TRANSPORT PROBLEMS 2026 Volume 21 Issue 1
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2026.21.1.11

Keywords: road user behavior; signalized intersections, traffic management

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SOCIETAL ASSESSMENT OF DESIGN PARAMETERS AND SOLUTIONS FOR URBAN TRAFFIC SIGNAL SYSTEMS

Summary. Traffic-signal design standards differ worldwide, and Poland is no exception. The primary purpose of traffic signals is to enhance road-user safety by temporally separating conflicting traffic streams while accommodating pedestrians, cyclists, and vehicles on minor approaches. However, Polish practitioners often report operational inefficiencies and design inconsistencies. Therefore, this study evaluates traffic-control systems from the road-user perspective. A questionnaire survey of 844 respondents was used to obtain their opinions on signals currently in operation. The results show that drivers are generally willing to tolerate longer red phases than those assumed in Polish design guidelines, although this tolerance decreases with increasing driver age and experience. Respondents most often criticized (i) insufficient intersection capacity, (ii) pedestrian–vehicle conflicts, (iii) inadequate signal conspicuity, and (iv) the lack of countdown information. These findings clarify sources of public dissatisfaction with existing signal control and offer engineers user-centered guidance for revising design standards and operational strategies.

1. INTRODUCTION

Although many nations are signatories to the Vienna Convention on Road Traffic [1] and the Convention on Road Signs and Signals [2], road-user behavior still varies noticeably across countries. Regardless of how rigorously traffic engineers advocate for signal control, it remains difficult to persuade the average driver, pedestrian, or cyclist that traffic signals enhance network efficiency and safety; complaints about "excessive" delays and "unnecessary" stops are routine.

This raises a fundamental question: Does a given signal-control scheme effectively promote safe and efficient user behavior, or might it provoke responses that compromise safety? Excessive delays before the onset of green or a green interval that is too short can be problematic for pedestrians and motorists. Just as important is whether the adopted solution satisfies user expectations while fulfilling formal operational and safety standards. Accordingly, this study investigates road-users' opinions on signal-controlled traffic management.

Opinions about traffic signals are ubiquitous yet difficult to verify empirically because suitable data sets are rare. Traffic signals' prevalence does not absolve them from scientific scrutiny. Empirical studies consistently show that installing traffic signals improves safety at intersections [3, 4], chiefly by reducing angle collisions, although rear-end crashes tend to increase. When signals are coordinated, network performance improves, and minor-road delays drop [5, 6]. Signal priority likewise benefits public-transport patrons by shortening trip times and mitigating environmental impacts [7, 8].

Local crash statistics for signalized intersections (e.g., in Poland [9]) identify common crash types and causal factors, while international studies explore the issue more broadly [10, 11]. Driver behavior

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in the “dilemma zone” during the green-to-red transition has been examined extensively [12, 13], informing the reactive adjustment of yellow and all-red intervals. Other research using electroencephalography shows that drivers perceive signal colors differently [14].

A growing trend in signal research is the use of machine-learning-based video detection. Generative models have been used to find interactions among road users [15]. At railway level crossings, graphics processing unit-accelerated image processing and deep neural networks detect high-risk situations in real time [16], and enhanced versions of these systems archive potential conflicts for statistical and legal purposes [17]. Similar applications have been reported elsewhere [18]. Neural-network-based traffic-flow models have been proposed to classify current states and predict vulnerable-road-user trajectories [19]. Another study introduced an intelligent surveillance system that infers cyclists’ intentions at signalized intersections by tracking the front-wheel contact point at the curb line [20].

While the literature shows that behavior at signalized sites is diverse and professionally researched, empirical evidence on how users rate engineering solutions is still scarce. Explicit statements of driver, pedestrian, or cyclist expectations are particularly hard to find, as existing studies tend to focus on general traffic psychology and perception [21, 22]. Engineers, therefore, rely largely on average statistics without fully understanding individual decision-making processes.

Poland imposes no professional-certification requirement for designing or approving signal-control plans. Approval rests with the road authority responsible for the relevant public road class [23, 24]. Comprehensive technical guidelines for signal design and maintenance are likewise lacking. Designers must rely chiefly on the national regulations specifying technical conditions for signal heads and their application [25]. Since 2022, patterns and standards for road-infrastructure design (e.g., for intersections [26] or pedestrian crossings [27]) have begun to appear, but they do not address signal-control design.

2. METHODS

The present research employed a survey that was conducted remotely via a Microsoft Forms questionnaire. A total of 844 respondents participated; their socio-demographic composition is shown in Figure 1. The instrument was designed to capture user-defined critical performance outcomes of signal control (e.g., the maximum acceptable wait time for a green signal).

The questionnaire consisted of 20 items, which are presented in the appendix. Two open-ended questions invited participants to state “what irritates you most about signalized traffic,” first from the perspective of a motor-vehicle driver and then from that of a pedestrian or cyclist. Six items concerned prevailing traffic-flow conditions. For drivers, four questions addressed signal countdown timers and one addressed speed-advisory displays. For pedestrians/cyclists, one question focused on countdown timers and one on push-button detectors. The final four items captured basic respondent descriptors. Owing to the markedly male-skewed sample, detailed sex-based comparisons were not pursued. The dataset was collected to answer a single research question: Does the operational quality of signal-controlled traffic meet driver expectations?

Prior to analysis, the dataset was cleaned of incomplete or internally inconsistent responses and all variables were recorded for statistical processing. The initial descriptive analysis examined response distributions for key operational parameters in urban settings (e.g., maximum tolerable delay, queue length, number of signal cycles observed), and percentage distributions were plotted to reveal social tolerance thresholds.

Subsequently, relationships between questionnaire outcomes and respondent socio-demographics (age, years of license possession, settlement size) were explored with Spearman’s rank-order correlation, proper for ordinal data. To assess whether preferences for specific traffic-management features differed significantly across respondent strata, we conducted χ^2 tests of independence using contingency tables formed by age, sex, driving tenure, and settlement size.

The open-ended responses were analyzed separately using semantic-content analysis to identify recurring motifs and critical remarks about signal operation. This procedure highlighted the primary shortcomings perceived by road users, namely a lack of signal coordination, the misalignment of signal timings with actual demand, and deficiencies in visual information.

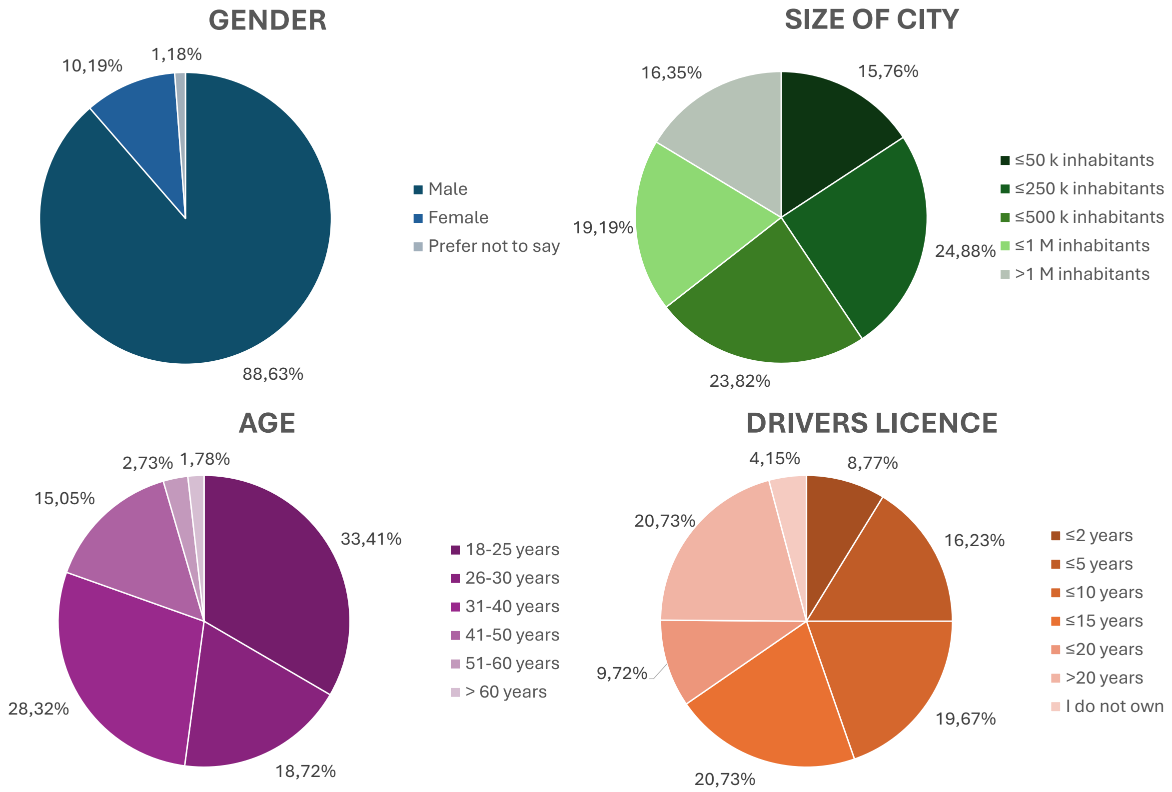

Fig. 1. Structure of people taking part in the survey

3. RESULTS

3.1. Drivers' opinions on operating conditions

Figure 2 summarizes the socially accepted threshold values for four key signal-performance indicators in an urban environment: delays (time losses), queue size (number of vehicles), queue reach (meters), and the number of signal cycles tolerated before service (lost green signal). The responses reveal a generally low tolerance for extended delay, irrespective of the metric considered. Because these parameters are functionally interdependent, they jointly determine intersection quality of service: longer delays usually coincide with larger queues, greater spatial spill-back, and the need to wait through multiple cycles. Therefore, the survey captures both individual tolerance limits and collective expectations regarding efficient signal control.

The first indicator examined was the maximum acceptable delay. Almost half of the respondents (45.5%) considered up to 100 s tolerable, while 30.7% set the limit at 50 s. Only 5.5% accepted delays exceeding 150 s, underscoring the low social tolerance for prolonged waits.

Regarding the number of lost signal cycles, 53.8% of drivers were willing to wait through at most two cycles (i.e., to be served on the "third green"), while 32.9% expected service within the first cycle. Thus, delays exceeding two cycles are perceived as inefficient and potentially frustrating.

For the queue length expressed in vehicles, 54.5% considered $\leq$ 20 vehicles acceptable, and another 33.6% accepted $\leq$ 40 vehicles. As such, exceeding the 20-vehicle threshold is interpreted as an unacceptable traffic condition. When queue length was expressed in meters, responses clustered around two limits: $\leq$ 100 m (40.6%) and $\leq$ 200 m (40.8%). The near-even split likely reflects local geometric and demand characteristics.

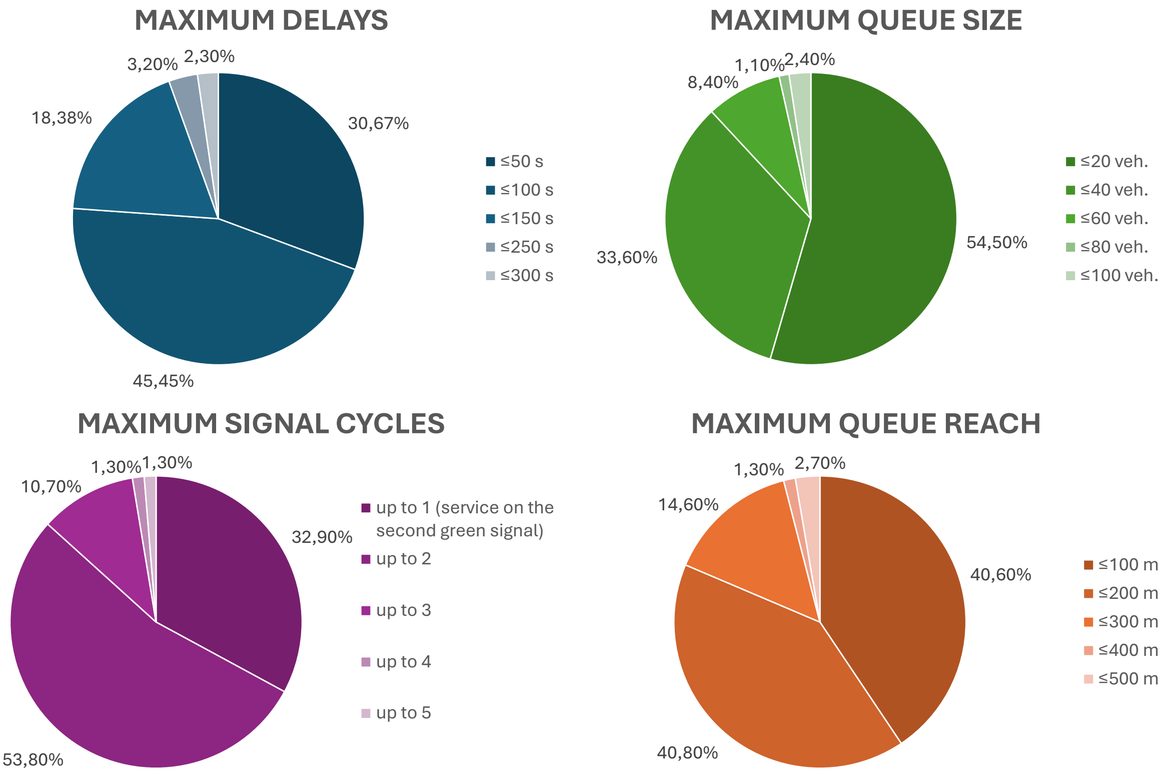

Fig. 2. Distribution of social acceptance of selected parameters of traffic conditions at traffic lights

Respondents were then asked which single parameter most strongly shapes their feelings about traffic conditions at signals. The dominant criterion was the number of cycles required to clear the intersection (48.1%), followed by overall time loss (34.8%). Queue size in vehicles (12.0%) and queue length in meters (5.1%) were much less influential. Hence, drivers' subjective evaluation focuses chiefly on cycle-based service efficiency and personal delays rather than external observations of queue formation.

To relate tolerance thresholds to user characteristics, we considered three independent variables: settlement size, driver age, and license-holding tenure (a proxy for driving experience). Spearman rank correlations (Table 1) revealed no significant association between any demographic variable and the maximum acceptable delay, suggesting a uniformly low tolerance across user groups.

In contrast, significant negative correlations were found between both age and driving experience and the accepted values for queue length (vehicles) and number of cycles, with the association being stronger for the latter. Older and more experienced drivers thus exhibit lower tolerance for waiting through multiple cycles or for long queues. A weaker yet significant negative correlation with both age and driving experience was also found for queue reach measured in meters.

Notably, settlement size had no statistically significant effect on any parameter. Whether respondents traveled in small towns (< 50,000 inhabitants) or large metropolitan areas (> 1 million inhabitants) had no discernible influence on their assessment of signal-control quality, showing a broadly shared feeling of acceptable traffic conditions.

Table 1
Relationship between demographic characteristics and limits of acceptability of traffic signal parameters (Spearman correlation coefficients)

No.	Description	City	Age	Driver's license
1.	Limit value of maximum acceptable delays at traffic signal approaches	0.027	-0.047	-0.063
2.	Limit value of maximum acceptable number of vehicles in queue at traffic signal approaches	0.033	-0.166**	-0.155**
3.	Limit value of maximum acceptable queuing range at traffic signal approaches	-0.020	-0.106**	-0.091**
4.	Limit value of maximum acceptable number of signaling cycles at traffic signal approaches	0.040	-0.220**	-0.202**
Note: **, * – correlations significant at $p < 0.01$, $p < 0.05$				

3.2. Traffic control preferences

Respondents were asked to choose between two alternative strategies for improving operations at signalized intersections: (i) longer green intervals delivered less frequently or (ii) shorter green intervals delivered more frequently within the hour. A clear majority (67.5%) favored the first strategy, indicating a preference for a higher likelihood of clearing the intersection within a single cycle at the cost of a longer wait for the next green.

Figure 3 shows how drivers rated countdown timers that display the residual duration of the red or green phase. The device enjoys strong public support, as 91.5% judged red-phase timers to be safe and 90.5% considered them beneficial for traffic flow. For green-phase timers, 86.7% perceived a positive effect on flow, and 83.8% regarded them as safe. Countdown displays, therefore, are widely accepted tools that enhance both traffic fluidity and predictability.

To assess whether these opinions varied across socio-demographic groups, we conducted χ^2 tests of independence (Table 2). In most cases, response distributions did not differ significantly, suggesting broadly consistent evaluations regardless of personal background. Significant heterogeneity emerged in three key areas:

- Preferred improvement strategy (long-versus short-green choice). Acceptance of the "long, infrequent green" increased with both age and driving experience, while less-experienced drivers tended to favor the "short, frequent green." This trend implies that seasoned or older drivers value uninterrupted progression and are willing to tolerate a longer cycle length to minimize the number of stops.
- Perceived usefulness of green-phase countdown timers. Opinions diverged by license-holding tenure, as less-experienced drivers expressed greater reliance on visual aids when deciding whether to proceed or prepare to stop.
- Effectiveness of speed-advisory displays. Significant differences surfaced by age and sex. Younger respondents and men were more likely to recognize their positive impact on flow efficiency, perhaps reflecting greater openness to appearing in-vehicle or roadside technologies.

Consistent with earlier findings (Section 3.1), settlement size exerted no statistically significant influence on any of the evaluated aspects. Thus, opinions on signal-control quality were remarkably uniform across urban contexts ranging from towns (< 50,000 inhabitants) to large metropolitan areas (> 1 million inhabitants).

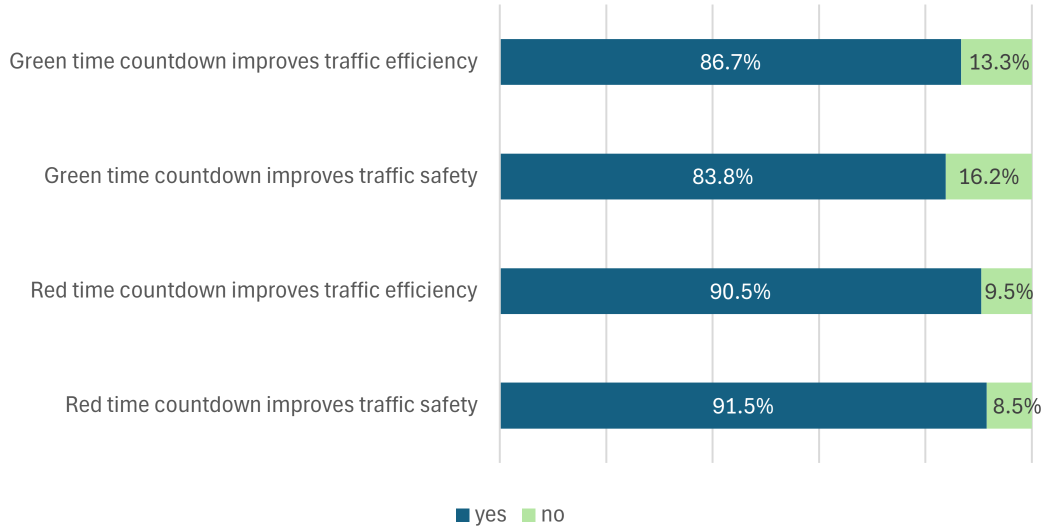

Fig. 3. Respondents' opinions on the use of time counters at traffic lights

Table 2

Variation of respondents' opinions according to metric variables (chi-square test)

No.	Description	City	Age	Driver's license
1.	Option to improve traffic conditions at traffic signals	3.367	16.238**	22.755***
2.	Improving traffic conditions by using red signal timing counters	2.116	4.986	12.071
3.	Safety of using red signal timers	5.192	2.891	9.924
4.	Improving traffic conditions by using green signal timing counters	1.018	5.237	15.311*
5.	Safety of using green signal timers	3.170	2.015	8.113
6.	Improving traffic conditions by using the recommended speed displays for traffic signal coordination's	2.445	21.866***	3.160
Note: ***, **, * – correlations significant at $p < 0.001$, $p < 0.01$, $p < 0.05$				

3.3. Perspective of vulnerable road users

Figure 4 summarizes respondents' views on time counters and pedestrian detectors for signalized crossings and their perceived usefulness and safety benefits for pedestrians and cyclists. The overall acceptance for both measures is high.

Although a majority of respondents (71.1%) favored countdown timers on pedestrian crossings and cycle tracks, 28.9% opposed their use. The relatively large dissenting group suggests lingering concerns about the effect of timers on the safety and comfort of unprotected road users. Nevertheless, χ^2 tests revealed no statistically significant variation in timer acceptance across any socio-demographic strata.

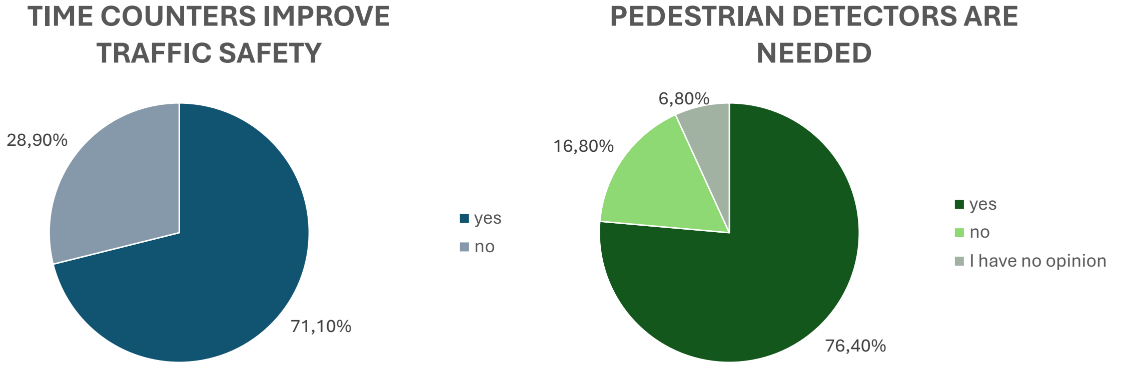

Fig. 4. Pedestrians' and cyclists' opinions on the impact of timers and traffic detectors on signal safety and functionality

Even stronger support was expressed for presence detectors that actuate pedestrian or cyclist phases: 76.4% considered them necessary, 16.8% were opposed, and 6.8% were undecided. The high approval rate shows substantial demand for smarter, more adaptive signal systems that respond to the real-time presence of vulnerable users, thereby enhancing both flow efficiency and safety. Again, statistical testing showed no significant differences in opinions as a function of age, sex, driving experience, or settlement size.

3.4. The primary areas of criticism of traffic lights: Semantic analysis

The 844 open-ended statements collected in the survey were examined using semantic content analysis to extract the most frequently recurring motifs and problem areas (Figure 5). The most common concern was systemic inefficiency, as signals were described as rigid and insufficiently responsive to prevailing demand ("phase durations do not match actual traffic volumes, leading to unnecessary queues"). Respondents also condemned poor signal coordination ("driving across town means stopping every 300 m") and hazardous phase sequencing, particularly regarding conflicts between pedestrian and turning-vehicle flows ("pedestrians receive green simultaneously with turning cars—this is dangerous!").

Many comments highlighted deficiencies in visual information, notably, the absence of countdown timers or directional arrows ("one has no idea how long the green will last—deciding whether to proceed is difficult"). Additional critiques focused on lax rule enforcement and low compliance with signal indications by both drivers and cyclists ("cyclists completely ignore the red light") and on imbalanced phase proportions ("you wait two minutes and then get only five seconds of green—absurd"). Finally, respondents objected to being required to stop in the absence of cross-traffic ("I sit at a red light when nobody is coming—even at night"). Taken together, these findings point to systemic shortcomings that strongly influence road-users' feelings about the quality of urban traffic-signal management.

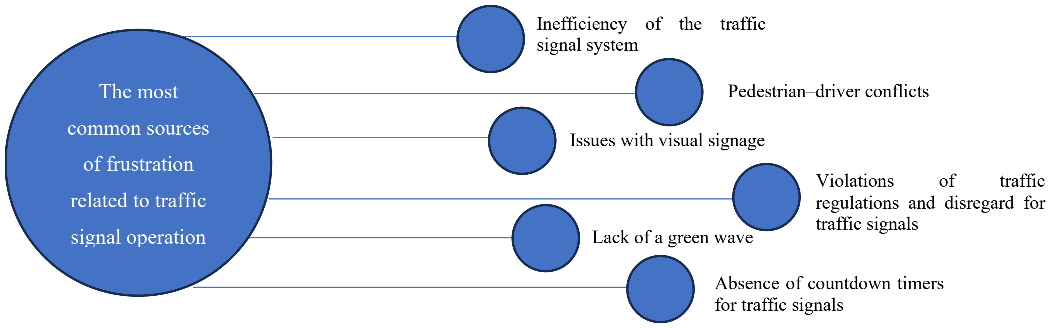

Fig. 5. Primary areas of criticism of traffic signal operation based on respondents' statements

4. DISCUSSION

A striking finding is the public willingness to tolerate delays that exceed the 80 s-per-vehicle benchmarks stated in the Polish signal-capacity procedure. Equally noteworthy is that the majority of respondents feel that getting through an intersection on the third green is acceptable. Because virtually all Polish signal programs operate with a maximum cycle length of 120 s, this implies that many drivers implicitly accept cumulative delays close to (or even over) 160 s. Therefore, we hypothesize that road-users' feelings are guided more by intuitive milestones (e.g., How many greens do I miss?) than by consciously tracked delays in seconds. This observation invites a change in basic assumptions: Design targets might be reframed to guarantee clearance of the maximum queue by the third cycle, rather than to minimize average vehicular delay.

Respondents also provided inconsistent estimates of acceptable queue length, both in terms of vehicles and in meters, even if a nominal space consumption of 6 m per vehicle is assumed [28]. This result suggests that drivers do not perceive these geometric aspects of congestion accurately.

Contrary to our initial expectation, city size showed no statistical association with perceived service quality. One might expect residents of larger urban areas—who routinely face high traffic volumes—to show a higher tolerance for degraded conditions. However, the data show no such trend. This is surprising, given that Polish unsignalized-junction capacity models explicitly adjust critical gap values downward in densely built-up areas; a similar urban-scale effect was expected for signalized sites but was not observed.

The higher acceptance of red-phase countdown timers compared to green-phase timers likely stems from their being perceived as predictable and safe. Knowing the remaining red time allows drivers to prepare to proceed, improving discharge efficiency and reducing the stress of uncertainty. By contrast, a green-phase countdown may encourage last-second accelerations as the timer nears zero. Thus, red-phase timers are viewed as enhancing both comfort and safety, which explains their greater popularity.

A comparable level of enthusiasm was recorded for speed-advisory displays that recommend an optimal approach speed to reach the next intersection on green: 86.3% of respondents believed that such devices improve traffic conditions at signals. The finding underscores the positive reception of technologies that enhance the predictability and smoothness of progression, benefiting both driver comfort and signal-system efficiency.

It is worth noting that the results presented in Figure 3 were confirmed in a previous study [29]. The authors of this article found, for example, that drivers pay more attention to the countdown timer during the green signal period, which may indicate less concentration when perceiving the surroundings when passing through an intersection with traffic lights. This may be consistent with the respondents' suggestion that the countdown timer is less safe during the green signal countdown.

Finally, the pronounced preference—particularly among less-experienced drivers—for shorter but more frequent greens contradicts the dynamic queue-dissipation theory [30], which holds that longer greens are more effective at clearing maximum queues because each vehicle accelerates more quickly than its predecessor. However, the preference is consistent with the saturation-flow phenomenon whereby exceedingly long greens eventually result in higher exit speeds and, consequently, longer headways, reducing the effective saturation flow rate [31].

5. CONCLUSIONS

The present study aimed to identify the preferences and expectations of motorists and pedestrians using road infrastructure operating under traffic-signal control in Polish cities. The 20-item questionnaire (including two open-ended questions) collected data on tolerated operating parameters, control-strategy preferences, and feelings of supporting measures such as countdown timers, speed-advisory displays, and pedestrian/cyclist detectors.

From a quantitative standpoint, respondents generally confirmed a patience limit of about two minutes of delay while waiting for a green signal. The most important factor was the number of signal cycles in which service on green was missed. Most drivers prefer longer green intervals that appear less frequently within an hour as opposed to shorter, more frequent intervals. High approval was also expressed for displays showing the amount of time remaining until the onset of a red or green signal.

Respondents primarily criticized the rigidity of fixed-time signal programs and their lack of adaptation to current demand, the absence of coordinated green waves, turning phases that conflict with pedestrians, and deficiencies in visual information. A pervasive feeling of insufficient flexibility and predictability undermines road-users' confidence in the system's effectiveness.

Recommendations for practitioners can be summarized as follows:

- When designing a signal program, a new level-of-service metric should be adopted. Vehicles should be discharged by no later than the third signal cycle.
- Countdown displays for the remaining red time and speed-advisory displays within coordinated systems can enhance travel comfort.
- Pedestrian and cyclist detectors receive strong public acceptance.
- The lack of an effect of city size suggests universal expectations, implying that solutions developed for large metropolitan areas may be equally effective in smaller communities.
- A signaling program with a lower degree of collision between vehicle and pedestrian traffic flows in the same signal phase should be designed.

The findings show that road users value flow expressed by the number of cycles endured and by reliable visual information and that the deployment of adaptive, user-friendly support tools could markedly improve public feelings about traffic-signal control in Poland.

Acknowledgements

This article is based on the results of research as part of the work on the Benchmarks and Standards for Traffic Signal Designers, which was carried out by the Road and Bridge Research Institute in Poland.

Appendix

List of questions included in the questionnaire:

1. As a driver, what do you find most irritating in traffic controlled by traffic signals (at a signalized intersection or at a signalized pedestrian/cycle crossing)?
2. In your opinion—from the driver's perspective—which of the following aspects is the most important when assessing the *traffic conditions* at a signalized approach (e.g., at a signalized intersection approach)?
    - overall time lost (time spent waiting in front of the signal head)
    - number of vehicles in the queue (in the lane in front of the signal head)
    - physical length of the vehicle queue in the lane, measured from the stop line
    - number of signal cycles (green intervals) during which you were unable to pass through
3. In your opinion, what is the maximum acceptable value of **time loss** at traffic signals (e.g., on an approach to a signalized intersection)?
    - up to 50 s
    - up to 100 s
    - up to 150 s
    - up to 250 s
    - up to 300 s
4. In your opinion, what is the maximum acceptable **number of vehicles in the queue** (in a lane) at traffic signals (e.g., on an approach to a signalized intersection)?
    - up to 20 vehicles
    - up to 40 vehicles
    - up to 60 vehicles
    - up to 80 vehicles
    - up to 100 vehicles

5. In your opinion, what is the maximum acceptable **queue length** (measured from the stop line) at traffic signals (e.g., on an approach to a signalized intersection)?
   - up to 100 m
   - up to 200 m
   - up to 300 m
   - up to 400 m
   - up to 500 m
6. In your opinion, what is the maximum acceptable **number of signal cycles** (lost green intervals) during which it is not possible to be served at traffic signals (e.g., on an approach to a signalized intersection)?
   - up to 1 (served on the second green)
   - up to 2 (served on the third green)
   - up to 3 (served on the fourth green)
   - up to 4 (served on the fifth green)
   - up to 5 (served on the sixth green)
7. In your opinion – from the driver's perspective – which option is better for improving traffic conditions at traffic signals?
   - increasing the duration of green signals within the cycle (lower frequency of green in an hour)
   - decreasing the duration of green signals within the cycle (higher frequency of green in an hour)
8. In your opinion, from the driver's perspective, does the use of **countdown timers indicating the remaining red time** improve traffic conditions at traffic signals?
   - yes
   - no
9. In your opinion, from the driver's perspective, is the use of **countdown timers indicating the remaining red time** safe?
   - yes
   - no
10. In your opinion, from the driver's perspective, does the use of **countdown timers indicating the remaining green time** improve traffic conditions at traffic signals?
    - yes
    - no
11. In your opinion, from the driver's perspective, is the use of **countdown timers indicating the remaining green time** safe?
    - yes
    - no
12. In your opinion, from the driver's perspective, does the use of **advisory speed displays** (e.g., to the next intersection, in order to arrive or "catch" the green signal) improve traffic conditions at traffic signals?
    - yes
    - no
13. From the perspective of a pedestrian or cyclist, what do you find most irritating about traffic signal operation?
14. In your opinion, does the use of **countdown timers** at pedestrian crossings or cycle crossings improve road safety?
    - yes
    - no
15. In your opinion, is the use of **pedestrian or cyclist detectors** necessary?
    - yes, so that the green signal is called only when pedestrians are actually present in the crossing area
    - no, the green signal for pedestrians should be displayed whenever there is an opportunity to do so
    - no opinion

16. Please indicate the size of the city or town in which you usually travel on the road network on a typical working day:
    - up to 50,000 inhabitants
    - up to 250,000 inhabitants
    - up to 500,000 inhabitants
    - up to 1 million inhabitants
    - more than 1 million inhabitants
17. Please indicate your gender:
    - female
    - male
    - prefer not to say
18. Please indicate your age:
    - 18–25 years
    - 26–30 years
    - 31–40 years
    - 41–50 years
    - 51–60 years
    - over 60 years
19. Please indicate for how long you have held a driver's license for a passenger car (Category B):
    - I do not hold a driver's license (I am completing the questionnaire from the perspective of a passenger, pedestrian, cyclist, etc.)
    - up to 2 years
    - up to 5 years
    - up to 10 years
    - up to 15 years
    - up to 20 years
    - more than 20 years
20. Please indicate your sector-related education and professional qualifications (if any):
    - civil engineering (road engineering)
    - transport (traffic engineering)
    - road safety auditor
    - traffic management/traffic control designer without sector-specific higher education
    - student of civil engineering or transport
    - none

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Received 11.11.2024; accepted in revised form 24.02.2026