C2+C3}{1{,}000}\right) = 7.5 + 10 * \left(\frac{C1+C2+2*C3}{1{,}000}\right) \qquad (23)$$

By solving equation (23), we obtain:

$$C_1 = C_2 = 250 \text{ vehicles/hour}; \; C_3 = 500 \text{ vehicles/hour}; \; t_1 = t_2 = t_3 \qquad (24)$$

Analyzing the obtained results, paradoxically each bridge will be loaded with 50% more road vehicle traffic, thus increasing the maximum travel time from 20 minutes in the initial case to 22.5 minutes for the optimized variant. The paradox can be explained by the fact that more drivers choose the fast T_3 road section, disregarding the fact that they now have to cross two critical points (bridges P_1 and P_2), compared to only one bridge in either of the initial variants. If the travel time between the two bridges were 5 minutes, all drivers would choose the T_3 road section and the journey would take 25 minutes.

Conclusions

The zipper rule is an effective way of smoothing road traffic and reduces the risk of accidents because drivers are more predictable.

The value of the capacity of a flow of vehicles on a road is not constant but depends on the speed achieved, which in turn depends on the degree of congestion on the road. This dependence of the quality of supply on the level of demand is a form of externality effects, both between users and with regard to the riparian area. It is quite clear that increasing the capacity of congested infrastructure is not a lasting solution that will reduce congestion; indeed, it is a well-known saying among specialists in the field that any new infrastructure development will attract traffic and will soon lead to congestion again.

A sustainable solution to limit road congestion is to improve urban public transportation service.

The three paradoxes presented are more abstract theories of vehicular road traffic. Their results have been and are successfully applied to solve real road traffic problems that seemingly have no solution. The presented paradoxes have turned over time into real fundamental laws of modern road traffic.
Organizational actions to reduce congestion aim at flattening traffic peaks by staggered scheduling of the start of working hours at companies, providing travel fare concessions for public transport at times that are not considered peak demands on the system, staggered scheduling of rest holidays. The effects of congestion must be limited and reduced through early and permanent education of young people so that they acquire a travel behavior in line with the requirements of sustainable development. Schools must become an active factor in helping young people to identify and discover the long-term benefits of limiting car use. In this way, society will save resources and develop harmoniously in the current context of the technical and information technology revolution.
Japanese researchers conducted a simple experiment demonstrating that traffic congestion problems are also caused by human error when there is no actual obstacle (Figure 14). The experiment was conducted with 22 vehicles driving constantly in a circle at a speed of 30 km/h. All was going perfectly until one driver braked slightly. The driver behind him braked as well, then the next one braked even harder, and after a few seconds a complete traffic jam had formed, without any real obstacle or reason. This type of traffic jam is called *"phantom traffic"* and is created exclusively by chain reactions among drivers. Traffic jams on highways occur in the same way, even if there are no real obstacles or accidents (Figure 15). One driver brakes, and those behind react in a chain reaction, creating a massive traffic jam. Regarding this aspect, we conclude and specify that: road traffic is not exclusively related to road transport infrastructure, but also to the psyche, to the way drivers think, the distance from the vehicle in front, smooth driving, and sudden braking, all of which exponentially influence the formation of traffic jams.

Figure 14. Aspects during research.

Figure 15. Creating traffic jams on highways.

References

[1] scribd.com, „Elements of Traffic Congestion Theory," Scribd, 9 January 2025. [Interactiv]. Available: https://www.scribd.com/document/379017872/C11. [Accessed January 9, 2025].

[2] G. Neamțu, Contributions regard on the integration of knowledge management in the sustainable development of road transport - PhD Thesis, N. U. o. S. a. T. P. Bucharest, Ed., Bucharest, Romania: National University of Science and Technology Politehnica Bucharest, 2023.

[3] M. F. Grigore, V. Dragu și C. Zanfir, „Reducing traffic congestion through urban resilience," *AGIR Bulletin,* vol. 1, pp. 59-65, January - March 2024.

[4] Ș. Raicu, Transportation systems, Bucharest: AGIR, 2007, p. 484.

[5] F. D. Hobbs, Traffic Planning and engineering, P. Press, Ed., Oxford; New York: Pergamon Press, 1979.

[6] E. Commission, "White Card.," Roadmap to a Single European Transport Area - Towards a

Single European Transport competitive and resource efficient transport system , 28 March 2011. [Online]. Available: https://eur-lex.europa.eu/legal-content/RO/TXT/PDF/?uri=CELEX:52011DC0144. [Accessed January 10, 2025].

[7] C. Dimon, „Project Title: Digital techniques for road traffic control and optimization using artificial intelligence algorithms," Microsoft Word, Bucharest, 2023.

[8] tomtom.com, "Maps and location technology to keep the world moving," TomTom, 10 January 2025. [Online]. Available: https://www.tomtom.com/. [Accessed January 10, 2025].

[9] M. Beuran , Design and construction, Cluj Napoca: Lithography of the Faculty of Construction, 1977.

[10] F. Răvdan, „What is the "zipper rule" that contradicts traffic rules. "It ensures fluidity. In other countries it's become a traffic rule, in ours it's refused"," DcNews, 18 October 2023. [Interactiv]. Available: https://www.dcnews.ro/ce-este-regula-fermoarului-care-contrazice-regulile-de-circulatie-asigura-fluiditate-in-alte-tari-a-devenit-regula-de-circulatie-la-noi-se-refuza_934636.html. [Accessed January 10, 2025].

[11] R. Dinu, „What's the "zipper rule", the ingenious solution unknown to Romanian drivers: "That's why we're sitting like idiots in traffic! It should be taught in schools"," Sports Gazette, 12 March 2021. [Interactiv]. Available: https://www.gsp.ro/sporturi/noutati-auto/regula-fermoarului-trafic-626080-galerie-foto.html. [Accessed January 10, 2025].

[12] living.acg.aaa.com, "The Zipper Merge: The Best Way to Merge in Traffic. The surprising reasons why zipper merging works best for lane closures," living.acg.aaa.com, 10 January 2025. [Online]. Available: https://living.acg.aaa.com/auto/zipper-merge-keeps-traffic-moving. [Accessed January 10, 2025].

[13] IN.gov, "Zipper Merge: Keep Traffic Moving," Indiana Department of Transportation, 10 January 2025. [Online]. Available: https://www.in.gov/indot/safety/zipper-merge/. [Accessed January 10, 2025].