Int. j. adv. multidisc. res. stud. 2026; 6(3):388-404

Received: 24-03-2026
Accepted: 04-05-2026

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Principles and Techniques of Traffic Calming at Intersections with Traffic Lights

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Abstract
There isn't a big city whose intersections aren't controlled by traffic lights. Today, the three lights seem commonplace, but many drivers don't realize that there was a time when traffic lights were changed manually. This scientific paper presents in a concrete and elegant manner a research carried out by the authors with the aim of highlighting how to achieve traffic fluidization of road vehicles at intersections of roads or streets with traffic lightsIn this way, those interested can learn about the types of electric traffic lights used in road traffic, some basic principles regarding the calculation of phases and the traffic light cycle in road or street intersections and three specific examples, presented through case studies on the calculation of the minimum yellow and the dilemma area in traffic lights, on a single traffic phase. The three case studies presented in this scientific paper can be successfully applied in the development and training of students in the specialization of transport and traffic in the faculties of transport and traffic engineering. At the end of the paper, conclusions are drawn and some recommendations and observations from the authors on the field are presented.

Keywords: Traffic Light, Safety, Saturation Rate, Green Wave, Traffic Light Cycle, Traffic Light Phase, Dilemma Area

1. Introduction

Road passenger and goods transport is the driving factor, a key element of the knowledge-based economy and social cohesion. In recent decades there has been a steady increase in the number of road vehicles on the roads and public transport is on the rise. The current urban road infrastructure, built in the 50s and 60s, can no longer cope with the demands. Traffic accidents and congestion have a major impact on lives, reduce productivity and diminish energy. Traffic congestion, which causes environmental problems and accidents, is becoming increasingly acute. The benefits of transport are diminished by the growing number of negative effects (air pollution and accidents, increased stress for road users), resulting in a vicious circle in today's urban transport. In the latter part of the eighth decade of the last millennium, traffic density in major Western and developed country metropolitan areas reached impressive levels. The spectacular growth in road traffic cannot be satisfied in the short term by adequate road space development. For this reason, all developed economic environments have tried to find ways of reducing congestion in two ways: improving road space in order to increase utilization; and improving traffic flow parameters through control and monitoring. Increasing road traffic density requires the implementation of control systems to ensure the efficient use of the limited space allocated to traffic under conditions of increased safety and reduced pollution. The aim of traffic control in road traffic systems is to increase the traffic capacity of road networks under the following conditions: increased efficiency for road users (time and fuel savings, increased comfort through information and assistance services); increased safety for road users and for the people living in the vicinity of the road space by providing information about factors influencing road traffic (such as weather conditions: wind, cloud cover, precipitation, etc., or the level of traffic congestion in certain areas). The semaphore (in free translation from the French sémaphore) is an electrical optical signaling device, which indicates various signals relating to road, rail, maritime traffic [1]. In order to save electricity, today LED-lit electric traffic lights have become widespread in all transportation systems, where they justify their efficiency and effectiveness. The research on ctritical movements at intersections is evolving according to a fundamental principle that the amount of time in an hour is precisely defined, because two vehicles (or a vehicle and a pedestrian) cannot occupy the same space at the same time. The traffic signal cycle time is the total time in seconds calculated for a group of vehicles or pedestrians from each entrance to pass through the roadway space of the intersection, public road or street, including the evacuation of these groups. The critical movement analysis identifies a set of movements that cannot overlap in time and needs more time to be realized. The traffic signal cycle is divided into phases and sub-phases, represented by the colors, red-yellow-green for the traffic signal for motor vehicles and red-green for the pedestrian signal. The traffic signal cycle is determined by calculation, based on the hourly traffic volume and the number of traffic lanes of the intersection arms. The actual traffic signal cycle, in seconds, is the time elapsing, at any traffic signal at each intersection entrance, from the appearance of the green traffic signal color, the end of the green time, the appearance and end of the red time, and the appearance of the green color again. The phase of the traffic light cycle, is represented by the duration of the green-on time in the intersection, including the intersection evacuation time. The duration of green time, in a phase of the traffic signal cycle, is dependent on two factors: 1) the amount of traffic in a traffic lane (the most heavily used) and 2) the number of roadway lanes of the intersection arm. The red time duration, also includes two parts: 1) the duration of the evacuation time of the same phase and 2) the waiting time, the time during which the traffic on the other antagonistic directions is moving. The duration of the evacuation time (inter-green) ensures the safety of the traffic flow when changing from one traffic light phase to another and is determined by calculation [2].

2. Literature review

The Romanian legislation regulating road traffic signaling is based on the Romanian Standard SR 1848 - 4 of July 1995, classification index G 75, Traffic safety, traffic signals for traffic direction, location and operation, approved by the IRS General Directorate on 26 January 1995, with application from July 01, 1995. This standard replaced the old Romanian Quality Standard STAS 1848/4-86. It is important to add that, at the date of approval of the Romanian Standard SR 1848 - 4 of July 1995, there was no international or European standard referring to this subject [3].

Other reference documents:

- ✓ Romanian Standard STAS 1244/3 - 90, Traffic safety. Railroad grade crossings. Automatic signaling installations;
- ✓ The Regulation implementing the Emergency Ordinance of the Government of Romania no. 195/2002 on Traffic on Public Roads of October 4, 2006, published in the Official Gazette of Romania, no 876 of October 26, 2006, Part I, which entered into force in Romania on December 1, 2006 [4].
- The Regulation implementing the Emergency Ordinance of the Government of Romania no. 195/2002 on Traffic on Public Roads of October 4, 2006, at the Section 1, Illuminated signals, Paragraph 1. Signal lights for the direction of vehicular traffic, it is provided [4]:

Art 47. (1) Signals are white or differently colored lights, emitted successively, continuously or intermittently, by one or more luminaires composing a traffic signal. (2) According to the number of luminaires, traffic signals are:

(a) with one luminaire with flashing warning light;

(b) with two luminaires, for pedestrians and cyclists;

(c) with three luminaires, for vehicles;

(d) with four or more luminaires for trams.

(e) (3) The traffic signals shall be mounted in the vertical axis of the pole or on the cantilever, on the portal or suspended on cables, the sequence of the colors of the lenses, from top to bottom, being as follows:

(f) at three-color traffic lights the order of the signals shall be: red, yellow, green;

(g) at two-color traffic lights the order of the signals is: red, green;

(h) at tramway traffic lights there shall be three horizontally arranged at the top and one at the bottom, all with white light.

Art. 48. (1) Traffic signals which generate traffic light signals for the purpose of directing traffic at intersections shall be installed before the intersection in such a way as to be visible from a distance of at least 50 m. They may be repeated in the middle of, above or on the other side of the intersection. **(2)** The meaning of the vehicle direction indicator signals shall be valid for the entire width of the roadway open to the traffic of the drivers to whom they are directed. On roads having two or more lanes in each direction, for different directions, delimited by longitudinal markings, traffic signals may be installed above one or more of the lanes, in which case the significance of the signal lights shall be limited to the lane or lanes so marked;

Art. 49. Red or green traffic signal lamps may have black arrows on them indicating the corresponding direction of travel. In this case the prohibition or permission to pass imposed by the signal light shall be limited to the direction or directions indicated by these arrows. The arrows on the additional panels at the bottom of the traffic light signals have the same meaning. The forward arrow points upwards;

Art 50. (1) The traffic signals for trams shall be in the form of a box with four white lighting units, three of which are positioned horizontally and one below the middle one, accompanied by additional sign panels. **(2)** The signal for tramway traffic is given by the combination of the lower lamp and one of the three lamps located at the top for direction indication. **(3)** The signal prohibiting the passage of the tramway is given by the simultaneous illumination of the three lamps at the top of the box;

Art 51. (1) The green signal allows the passage. **(2)** When the traffic signal is accompanied by one or more lamps flashing green light(s) in the form of an arrow or arrows on a black background to the right, they shall permit passage only in the direction indicated, whatever the signal of the traffic signal in operation at the time;

Art 52. (1) The red signal prohibits the crossing. **(2)** At a red signal, the vehicle must stop before the stop sign or, as the case may be, the pedestrian crossing, or, failing this, in front of the traffic light. If the traffic light is installed above or on the other side of the intersection, in the absence of a stop or pedestrian crossing mark, the vehicle must stop before the edge of the roadway of the road to be intersected. **(3)** When the red signal operates simultaneously with the yellow signal, it shall announce the green signal;

Art 53. (1) When the yellow signal appears after the green signal, the driver of the vehicle approaching the intersection shall not pass the places provided for in Article 52, paragraph. **(2)** The flashing yellow signal shall permit the vehicle to pass, the driver of the vehicle being obliged to drive at reduced speed, to comply with the meaning of the road signs and the traffic rules applicable in that place;

Art 54. At intersections, the traffic of trams can also be directed by traffic lights with white signal lights, correlated with the signal lights for the other vehicles;

Art 55. The illuminated sign intended solely for bicycle traffic has in its field the image of a red or green bicycle on a black background. A traffic light signal with an additional panel showing a bicycle has the same purpose;

Art 56. (1) When devices emitting red and green signals are installed above traffic lanes, they are intended to signal lanes with reversing traffic. The red signal, in the form of two crossed bars, prohibits the entry of vehicles into the lane above which it is located, and the green signal, in the form of a downward-pointing arrow, permits the entry of vehicles and traffic to move in that lane. (2) An intermediate light signal in the form of a yellow or white arrow or arrows pointing downwards to the right or left shall indicate that the green signal has changed, in the case of reversible lanes, or that the lane above which it is located is about to be closed to the drivers to whom it is directed and that they must move into the lane or lanes indicated by the arrows;

Art 57. The driver of a vehicle entering an intersection at a green traffic light is also obliged to obey the meaning of the signs installed inside the intersection.

- In Section 1, Illuminated signs, Paragraph 2. Pedestrian signals, it is provided [4]:

Art 58. (1) Pedestrian signals shall be green and red. (2) The green signal may have in its field the image of a pedestrian in motion and the red signal may have in its field the image of a pedestrian stationary. (3) Pedestrian signals may be accompanied by audible signals to ensure that blind persons can cross the road. (4) On stretches of road where traffic values permit, the public road administrator, with the approval of the police, may place traffic lights or special signs in the area of the pedestrian crossing markings with manual control of the green signal request, which may be made directly by pedestrians;

Art. 59 (1) The green colored signal allows passing. **(2)** When the green signal starts flashing it means that the time for crossing the road is running out and the red signal follows. In this case, the pedestrian caught crossing the road must hurry and, if the road has a refuge or a space closed to vehicular traffic, wait for the green signal to appear;

Art. 60 The flashing green signal and the red signal prohibit pedestrians from crossing the roadway.

- In Section 1, Illuminated Signals, Paragraph 3. Other light signals, it is provided [4]:

Art 61. In the case of correlated traffic signals, timing devices may be installed along a route to indicate the time of the color, as well as luminous devices to show the traffic participants the times set by the traffic light program and, for motorists, the speed of travel;

Art 62. The warning signal is installed at the exit of the intersection and consists of a luminaire with a flashing yellow light. It may have in its field the image of a moving pedestrian in yellow on a black background;

Art 63. Mobile traffic lights may be temporarily installed to signal and direct traffic on road sections where roadworks are being carried out on the carriageway, except on motorways, with the obligation to pre-signalize them.

3. Traffic light history

In Europe, traffic lights appeared long before the advent of the automobile and were dedicated to carriage and pedestrian traffic. In London, for example, such a traffic light was installed as early as 1868 at the junction of George Street and Bridge Street, near the Houses of Parliament (Fig 1). It was a mechanical traffic light that used a set of horizontal arms to control dense carriage traffic. At night, a gas lamp was lit and a set of green and red colored bottles indicated to traffic participants what to do. Initially, these traffic lights were manually controlled by a police officer, who decided the traffic light's indications according to the traffic and whistled before changing its position. This type of traffic light proved to be dangerous because of the gas pipes running underneath it. In 1869, one such traffic light exploded, seriously injuring the policeman who operated it, and London abandoned this type of traffic control system.

Fig 1: The appearance of the first traffic light in Europe [5]

We are at the beginning of the 20th century, when the automobile was already a reality that had gone beyond the stage of curiosity. In America, automobiles were spreading rapidly and becoming an everyday reality. With them came the first traffic jams. A little more control was needed at intersections, and cops couldn't stay in one place for 24 hours. Thus came the world's first electric traffic light like the one first installed in Cleveland, Ohio. It was the first dedicated traffic light and was installed on August 5, 1914 at Euclid and East 105th Streets. It used only two colors, red and green, as well as an audible signal to warn of the impending color change. At a time when engines didn't sound so loud and in-car music was still a pipe dream, audible signals were a useful traffic feature. It was only 6 years before the color yellow appeared on traffic lights. The three-color traffic light was created by William Potts, a Detroit police officer. Potts was inspired by the signals used near railroads, and the first three-color traffic light was installed in 1920 at the intersection of Woodward and

Michigan boulevards in Detroit. A year later, there were already 15 traffic lights in Detroit [5]. The little man at pedestrian traffic lights is over 60 years old.

Fig 2: Traffic light at Postdamer Platz, Berlin [5]

In Europe, car traffic started to take off in the early 20s. After the war, European countries were recovering, and the automobile was already in power. In addition to cars, major European cities already had well-defined networks of trams and buses dedicated to public transport. The busiest intersection in Europe was the famous Potsdamer Platz in Berlin (Fig 2). Five boulevards converged on this square, and the first electric traffic light was installed here in 1924. The five traffic lights were mounted high on a tower from which traffic could be observed by a policeman. The European traffic lights were built by Siemens. While originally controlled by the policeman at the intersection, various inventors in the following years searched for solutions to control the traffic lights. Systems were developed that detected the car horn or were activated by pressure sensors when the car approached the intersection [5].

Fig 3: Traffic Light Tree, modern sculpture in Canary Wharf, London [5]

In England, the nation that embraced the automobile earlier than other countries, the electric traffic light was adopted in 1926. The first one was installed at the famous Piccadilly Circus intersection in central London. By 2014 there were more than 25,000 traffic lights in the UK, and the British have even dedicated a famous sculpture to the traffic tool. The Traffic Light Tree is a work of art created by French artist Pierre Vivant: 75 traffic lights have been merged into a huge tree, and the sculpture has become a symbol of London's Canary Wharf area, where it has been installed [5].
The first traffic light in Romania's capital city of Bucharest appeared on April 29, 1933 (Fig 4). It was mounted high on Calea Victoriei, at the intersection of Academiei and Elisabeta boulevards. As the name traffic light did not exist in the vocabulary of the time, the press of the time called it *"the newest signaling device"*. The Romanian traffic light used only the colors red and green and was operated manually by a policeman at the intersection. Throughout 1933, more traffic lights were to appear in Bucharest. Before this traffic light with lights, there was apparently another one with mechanical arms at the same intersection in 1929. It was called the *"one-eyed traffic light"*.

Fig 4: The first traffic light in Bucharest, Romania [5]

4. Types of electric traffic lights used in road traffic

Traffic lights, or traffic signals, are essential devices used to control traffic flow and ensure safety at intersections. Although the basic principle of traffic signals remains consistent, there are several types that serve different purposes and address different traffic conditions.
The following is a generalized classification of the main types of electric traffic lights for road vehicle traffic control.
The standard traffic lights, (Fig 5). The most common type, consisting of three colors (red, yellow and green) in a vertical or horizontal arrangement. These lights indicate when to stop, prepare to stop, and proceed, respectively.

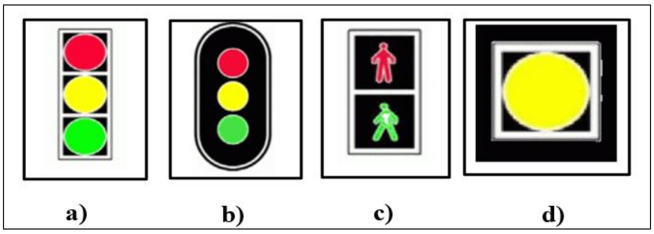

Fig 5: a) Standard traffic light; b) Traffic light with contrast panel; c) Standard pedestrian traffic light; d) warning traffic light [9]

Arrow traffic signals, (Fig 6) In addition to the standard colors, arrow traffic signals display directional arrows pointing left, right or straight ahead. They provide more specific instructions for turning movements, helping to manage complex intersections. The arrows can be applied (inserted) directly onto the colored glass of the lamps or via additional pads (next to the lamps), distinct for each color.

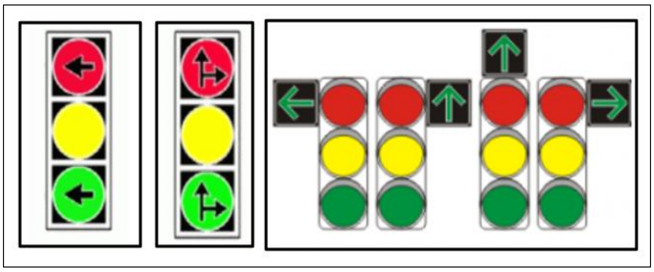

Fig 6: Arrow traffic lights [9]

Traffic lights for pedestrians, (Figure 5c and 7 a, b). Designed specifically for pedestrians, these lights often include a 'walk' or 'do not walk' symbol in addition to the standard colors. They indicate when it is safe for pedestrians to cross the road. One of the measures introduced in many European cities (including Romania) to make traffic flow more smoothly is for cars to have the green light until pedestrians approach the crossing and press a button mounted on the traffic light. Researchers have developed a type of traffic light with artificial intelligence to eliminate traffic congestion and improve the flow of vehicle traffic. This type of traffic light consists of a pedestrian zone monitoring system equipped with video cameras that continuously scan a 9x3 meter area. When the system detects that one or more pedestrians intend to cross, the system transmits the information to the traffic light, which gives the pedestrians the green light. Researchers claim that such a system is 3 to 4 seconds faster than the traditional system where the pedestrian presses a button alone. The new system also has the potential to improve traffic flow. For example, in the case of a large group of pedestrians, the system can extend the time that pedestrians have the green light. At the same time, it can give cars the green light more quickly if only one pedestrian is crossing the street [6].

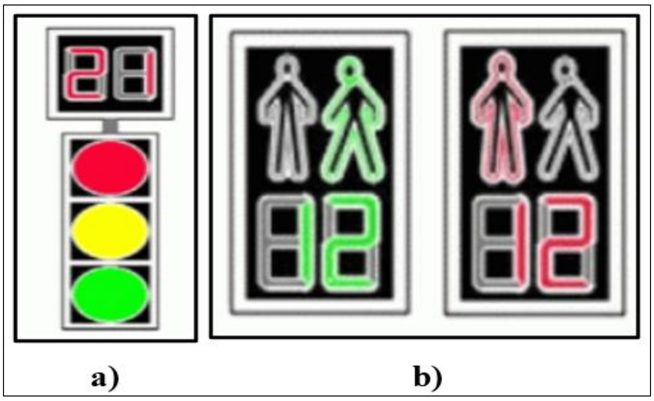

Fig 7: Countdown traffic lights a) for road vehicles; b) for pedestrians [9]

Countdown traffic lights, (Fig 3): some modern traffic light systems incorporate countdown timers that display the time remaining before the traffic light changes. This feature gives drivers an additional visual cue, improving traffic flow and reducing uncertainty.

Special purpose traffic lights, (Figures 8 and 9). There are also specialized traffic lights designed for specific situations, such as traffic lights for trams or for cyclists. Special traffic signals are also required for school zones, construction zones or intersections with high volumes of emergency vehicles, etc.

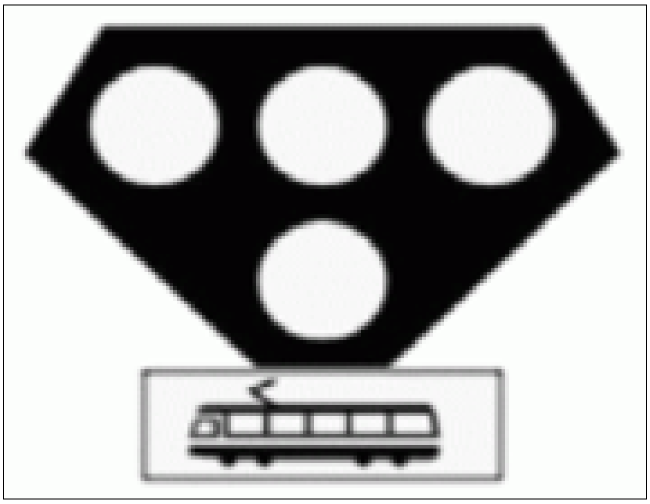

Fig 8: Special traffic lights for trams [9]

Fig 9: Special traffic for cyclists [9]

These lights may have additional colors or signals to provide unique instructions. Fig 10 shows the operation and meaning of the electric traffic lights for tram traffic.

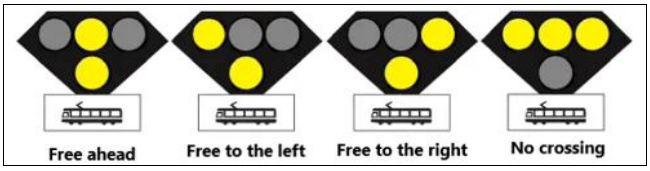

Fig 10: Operation and meanings of tram traffic lights

Adaptive traffic lights, (Fig 11). These advanced systems use sensors and algorithms to adjust the timing of traffic lights based on real-time traffic conditions. They can optimize traffic flow, reducing congestion and improving travel time.

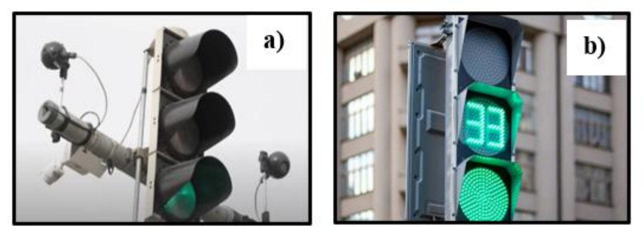

Fig 11: Adaptive traffic lights a) for road vehicles; b) for pedestrians [9]

It is important to keep in mind that the exact number and types of traffic lights used in a given location may vary depending on factors such as traffic volume, road design and local regulations. The above categories represent the most common types of traffic signals found in use worldwide.

4.1 Traffic light classification based on intersection demand detection and interpretation

Signalized intersections work in two ways:

- ✓ The manner where the controller (the *"traffic light computer"*) interprets the local request;
- ✓ The controller's relationship with other neighboring controllers.

From this point of view (demand being defined as the number - and possibly type - of vehicles or pedestrians who at a given time wish to cross the intersection on a given relationship), we can classify traffic signals into:

Timed traffic lights. They do not receive any information about the flows waiting/coming at the intersection, and run traffic light cycles with predefined times.

But time:

- Can have the same values all the time (the most disadvantageous and inefficient way of operating traffic lights, and unfortunately found in the vast majority of intersections in Romania);
- May have preset values depending on the time of day (e.g. morning rush hour, between rush hours, evening rush hour and night) or week/year (different on weekdays compared to weekdays, or different during school vacations).

Traffic lights with fixed times are generally inefficient, especially if the pre-programmed times are the same throughout the day. Therefore, a minimal improvement (to be considered by all cities) that can be made relatively easily and without capital expenditure (i.e. without installing sensors) is to refine the fixed times by scheduling various predefined traffic light cycles according to time of day/day. The improvements can be significant, particularly in reducing off peak traffic light waiting times.

Actuated traffic lights. Detectors (sensors) installed in the proximity of the intersection provide real-time information about vehicles waiting (or about to arrive) at the intersection to the controller, which runs traffic signal phases according to the actual demand, as follows:

- If detectors are only installed for certain relationships (normally those with minor flows, i.e. accesses from the secondary street/streets and dedicated left turns from the main street, if they exist), the traffic lights can be called "semiactuated";
- If detectors exist for all traffic relations then they could be called “fully actuated”.

Actuated traffic signals (working in isolation or synchronized, see below) can solve the vast majority of traffic problems, and the use of adaptive traffic signals should only be considered if it is clearly demonstrated that the related problems cannot be solved by "classical" actuated traffic signals.

On the other side, their level of complexity can also be classified according to whether or not the length of the traffic light phases is adjusted:

- If detection is used only to serve or not to serve certain phases (e.g. if the traffic light runs a dedicated green phase on one of the side streets only on detection of vehicles on that street, but the duration of the green phase is always the same) then these are "timed traffic lights with certain phases activated". In these cases the traffic light gives priority to the main phases (forward directions on the main street), which do not benefit from detectors, and the secondary phases are only served if there are vehicles ”"requesting” (with the help of detectors) these relationships;
- If the detection is also used to determine the length of the traffic signal phases, then these are "variable timed traffic signals".

Adaptive traffic lights. They use data received from detectors (whose optimal positioning and proper operation is absolutely critical in this case), some of them positioned upstream (away) from the intersection, to adjust within much wider limits (compared to actuated traffic signals) the traffic signal variables and even parameters, being able to better respond to even longer term changes in traffic demand. Adaptive traffic signals require more sensors (positioned in different locations and on different traffic lanes), much more careful calibration, both at the installation of the traffic light system and over time, during their operation. The maintenance effort is also significantly higher. Metaphorically speaking, investing in an adaptive traffic light system without ensuring its subsequent maintenance and calibration is like investing in a luxury car and then driving it on forest roads without ever changing the engine oil.

4.2 Classification of traffic lights by interaction with other traffic lights

Looking at the interaction with traffic light controllers at other intersections (i.e. other traffic light locations), we can talk about:

Isolated traffic lights that operate independently of other traffic lights;

Synchronized traffic lights, where there is a temporal dependency relationship, conditionality, between the phases run by different neighboring traffic lights. Synchronized traffic signals allow priority (fewer stops and delays) to be given to traffic flows that are considered to be of higher priority (and therefore with higher traffic volumes) for which a 'green light' facility is provided, generally to the detriment of the efficiency of secondary flows, but overall the ”common good” (or overall utility) is greater in the synchronized version.

5. Calculation principles and notions of traffic lights at road or street intersections

To better understand how an electric traffic light works, let's assume a three phase traffic light cycle, represented as a circular dial divided into full lengths equivalent to the green times of each phase and a dot, the escape times (Fig 12).

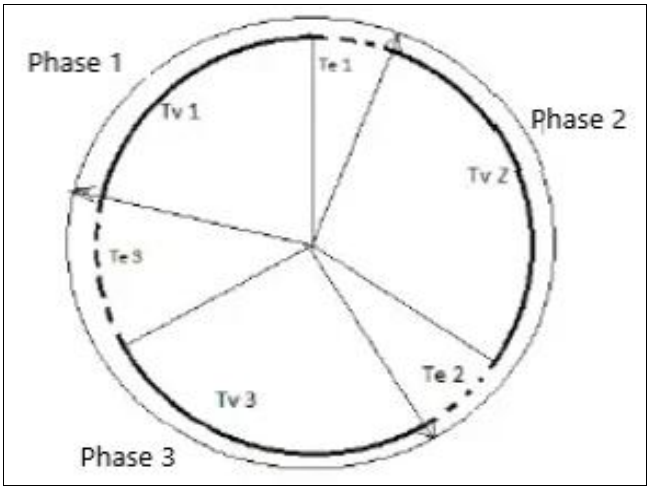

Fig 12: The cycle and phases of an electric traffic light [2, p. 10]

The value of each phase in this case becomes:

$$F1 = Tv1 + Te1; \quad (1)$$

$$F2 = Tv2 + Te2; \quad (2)$$

$$F3 = Tv3 + Te3. \quad (3)$$

The value of the traffic light calculation becomes:

$$C = F1 + F2 + F3 \quad (4)$$

Green times are active times, which favor traffic capacity, and evacuation times are inactive times, which ensure road safety. For this reason, particular attention will be paid to the calculation of evacuation times. This aspect must be taken into account because their value in the program of electric traffic lights does not instinctively mean an increase in safety, as is observed at the vast majority of intersections controlled by electric traffic lights.

On some directions, at pedestrian crossings, the color red sometimes appears including all directions of flow unnecessarily. Pedestrians notice the anomaly and do not obey the red color indication either when they should or when they should not [2, p. 10].

That's why frequent road accidents involving pedestrians happen.

5.1 Methods for determining the cycle and phases of electric traffic signals

In everyday reality, electric traffic light programs (cycles and phases) are designed in two ways:

1. Write a traffic light schedule based on the cycle value (e.g. ***C*** = *60 seconds*), then calculate the traffic light phases;
2. Realizing the phases of the electric traffic lights and then defining the value of cycle ***C*** by summing.

In these cases, the determination of cycles and phases do not comply with the design conditions when real-time traffic signal equipment is used, i.e. when traffic detectors are also present in the system.

For the first method of determining the cycles and phases of an electric traffic signal, the following are some values recommended by the specialist in this field, J. Wilhem Korte, in Grundlagen der strassen vekehrs planung in stadt und land - Germany, which states [7]:

(A) Unanimously, the cycle value cannot decrease below 35 seconds and cannot increase above 120 seconds, thus:

- ✓ At simple intersections with 3-4 access arms:
  - Minimum 35 seconds at two phases/ traffic light cycle;
  - Minimum 45 seconds at 3-4 phases/ traffic light cycle;
  - Normal 45-60 seconds/ traffic light cycle;
  - Maximum 80 seconds/ traffic light cycle.
- ✓ At intersections with more than 4 access arms:
  - Normal 70-90 seconds/ traffic light cycle;
  - Maximum 120 seconds/ traffic light cycle.

The value of a predefined traffic light cycle is divided into traffic light phases and is directly proportional to the value of the flows and inversely proportional to the number of lanes of the roadway, using mathematical relationships:

$$\frac{F1}{F2} = \frac{\frac{M1}{M2} \cdot b2}{b2} \quad (5)$$

$$F1 + F2 = C \quad (6)$$

And for the multi-phase traffic light cycle the calculation is done with the mathematical relation:

$$\frac{F1}{C} = \frac{\frac{M1}{b1} \cdot 1}{\frac{M1}{b1} + \frac{M2}{b2} + \cdots \frac{Mn}{bn}} \quad (7)$$

$$C = F1 + F2 + \ldots Fn \quad (8)$$

Where,

C is the chosen traffic light cycle time (seconds);
F1, F2, Fn – phase time 1, 2, n (seconds);
M1, M2, Mn – values of flows entering the intersection/phase (vehicles/hour);
b – number of carriageway lanes/phase.

(B) Methods of exact calculation of the traffic light cycle, using different mathematical relations according to *"Traffic engineering"* [8], the general mathematical relation by which the semaphoric cycle ***C***, becomes:

$$C = \frac{3{,}600 * Kx}{3{,}600 * fx * DKx} \quad (9)$$

Where,

C is the traffic light cycle time (seconds)
Kx = 4,75 - delay factor;
fx - the highest flows and lanes converging at the intersection (vehicles/hour);
DKx - the time between two vehicles.

After Greenshuelds ***DKx*** = *2,1 seconds* between the fifth and the following vehicles.

For *DKx = 2,1 seconds* the mathematical relation (9) becomes:

For two-phase electric traffic signals, $C = \frac{34,200}{3,600-(M1+M2)*2.1}$ (10)

For three-phase electric traffic lights, $C = \frac{51,300}{3,600-(M1+M2+M3)*2.1}$ (11)

For four-phase electric traffic lights, $C = \frac{68,400}{3,600-(M1+M2+M3+M4)*2.1}$ (12)

5.2 Saturation rate in the movement of vehicles in the signalized intersection

The saturation rate in the movement of vehicles in the signalized intersection can be analyzed by means of the graph in Fig 13. Analysis of the data presented in Fig 13 shows that the *x* axis of the graph represents the number of vehicles at the intersection and the *y* axis is represented by the time divided by the successive colors of the electric traffic light (red, yellow and green). It can be seen that the green color is usually not fully exploited by drivers, and the interpretation of the graph is as follows: between the dead time represented by the red color and the useful time represented by the green color is the curve rise (green color), generated by the flow of road vehicles.

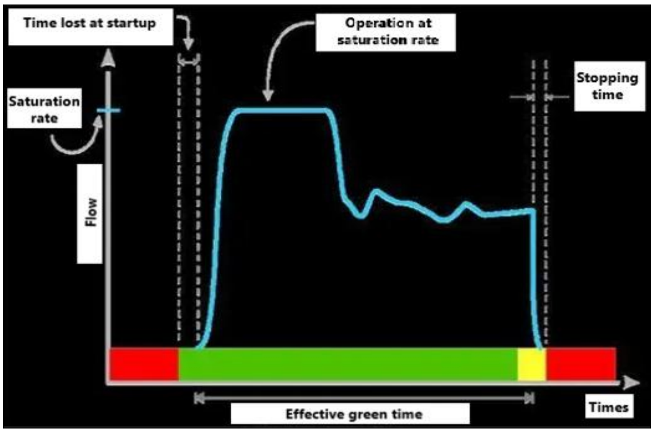

Fig 13: Times at traffic lights [2, p. 13]

The intersection saturation time (the saturation rate on the green color of the electric traffic light) occurs approximately a few seconds after the green color of the electric traffic light and lasts for 45% of the green duration, representing the interval when the green color is most effective. The curve then becomes downward, this is defined by vehicles in the far positions when crossing the intersection. The curve is downward until it reaches zero, with peaks defined by vehicles crossing the intersection at the speed limit, and at the end of the curve there are steep decreases in vehicle flow, defined by the stopping time generated by the appearance of the yellow (transition colour), until the red of the electric traffic light.

The actual useful time for running vehicles at the traffic light intersection can be calculated by the mathematical relationship:

$$v = V + G + R - (tP + tO) \quad (13)$$

Where,

v is the actual green time;
V – during the initial green color;
G – during the initial yellow color;
R – during the initial red color;
tP - time lost when leaving the scene;
tO - stop time (when the yellow color appears).

Intersection capacity is defined by two elements:

a) the maximum number of road vehicles that can pass through a given point in a given time interval (usually one hour) under certain conditions (knowing the saturation rate of the signalized intersection);
b) the length of time during which road vehicles can enter the intersection, defined by the mathematical relationship:

$$C = s * \frac{v}{dC} \quad (14)$$

Where,

C is the capacity of the intersection;
s – aturation/hour;
v – effective green color (s)
dC – the duration of the electric traffic light cycle.

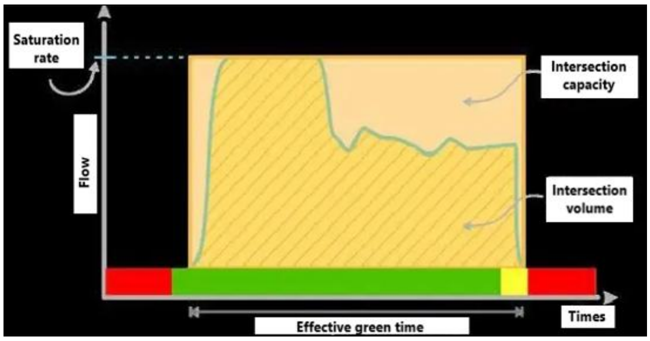

Fig 14: Intersection dimensions [2, p. 15]

Fig 14 shows the size of an intersection. Analysis of the data shown in Fig 14 shows that the hatched area represents the volume of the intersection and the unhatched area represents the capacity of the intersection. The notion *of minimum green (minimum green)* for the flow of road vehicles is represented by the interval during which the green color of the electric traffic light stays on. Drivers' expectations regarding the notion of minimum green are to travel through the intersection within the time corresponding to the green color of the electric traffic light, so that it lasts as long as possible, and to avoid being blocked in the middle of the intersection by an electric traffic light that quickly changes green color, successively changing to yellow, then to red.

The length of the green minimum may also be based on the length of the green signal time or pedestrian time in the absence of pedestrian crossing (zebra) buttons/pedestrian controls. Too long a minimum green signal may lead to too much time wasted at the intersection, and too short a signal may lead to driver expectation or pedestrian safety violations [2, p. 15].

The green minimum for vehicles is defined and depends on the actual programming of the electric traffic lights. Some scheduling applications rationalize the green time for road vehicles to 15 seconds or more.

The pedestrian flow green minimum shall meet the requirements of pedestrians crossing the street in phases not associated with the push of an electric traffic signal control button (where the traffic signal is associated with such a control).

The mathematical relationship can be used to determine this type of crossing:

$$vP = tSP + t0 \quad (15)$$

Where,

Vp is the green color of the electric pedestrian traffic light (the minimum duration of green needed to meet the pedestrian's need to cross the road);

tSP – the time (duration) of the traffic light;

t0 - wasted time (time spent unnecessarily), in engaging in and completing the pedestrian crossing.

The maximum green is the maximum duration of the green traffic light signal when there is a need for vehicles to pass and pedestrians to pass. Maximum green is used to limit the delay of any other movement in the intersection and to keep the cycle time at a maximum interval. Maximum green also prevents too long a green signal due to continuous need (demand) for green or faulty detectors. If the green signal is too long, it will result in loss of time in the intersection, and if maximum green is too short, it will result in a number of vehicles not being able to take advantage of the green color to run (phase inappropriate to traffic demand).

Yellow and red color of electric traffic lights. The interval duration for the yellow color is based on the driver's perception-reaction time plus the distance required to safely stop the vehicle at an intersection. This duration may also differ from country to country depending on the permissive yellow or restrictive yellow factor. The yellow permissive factor refers to a road traffic law that allows motor vehicles to proceed as when the traffic light is green. Restrictive yellow factor refers to a road traffic law which prohibits the operation of motor vehicles during the yellow traffic light display, with the same prohibition as for the red traffic light.

The red color of the electric traffic signal is the color that prohibits vehicle travel, and most often corresponds to the green displayed at the pedestrian electric traffic signal or the green-yellow color for other directions of travel. The prohibitive red color prevents the intersection of vehicle travel directions [2, p. 16].

5.3 Simple progressive system (green wave)

An increasingly common method of interconnecting electric traffic signals is to use a common cycle time (a complete series of stages in which all traffic maneuvers and actions are completed in turn, the traffic signal cycle time being the sum of all stages) for all intersections and traffic signals. These installations for command and control of road vehicle traffic are synchronized in such a way that the periods of departure from the electric traffic lights are in relation to each other, but in accordance with the legal speed of traffic on the road or street in question (if the legal speed is respected and the distance between the traffic-light intersections is not covered at a speed below the legal limit, vehicles may cross the other intersections on the route on the green light of the electric traffic lights).

This results in a development of green periods all along the roads or streets in both directions. If exceeding the legal speed of road vehicles on that section of road or street was a habit of drivers before this coordination was achieved, then the measured speed becomes dangerous for safe travel. For this reason a regulated, moderate speed should be used to ensure the safe movement of columns of road vehicles and to catch the green traffic light for a succession of traffic lights installed at successive intersections.

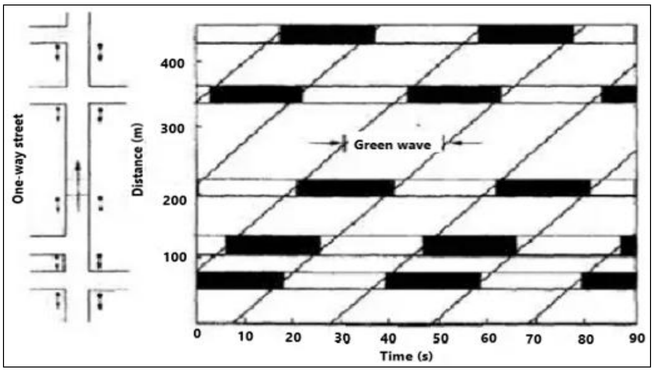

Fig 15: Coordination of electric traffic light signals on a one-way street

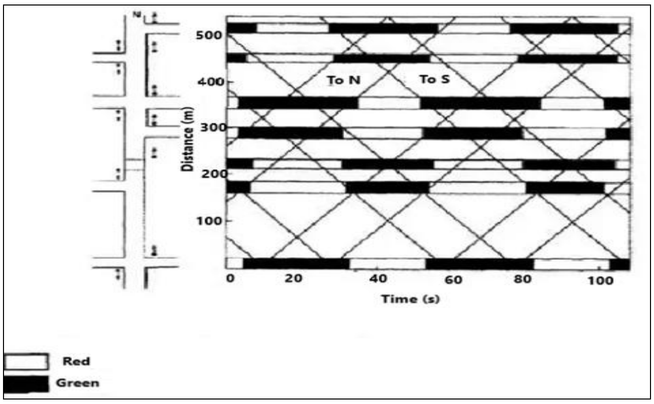

Fig 16: Coordination of electric traffic light signals on a two-way street

In the diagrams in Figures 15 and 16 we show the electric traffic light times for a simple progressive system. Analysis of the data presented in the two figures shows that the distances between intersections along the road are plotted on the abscissa (*y* axis) and the travel times are presented on the ordinate (*x* axis). The slanted lines in the graphs represent the travel speeds of road vehicles chosen for the progression and the stages of view at successive intersections. Normally the problem is one of determining, by trial and error, the optimum speed for a given cycle type.

For the one way road, the green lanes follow each other in sequence.

The driver, thus passing through an intersection, will have (will catch) the green color of the electric traffic lights of the cascading intersections.

If the street or road is two-way, and the intersections are not equally spaced, complex situations arise and compromises are necessary for the progress of the two directions. For this reason, it is also necessary to take into account the flows of vehicles accessing the main artery from the side, which would influence the constant legal speed of the flow of vehicles on the main road (the road on which the progressive system - green light - is applied).

The distance - time diagram method can be used to favor a particular direction (e.g. favoring the morning peak traffic in one direction at the cost of increasing the delay of some vehicles traveling in the opposite direction). This situation can be reversed for the evening peak. The cycle time for a coordinated traffic signal system is usually set by signaling major intersections (e.g. the intersection with the highest traffic flow). In this way, the additional green time that becomes available can be dedicated to freeing up the traffic of road vehicles entering the main road from secondary roads. This way the platoon of road vehicles crossing the intersection is not delayed.

5.4 Calculating the traffic capacity of intersections of roads or streets equipped with electric traffic lights

Today, as road traffic has become more and more intense and congested, traffic lights at intersections have been used for safety reasons. Depending on the required traffic capacity of the road or street intersections, it is necessary to determine the sequences and durations of the various signals emitted by the traffic lights in order to take over and clear the flows of vehicles or pedestrians which have become incidental, in conditions of safety and minimum crossing time.

The following shall be taken into account when calculating the through capacity of road vehicles through intersections [2]:

- ✓ The traffic light times or sequences corresponding to green ***tv*** time, yellow ***tg*** time and red ***tr*** time;
- ✓ Phase of traffic lights, in which the movement of the incident streams of vehicles having simultaneous priority takes place and includes the green tv admission time, set for the direction of travel that is most heavily used, and the time for the clearance of the intersection by the entering traffic participants (intermediate time or interverde ***ti***). This time elapses between the end of the green time on one phase and the start of the green time on the next phase, which must be at least equal to the yellow time after green ***tgv***. For this purpose, road traffic routing systems with two traffic light phases as in Fig 17, with three traffic light phases as in Fig 18 and with four traffic light phases as in Fig 19 can be developed;

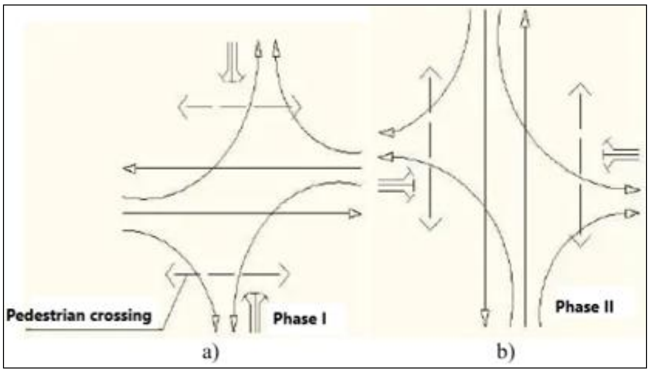

Fig 17: Road vehicle traffic routing systems with two traffic light phases [2, p. 30]

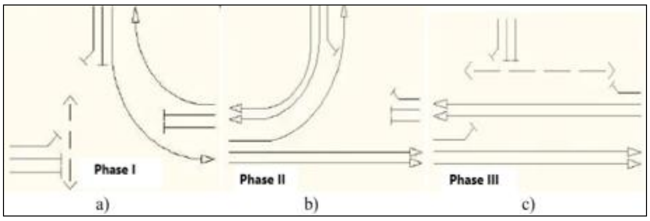

Fig 18: Road vehicle traffic routing systems with three traffic light phases [2, p. 30]

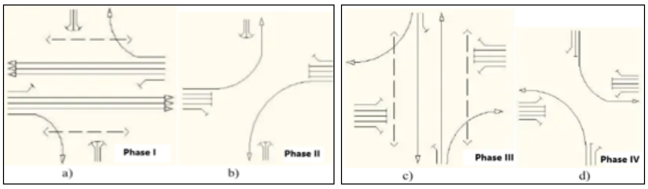

Fig 19: Road vehicle traffic routing systems with four traffic light phases [2, p. 31]

- ✓ The traffic signal cycle, which contains an absolute sequence of light signal replacement at all traffic signals in the intersection, i.e. the traffic signal phases;
- ✓ The traffic light operating schedule, which graphically represents the sequence and duration of the traffic light phases and the sequences for all traffic lights.

The number of standard vehicles formulates the capacity of a road lane. They can cross a road intersection on the green color of an electric traffic light, which is defined by the green time ***Qv***, or during one physical hour ***Q***.

Between the hour capacities ***Qv*** and ***Q*** there is the mathematical relationship:

$$Q = Qv\frac{tv}{TC} \tag{16}$$

Where,

t_v is the green time;

T_c – he duration of a traffic light cycle.

Vehicles arriving at a signalized intersection require a variable input to the intersection and are expressed by an instantaneous peak factor ***Fvi***, which can be determined by the mathematical relation:

$$Fvi = \frac{Number\ of\ vehicles\ arriving\ during\ peak\ hour}{4\ x\ Maximum\ number\ of\ vehicles\ arriving\ in\ 15\ minutes} \tag{17}$$

Fvi = 0,25.....1.

It is considered:

- *Fvi* = 0,25 for concentrated flows in 15 minutes;
- F_{vi} = 1 or uniform arrival flows.

A balanced distribution of road vehicle traffic on the network becomes balanced when ***Fvi*** *≥ 0.5*. If this condition is not met, an optimization of the organization of road traffic on the network is necessary.

The degree of saturation Gs of an entrance to a signalized intersection formulates the traffic flow of road vehicles. The access of vehicles to the intersection becomes saturated when they wait at the traffic light for more than one traffic light cycle, after which they are allowed to enter.

The degree of saturation is determined with the mathematical relationship:

$$Gs = \frac{Number\ of\ saturated\ green\ phases\ at\ peak\ hour}{Total\ number\ of\ green\ phases\ at\ peak\ hour} \tag{18}$$

G_s = 0.....1.

For signalized intersections with ***Gs*** = *0,3.....1* the flow is poor. For this reason, it is necessary to redesign the intersection with the provision of a new equipment with command and control installations for the movement of road vehicles, or a reorganization of traffic on the network. The time taken for a road vehicle to cross the intersection is an effective quality indicator for the solution chosen at the intersection.

Specific traffic lights and relationships for a road or street intersection

The duration of a traffic signal cycle for a road or street intersection is, in principle, within the following thresholds:

- ✓ In a two-phase traffic light system, the minimum duration is 35 seconds, the current one is 45 - 65 seconds and the maximum is 80 seconds;
- ✓ In a three- or four-phase traffic light system, the minimum duration is 40 seconds, the current duration is 70 - 80 seconds and the maximum duration is 90 seconds.

Note that the maximum duration of a traffic signal cycle must not exceed 120 seconds. Above this value the junction becomes effective.

The green time should not be less than 10 seconds. The yellow time following the green time ***tgv*** and the yellow time following the red time ***tgr*** shall be determined in accordance with the requirements of the Romanian standard STAS 1848/4-86.

The green time (the free entry time of road vehicles in the traffic-light signaled intersection) will be established for the entrances and lanes heavily used during peak hours for each traffic light phase, by means of the mathematical relationship:

$$t_v = a + (n - 1) * e \quad [s] \qquad (19)$$

Where,

a is the drivers' perception-reaction time, which also includes the time of entry of the first vehicle at the signalized intersection (seconds);

n – the number of vehicles that must enter the signalized intersection during the green signal;

e – he start sequence interval (seconds).

Note: for light vehicles (cars) can be taken: *a = 6 seconds* and *e = 2,5 seconds;*

For heavy vehicles (load over 15 kN), including trams (motor wagon and a trailer) can be taken: *a = 6 seconds* and *e = 4,5 seconds.*

If the flow of road vehicles becomes intense enough, the sequence interval can be reduced up to 2.1 seconds for light vehicles and up to 4 seconds for heavy vehicles.

The free entry period for pedestrian traffic ***tvp*** can be determined by the mathematical relationship:

$$tvp = \frac{P}{b * k} \quad [s] \qquad (20)$$

Where,

P is the number of pedestrians collected at the crossing during the crossing delay;

b – number of pedestrian lanes for one-way traffic, 0.75 m wide;

k - pedestrian crossing capacity per lane (number of pedestrians crossing/second).

The period of free pedestrian passage ***tvp*** should be correlated with the corresponding vehicle time.

Where appropriate, consideration should be given to the number of lanes to be reconfigured.

The release period of the signalized intersection (intermediate or inter-greening time) ***ti*** results from the collision avoidance condition at the conflict points when the traffic light phases are exchanged. The calculation to be made shall take into account the last vehicle entering the traffic-light intersection, which is assumed to travel in the forward direction up to the first conflict point at 5,5 m/s (20 km/h) and the first opposing vehicle in the following phase moving towards the same conflict point at 16,7 m/s (60 km/h).

The evacuation period of ***ti*** vehicles can be determined by the mathematical relationship:

$$ti = \frac{d1-C}{5.5} - \frac{d6-C}{16.7} \quad [s] \qquad (21)$$

Where,

d_{1-C} și d_{6-C} are the distances between the points ***1*** and ***C*** (metri);

The evacuation period mainly ensures that the traffic light intersection is clear of vehicles that have been waiting for oncoming traffic to clear the intersection and then turn left [2, p. 34].

For this reason, the corresponding time for performing the maneuver specified above is composed of the time for starting the stationary vehicles in the central area of the intersection and the time for evacuating the flow of road vehicles to the left, as follows:

$$ti = ns * e + \sqrt{\frac{2d}{w}} \quad [s] \qquad (22)$$

Where,

n_s is the number of road vehicles turning left;

e – he start sequence interval (seconds);

d – left evacuation distance (meters), (***d*** *= dv/2);*

w – acceleration when starting (m/s^2).

Prescriptions for the traffic light program

The design of the traffic light program should be taken into account:

- ✓ Specific vehicle traffic characteristics;
- ✓ Intersection design;
- ✓ Traffic light installation.

The traffic light system consists of:

- ✓ Routing computers;
- ✓ Traffic lights;
- ✓ Traffic sensors;

Cable Network.

System can function [2, p. 35]:

- ✓ With a fixed program;
- ✓ With a variable program, set according to the number of road vehicles recorded by traffic sensors or according to the number of pedestrians.

The initial calculation of the traffic light schedules for unanalized intersections distributes the cycle time ***Tc*** over the green times of the traffic light phases, directly proportional to the intensity of the flows and inversely proportional to the width of the roadway [2, p. 35].

For an intersection between two streets or roads with traffic lights in a two-phase system, the mathematical relationship can be applied for the calculation:

$$\frac{tv1}{tv2} = \frac{N1}{N2} * \frac{B2}{B1}; \quad t_{v1} + t_{v2} = T_c - (t_{i1} + t_{i2}) \tag{23}$$

Where,

t_{v1} and t_{v2} are the green times of phases 1 and 2;

N_1 and N_2 – peak hour incident flux intensities corresponding to phases 1 and 2;

B_1 and B_2 – the widths of the carriageway of the accesses, corresponding to phases 1 and 2;

t_{i1} and t_{i2} - the intermediate times of phases 1 and 2.

Detailed calculation of the cycle time ***Tc*** can be done with mathematical relations:

$$T_c = \sum_{f=1}^{F} t_{vf} + \sum_{f=1}^{F} t_{if} [s] \tag{24}$$

$$T_c = \frac{\sum_{f=1}^{F} t_{gvf} + \sum_{f=1}^{F} R_f}{1 - \frac{e}{3600} \cdot \sum_{f=1}^{F} N_{if}} \tag{25}$$

Where,

F is the number of traffic light phases;

t_{vf} green time in seconds corresponding to the phase f;

t_{if} intermediate time, in seconds, corresponding to the phase f;

t_{gvf} yellow time after green, in seconds, corresponding to the phase f;

t_{if} intermediate time, in seconds, corresponding to the phase f;

R_f additional time in seconds corresponding to the phase f, which is determined with the mathematical relation:

$$R_f = t_{if} - t_{gvf} \quad [s] \tag{26}$$

N_{if} the peak hour road vehicle flow intensity on one lane in standard vehicles per hour corresponding to the phase f.

The duration of the traffic signal cycle thus determined shall be finalized only after checks have been carried out for all antagonistic and non-antagonistic traffic relations of vehicles and pedestrians, in the order of the unfolding of the currents according to the traffic signal phases [2, p. 36].

At intersections where pedestrian crossings are very congested, a ratio of pedestrians to road vehicles will be made and a traffic signal cycle time will be set according to the green time required by pedestrians. The duration of the traffic light cycle shall be kept within the limits specified above by taking the following measures [2, p. 36]:

- ✓ Increase the number of lanes to reduce the number of vehicles per lane and the green time (intersection avoidance);
- ✓ Reduction of the duration of the interval of succession on entering the intersection within the limits specified above;
- ✓ Merging the intermediate time for the different maneuvers for evacuation of the signalized intersection into the same duration;
- ✓ Restricting the space of the signalized intersection and the distances to be covered by vehicles;
- ✓ Fragmentation of pedestrian crossings with long lengths, while providing central refuges.

The sequence of operations required to draw up a traffic light program consists of [2, p. 36]:

- ✓ Analyzing initial data;
- ✓ Location of traffic lights;
- ✓ Setting points of conflict;
- ✓ Setting flow intensities on each traffic lane;
- ✓ Calculation of green and intermediary times;
- ✓ Determining the duration of the phases and the traffic light cycle;
- ✓ Calculation of the total crossing time and capacity reserve.

The traffic light program is concretized in a diagram, which will include all the phases with the color sequences and running times of all the traffic lights. Reducing the duration of a traffic light cycle can be achieved by a rigorous dimensioning and arrangement of the times that characterize it, by strictly interposing the intermediate times between the end of the green time of the current phase and the beginning of the green time of the following phase.

The calculations of the through capacity of the individualized signalized intersection with current traffic signals will be based on the dynamics of the traffic flow and can be applied to other traffic signal equipment with superior performance (moving from fixed program routing automata to automata directly operated by vehicles via traffic sensors, both for isolated intersections and for groups of coordinated intersections in linear systems, with axial green-wave, or in zonal subsurface systems with the support of a central dispatcher equipped with a process computer). The traffic light program and the intersection layout solution shall be finalized for the variant which ensures the maximum reduction of work volumes and time for the traffic light [2, pp. 36-37].

The number of direct lanes shall be at least equal to the number of lanes in the current lane when crossing intersections by road vehicles. As appropriate, on-road vehicle storage spaces and special avoidance lanes shall be provided. The storage areas will be sized according to the number of road vehicles stopped during the time of the red traffic light and their width will be determined in relation to the characteristics of the vehicles. The width of the storage areas shall not be designed and built to be less than three meters in the case of one lane of vehicles in a lane alignment.

6. Calculation of the minimum yellow time and the length of the dilemma zone at traffic lights on a single traffic phase. Case studies

- <u>**Case Study 1**</u>. ***Determination of the minimum duration of the yellow time for the case with known geometric characteristics of the intersection and known traffic parameters of the vehicle***

The direction of the flow of road vehicles at urban intersections in the event of high traffic volumes is achieved by means of electric traffic lights. According to STAS 1848-4 electric traffic lights have the following operating cycles:

- ✓ red-red-red/yellow-yellow-green-yellow;
- ✓ red-green-yellow.

The above mentioned standard and road traffic rules contain the following regulations: *when the yellow signal appears after the green signal and the vehicle is so close to the intersection that it cannot stop safely, it may enter the intersection and continue through it or stop inside it if it is equipped with interior parking and waiting areas. If the end of free access is signaled by flashing green, entering the intersection on the yellow light is prohibited* [3, 4].

When approaching a traffic light intersection, drivers are confronted with the situation when the green light changes to yellow and they have to choose between two options:
1. To continue driving and cross the intersection during the yellow light;
2. Braking to stop before entering the intersection at the stop line.
The area just before a junction where the driver has the choice between continuing or braking is called the ***"dilemma zone".***
It has been observed that there is a tendency for drivers who are surprised by the change from green to yellow to continue their journey by entering the intersection on the yellow light, which entails a high risk of road traffic accidents. To reduce this risk it is necessary to determine an appropriate time for the duration of the yellow sequence.

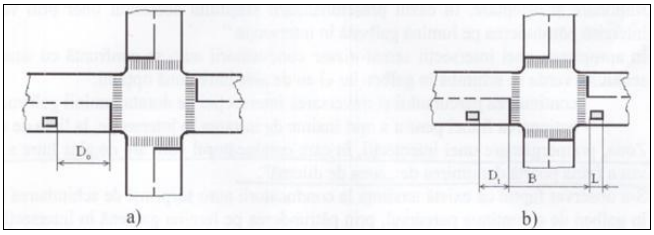

Fig 20: Position of the vehicle when the traffic light colors changes from green to yellow

Area of dilemma. To exemplify the dilemma area consider the following cases:
a) The motor vehicle traveling at speed v [m/s] is at distance ***D0*** from the STOP line of the intersection (Figure 20 a) when the electric traffic light changes from green to yellow. The driver decides to stop. In this case, the space required for braking will be:

$$Sf = v * tpr + \frac{v^2}{2af} \qquad (27)$$

Where,
S_f is the minimum space necessary for the vehicle to stop safely in front of the STOP line;
v - vehicle speed (m/s);
t_{pr} – driver perception - reaction time.

According to the Romanian standard SR 10144-6, the following values are considered for this time:
- t_{pr} = 4 seconds for vehicles up to 15 kN;
- t_{pr} = 4 seconds for heavy motor vehicles with a load exceeding 15 kN;

a_f - vehicle deceleration measured in m/s^2. According to the Romanian standard SR 10144-6, the following deceleration values are considered:
- a_f = 4 m/s^2 for motor vehicles up to 15 kN;
- af = 3 m/s^2 for heavy motor vehicles with a load exceeding 15 kN;

b) The vehicle traveling at speed v [m/s] is at a distance ***Dt*** from the STOP line of the intersection (Figure 20b), when the electric traffic light changes from green to yellow. The driver decides to continue. In this case the space to be traveled during the yellow time will be:

$$v = \tau_g = D_t + B + L \text{ sau } D_t = v * \tau_g - B + L \qquad (28)$$

Where,
v is the vehicle speed (m/s);
τ_g - the duration of the yellow time of the electric traffic light;
D_t – the distance from the vehicle to the STOP line when the signal changes from green to yellow;
B – intersection width (meters);
L – vehicle length (meters).

By comparing the value of the distances ***D0*** and ***Dt***, it can be determined whether a vehicle can or cannot safely pass through the intersection during the yellow time.

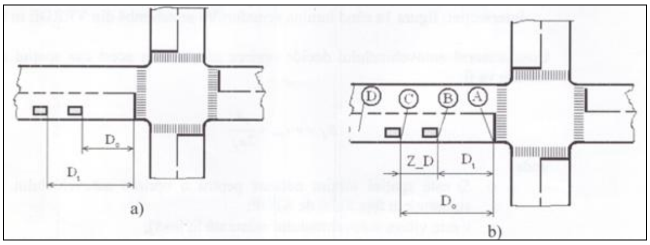

Fig 21: The dilemma area

In this sense, we meet the situations shown in Fig 21.
If ***Dt*** > ***D0***, Figure 21a, the driver may brake or run without braking to clear the intersection. In this case, the position of the vehicle when the yellow light is illuminated is irrelevant.
If ***Dt*** < ***D0***, Figure 21b, the driver has the following situations:este poziționat în intervalul *AB*, în acest caz poate să degajeze intersecția, dar nu poate să frâneze;
a) is positioned in the ***BC*** range, in which case it cannot clear the intersection and cannot brake;
b) is positioned in the ***CD*** range, in this case it can brake but cannot clear the intersection.

The range of ***BC*** in which the driver can neither brake nor safely clear the yaw is called the ***area of dilemma*** (***ZD***), (Figure 21b).
Minimum duration of yellow time. The length of the dilemma zone may be eliminated if the organization of the vehicular traffic through the signalized intersection meets the condition:

$$ZD = D_t - D_0 \rightarrow 0 \qquad (29)$$

We will have:

$$v * \tau_g - (B + L) - (v * t_{pr} + \frac{v^2}{2af}) = 0 \qquad (30)$$

Which gives the minimum time duration for the yellow color:

$$\tau_g = t_{pr} + \frac{v}{2af} + \frac{(B+L)}{v} \quad [\text{s}] \qquad (31)$$

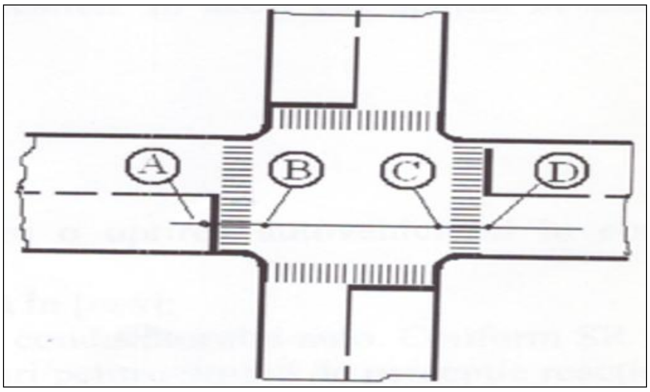

Fig 22: Intersection area

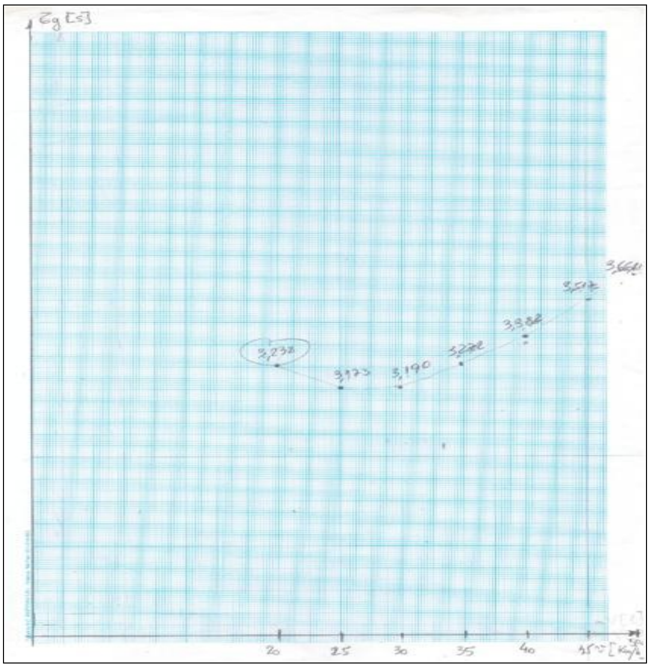

Fig 23: Yellow signal duration evaluation graph τg [seconds]

Research directions:

- Determination the minimum yellow time for an intersection whose geometric characteristics are shown in Fig 22;
- Determination of the minimum yellow time for different values of the intersection approach speed of vehicles. With the determined values, the graph (Fig 23) of the variation of the yellow time as a function of the variation of the approach speed of the motor vehicle approaching the intersection will be plotted and presented.

Initial data. Known:

- Dimensions of the intersection:

$$AB - CD = 1{,}8 + 0{,}1 * n \text{ [m]}; BC = 7 \text{ [m]}; \quad (32)$$

Where,
n is the order number (in our case $n = 18$); *n* is variable and can take any other value.
The result:

$$AB - CD = 1{,}8 + 0{,}1 * 18 = 3.6 \text{ m}. \quad (33)$$

- Length of vehicle is:
$$L = 4 + 0.2 * n \text{ [m]}; \quad (34)$$

The result:

$$L = 4 + 0.2 * 18 = 7.6 \text{ m}. \quad (35)$$

- The braking deceleration of the vehicle is:

$$a_f = 2.4 + 0.05 * n \text{ [m/s}^2\text{]}; \quad (36)$$

The result:

$$a_f = 2.4 + 0.05 * 18 = 3.3 \; m/s^2 \quad (37)$$

- The intersection approach speed of vehicles is:
$$v = 20.....60 \text{ [km/h]}; \quad (38)$$

- The driver's perception - reaction time is:

$$t_{pr} = 1 \text{ [s]}$$

Results obtained

In Table 1 we show the distance/time ratio for the speed range [20.....60 km/h], with equal jumps every 5 kilometers.

Table 1: Distance/time ratio for the speed range [20.....60 km/h]

Speed	Speed value [km/h]	Vehicle distance traveled in relation to speed [m/s]
v_1	20	5.55
v_2	25	6.94
v_3	30	8.33
v_4	35	9.72
v_5	40	11.11
v_6	45	12.50
v_7	50	13.88
v_8	55	15.27
v_9	60	16.66

In this case we have: $AB = 3.6$ m; $BC = 7$ m; $CD = 3.6$ m; $L = 7.6$ m.
It follows from this:

$$B = AB - BC + CD = 3.6 - 7 + 3.6 = 0.2 \; m \quad (39)$$

We apply the previous values in the mathematical relation (31) and obtain the results for the duration of the minimum time corresponding to the yellow color of the electric traffic light ($\tau g_{1...9}$), as follows:

$\tau_{g1} = 3.238$ s
$\tau_{g2} = 3.173$ s
$\tau_{g3} = 3.190$ s
$\tau_{g4} = 3.272$ s
$\tau_{g5} = 3.382$ s
$\tau_{g6} = 3.517$ s
$\tau_{g7} = 3.661$ s
$\tau_{g8} = 3.820$ s
$\tau_{g9} = 3.988$ s

Graphing on millimetric paper, (Fig 23). The plotting data of Fig 23 are presented in Table 2.

Table 2: Corresponding data plotted in Fig 23

Speed v [km/h]	Value τ_g [s]	Graphing on millimetric paper [mm]
$v_1 = 20$	$\tau_{g1} = 32.38$	80
$v_2 = 25$	$\tau_{g2} = 31.73$	100
$v_3 = 30$	$\tau_{g3} = 31.90$	120
$v_4 = 35$	$\tau_{g4} = 32.72$	140
$v_5 = 40$	$\tau_{g5} = 33.82$	160
$v_6 = 45$	$\tau_{g6} = 35.17$	180
$v_7 = 50$	$\tau_{g7} = 36.61$	200
$v_8 = 55$	$\tau_{g8} = 38.20$	220
$v_9 = 60$	$\tau_{g9} = 39.89$	240

Note: The following scale was used to make the diagram in Fig 23:

- for Ox axis: 1 mm = 0.25 [km/h];
- for Oy axis: 1 mm = 0.1 [s].

- **Case study 2.** ***Determining the minimum duration of the yellow time and the length of the <u>"dilemma zone"</u>***

Initial data: We known: limiting speed: $v_0 = 50\ km/h = 13.9\ m/s$; yellow signal duration: $\tau_g = 4.5\ s$; driver perception-reaction time: $\delta_2 = 1.5\ s$; comfort deceleration: $a_2 = 3m/s^2$; vehicle length: $L = 4.6\ m$; the width of the intersection: $l = 15.25\ m$.

Results obtained: The calculation of the critical distance for which the vehicle can stop safely (***Xc***) is done with the mathematical relationship:

$$Xc = v0 * \delta 2 + \frac{v0^2}{2a2} \quad (40)$$

Substitute the known data into the mathematical relationship (40) and we obtain:

$$Xc = 13.9 * 1.5 + \frac{13.9^2}{2*3} = 53.05\ m \quad (41)$$

The minimum duration of yellow time is calculated with the mathematical relationship:

$$\tau_{min} = \delta 2 + \frac{v0}{2af} + \frac{l+L}{v0} \quad [s] \quad (42)$$

We replace the initial data in the mathematical relationship (42) and obtain the minimum duration of the yellow time:

$$\tau_{min} = 1.5 + \frac{13.9}{2*3} + \frac{15.25 + 4.6}{13.9} = 5.25\ s \quad (43)$$

The length of the dilemma zone is calculated with the mathematical relationship:

$$L = x + l + L \quad (44)$$

Substitute the initial data into the mathematical relationship (44) and we get the length of the dilemma zone:

L = 53.05 + 15.25 + 4.6 = 72.9 m

Verification of the condition regarding the calculation of the critical distance for which the vehicle can stop safely:

$$X - v0\,\delta 2 \geq \frac{v0^2}{2a2} \Rightarrow X = 53.05 - 13.9 * 1.5 = 32.2\ m \geq \frac{13.9^2}{2*3} = 32.2\ m \quad (45)$$

Immediate conclusions: The duration of the yellow signal from the original data τg = 4.5 s, and the minimum duration of the yellow signal from the data calculated with relation (42) is τmin = 5.25 s. In this case, the driver cannot pass through the intersection in time ($\tau g < \tau min$). The driver complains about this. The critical distance for which the driver can stop safely ***Xc*** = 53.05 m and the length of the dilemma zone, ***L*** = 72.9 m. In this case the driver can stop safely because ***L*** > ***Xc***. The driver cannot complain about this.

- <u>**Case study 3.**</u> ***Determining the minimum duration of the yellow time and the length of the dilemma zone***

Initial data: We known: limiting speed: $v_0 = 50\ km/h = 13.9\ m/s$; yellow signal duration: $\tau_g = 4.5\ s$; driver perception - reaction time: $\delta_2 = 1.5\ s$; comfort deceleration: $a_2 = 3m/s^2$; vehicle length: $L = 4.6\ m$; lungimea vehiculului $l = 15.25\ m$.

Results obtained: The calculation of the critical distance for which the vehicle can stop safely (***Xc***) is done with the mathematical relation:

$$Xc = v0 * \delta 2 + \frac{v0^2}{2a2} \quad (46)$$

Substitute the known data into the mathematical relation (40) and we get:

$$Xc = 13.9 * 1.5 + \frac{13.9^2}{2*3} = 53.05\ m \quad (47)$$

We have:

$$X - v0 * \delta 2 \geq \frac{v0^2}{2a2} \quad (48)$$

From the mathematical relation (48) it follows that:

$$X = v_0 * \delta_2 = 13.9 * 1.5 = 20.85\ m \quad (49)$$

The mathematical calculation for the stopping procedure is:

$$\frac{v0^2}{2a2} = \frac{13.9^2}{2*3} = 32.2\ m \Rightarrow \text{stopping procedure} \quad (50)$$

20.85 m < 32.20 m, and the condition set by the mathematical relationship (48) <u>*IS NOT FULFILLED.*</u>

The minimum duration for the yellow sign has the same value:

$$\tau_{min} = \delta 2 + \frac{v0}{2a2} + \frac{l+L}{v0} = 1.5 + \frac{13.9}{2*3} + \frac{15.25+4.6}{13.9} = 5.238\ seconds \quad (51)$$

The length of the dilemma area is:

$$L = X_0 + l + L = 20{,}85 + 15.25 + 4.6 = 40.7\ m \quad (52)$$

Immediate conclusion: Drivers are complaining that they cannot cross the signalized intersection safely because the duration of the traffic light yellow signal was set incorrectly (τ_g = 4.50 s), and the calculation resulted in τ_{min} = 5.238 s. Drivers are complaining about this. The condition in the mathematical relation (48) is not fulfilled, because the length of the dilemma zone is shorter (40.7 m), than the critical distance for which the vehicle can stop comfortably (53.05 m). Deviation = given value - reference value.

7. Conclusions, Recommendations and Observations from the Authors

The scientific paper has achieved its purpose and objectives for which it was written.

From the gas-powered lamppost in London to today's complex networks of smart traffic lights, the traffic light has revolutionized urban mobility. Though often overlooked, these devices are witnesses to technological progress and symbols of order in a dynamic urban landscape.

It is not always more advantageous to operate in synchronized mode; for example, it is typical for corridors served in *"green light"* mode at peak hours to operate in isolated mode (traffic lights operate independently of each other) during off-peak hours.

An often common misconception is that synchronized traffic signals are only possible for fixed-time operation. In reality it is possible to design synchronized systems with a high degree of drive dependency, and they are much more efficient than synchronized systems with fictitious times. Synchronization is not necessarily just for general traffic; public transport operations (and even pedestrian or cyclist flows) can very well be synchronized, and this should be a basic objective for any city with real concerns for sustainable urban mobility.

By combining the variants described for the above two classes (interpretation of the local demand and the relation with neighboring controllers), we obtain the various possible traffic light modes. The vast majority of the Romanian operations are of the simplest kind (fixed time traffic light with isolated operation). At the opposite pole are adaptive operation models, which can be either isolated (e.g. MOVA, SPOT, etc.) or synchronized (at corridor or zone level), (e.g. SCATS, SCOOT, UTOPIA).

Designed by J.P. Knight, an engineer specializing in railroad signals, the first urban traffic light was an adaptation of the signals used on the railroad: structure: a metal pole about 7 meters high, on which a gas lantern was mounted; the colors: red for *"Stop"* and green for *"Go"*, manually controlled by a police officer at the base; safety: The light was bright enough to be visible at night.

Unfortunately, the system was not without risks: in 1869, a gas explosion seriously injured the policeman operating the traffic light and the device was temporarily abandoned.

Almost half a century after the London experiment, the traffic light has been reinvented. In 1914, the first electric traffic light was installed in Cleveland, Ohio, to regulate urban traffic: functionality: it used two colors (red and green) and was connected to a buzzer that announced changing lights; Automation: unlike the gas-powered version, it was powered by electricity, eliminating the risks associated with manual operation.

According to legend, in 1912 Officer Lester F. Wire was sent to a busy Salt Lake City intersection to direct traffic. At the time, the man was equipped with railroad-style plates to indicate which vehicle should pass first. It is said that, tired of hanging by his hands, policeman Lester F. Wire built a traffic signal made of plywood, painted yellow and perforated with holes on each side. He then painted it red and green and used a hand-operated switch to change the "lights" from red to green and tell drivers when it was time to enter the intersection. The invention, admittedly also manual, caught on quite well, and by 1917 Salt Lake City had six such intersections interconnected with the traffic lights invented by Lester F. Wire.

A smart traffic light has been installed in the Bavarian town of Essenbach, sparking excitement. Billed as the traffic light of the future, it promises a number of major benefits for road safety and traffic flow. Unlike traditional traffic lights, the smart traffic light prioritizes emergency vehicles: on detecting ambulances or firefighters, the traffic light will automatically stop traffic in all directions, allowing emergency vehicles to pass quickly, reports The Mayor. It also displays information dedicated to cyclists. Cyclists will receive clear information about the duration of their dedicated green phase. It has an anti-collision warning system to prevent collisions, as well as a smart assistant that will guide drivers around turns, optimizing traffic flow and reducing congestion. An intersection in Essenbach, a market town in the district of Landshut, administrative region of Lower Bavaria, state of Bavaria, Germany, was chosen as the pilot location due to its characteristics: the presence of a nearby fire station, allowing for testing the prioritization of emergency vehicles, a nearby bicycle path, ideal for testing cyclists' information, and good visibility on side streets. The cost of the smart traffic light is around €100,000.

A group of researchers in Austria have developed a new type of traffic light with an adaptive operating system designed to improve traffic flow. Once installed at intersections with pedestrian crossings, it could help traffic flow more smoothly by managing the timing of red and green phases more efficiently for road users. According to the Austrians, the new system is up to 4 seconds more efficient than the traditional push-button system. The operating system instantly scans a 9x3 meter area and can determine the presence of pedestrians intending to cross. At the same time, thanks to the permanent monitoring of the crossing, the system can adjust the timing of green and red phases for traffic participants. For example, if the intersection is to be crossed by a single pedestrian, the green phase for pedestrians will be shorter, and conversely, it can be extended if the intersection is to be crossed by a larger group of people or slower pedestrians. The new type of traffic light is still under development, but in the near future Austrian specialists plan to launch the first real tests in Vienna's city traffic.

The latest technology in road safety is smart traffic lights that turn red if drivers exceed the speed limit, detecting excessive vehicle speed. These systems are designed to increase road safety by automatically stopping vehicles that are driving too fast by changing the traffic light to red. In Romania, the Brașov City Municipality has expanded its smart traffic light pilot project, which aims to increase street safety for both pedestrians and drivers. Pedestrian crossings in the city have been equipped with radar detectors connected to traffic light systems for pedestrian crossings, according to a press release. If drivers exceed the legal speed limit, the traffic light switches to red for road traffic, thereby slowing down traffic and protecting pedestrians in the area. The installation of these systems does not affect the operation of pedestrian traffic lights. Pedestrians will continue to request a green light by pressing the button. Operation: Sensors integrated into traffic lights measure the speed of approaching vehicles. Action: If the speed exceeds the legal limit, the traffic light turns red to force the vehicle to stop. Aim: The measure aims to discourage speeding and prevent accidents, particularly in urban areas. So, if you exceed the speed limit, you will get a red light! This approach combines two functions—one for traffic control and one for pedestrian protection—without affecting the normal flow of traffic. The project is designed to prevent incidents, not penalize them, with authorities relying on road safety education and influencing driving behavior.

Stories about traffic lights unpublished:

- Evolution of colors: Yellow was only introduced in the 1920s to signal the transition from green to red to prevent accidents;
- Smart traffic lights: Many cities now use traffic lights equipped with sensors and algorithms that adjust the time it takes to change colors according to traffic flow;
- Traffic lights for the blind: The first audible traffic lights appeared in the 1980s, making cities more accessible.

Traffic lights in modern culture

- In Japan, *"green"* traffic lights have been referred to as *"blue"* in common parlance, due to a cultural ambiguity about colors.

A traffic light installed in Berlin is believed to be the oldest electric traffic light still in use, dating back to 1924.

The cases studies presented in this scientific paper can be successfully applied in the development and training of students in the specialization of transportation and traffic in the faculties of transportation and traffic engineering. Also these case studies can be part of the laboratory guidance of the road traffic and urban transport disciplines, or they can be used as practical applications in the seminars of the road transportation engineering training disciplines.

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