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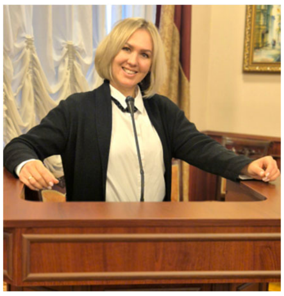
INTERACTION OF VEHICLES AT A SIGNALIZED INTERSECTION WHEN THE GREEN LIGHT IS ACTIVATED

ВЗАЄМОДІЯ ТРАНСПОРТНИХ ЗАСОБІВ НА РЕГУЛЬОВАНОМУ ПЕРЕХРЕСТІ ПРИ ВМИКАННІ ЗЕЛЕНОГО СИГНАЛУ



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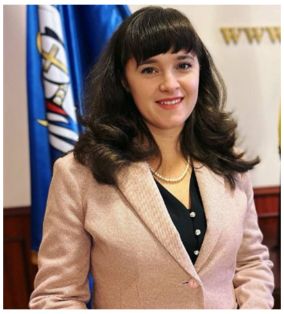

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Abstract. The organization and efficiency of traffic signal control at intersections are key factors influencing the capacity and congestion levels of the urban road network. Improper traffic signal operations can cause additional delays, reduce traffic flow efficiency, and increase the risk of accidents. The relevance of this study lies in examining the impact of vehicle start characteristics on the dynamics of movement through signalized intersections and assessing their effect on traffic flow optimization.

This paper analyzes the movement of two vehicles traveling sequentially through a signalized intersection when the green light is activated. The primary focus is on studying parameters such as the ratio of distances traveled by the vehicles, the ratio of their speeds, the start delay of the second vehicle relative to the first, and the variation of these indicators during movement. Evaluating the interrelation of these parameters allows for assessing the optimality of traffic flow and its safety level.

The described characteristics are essential for analyzing movement conditions both at the intersection and on the approach to it. Identifying patterns between speed ratios, distances, and start delays enables the assessment of the impact of traffic signal control on movement dynamics. In turn, this provides an opportunity to propose optimal parameters to improve the intersection's capacity and reduce road network congestion.

The findings of this study can be used to enhance traffic modeling and develop adaptive traffic management algorithms. Optimizing vehicle start parameters will contribute to improving the overall efficiency of the road network, reducing delays, and increasing safety levels at intersections. The proposed approach can be applied in urban planning and for the development of intelligent transportation systems that ensure efficient traffic flow management.

Key words: traffic signal control, signalized intersection, vehicle dynamics, start delay, speed ratio, traffic flow optimization, road network congestion, adaptive traffic management, intelligent transportation systems, intersection performance, intersection performance, vehicle interaction.

Introduction. Efficient traffic signal control at intersections is a crucial factor influencing the overall performance of urban road networks. Signalized intersections regulate traffic flow and ensure safety, but their improper operation can lead to increased congestion, unnecessary delays, and even safety hazards. The study of vehicle movement dynamics through intersections is essential for optimizing traffic management strategies and improving the efficiency of transportation systems.

One of the key aspects of traffic flow analysis is the sequential movement of vehicles at an intersection when the green signal is activated. In real traffic conditions, vehicles do not start moving simultaneously due to reaction times, acceleration differences, and variations in driver behavior. The relationship between the distances traveled by vehicles, their speed ratios, and the start delay of following vehicles plays a crucial role in assessing traffic flow efficiency and safety. Additionally, the rate of change in these indicators provides valuable insights into the overall performance of signalized intersections and their impact on road congestion [1 – 3].

This study aims to analyze the movement of two vehicles following each other at a signalized intersection, focusing on the relationships between key parameters such as distance ratios, speed ratios, start delay time, and acceleration differences [4, 5]. By evaluating these parameters, the research seeks to determine optimal conditions that can enhance traffic flow, minimize congestion, and improve intersection performance.

Understanding these movement dynamics is essential for developing adaptive traffic control strategies that respond to real-time conditions. The findings of this research can contribute to optimizing signal timing, reducing travel delays, and ensuring safer and more efficient traffic flow at intersections. Moreover, the proposed approach can be integrated into intelligent transportation systems to enhance urban mobility and transportation network resilience [6, 7].

Research design and discussion. The movement of vehicles when the green traffic light is activated depends on the reaction of the driver of the first vehicle. Thus, the first vehicle influences the subsequent movement of the vehicle queue [8].

The interaction of a pair of vehicles when responding to a green traffic signal occurs as follows.

At the yellow signal (preparation stage), the speed of vehicles is zero, and drivers are waiting for the green light. When the green signal is activated, the phase of movement initiation begins. The start of the first vehicle's movement depends on the driver's reaction time and competence in responding to the green signal, which results in uniformly accelerated motion of the vehicle [9].

The second vehicle starts with a delay. This delay depends on the moment the first vehicle begins moving, the driver's reaction time, and the dynamic characteristics of the second vehicle.

The second vehicle has restrictions on the start of movement due to the conditions imposed by the leading vehicle [10 – 11].

Mathematical Formula for the Motion Ratio of the Second Vehicle Relative to the First.

To evaluate the relative movement of the second vehicle compared to the first, we introduce the function of distance or speed ratio over time:

1. Distance Ratio:

$$R_s(t) = \frac{s_2(t)}{s_1(t)}, \quad (1)$$

де $s_1(t) \neq 0$

s_1 (t) – the distance traveled by the first vehicle at time *t*.

s_2 (t) – the distance traveled by the second vehicle at time *t*.

If R_s (t) = 1, it indicates uniform movement of the vehicles, ensuring optimal following conditions.
If R_s (t) < 1, the second vehicle is lagging behind, which increases the overall time vehicles spend at the intersection and contributes to network congestion.
If R_s (t) > 1, the second vehicle is overtaking, which increases the risk of traffic accidents.

***2.* Speed Ratio:**

$$R_y(t) = \frac{v_1(t)}{v_2(t)} \quad (2)$$

де $v_1(t) \neq 0$

v_1 (t) – the speed of the first vehicle.

v_2 (t) – the speed of the second vehicle.

$R_v(t)$ =1, it indicates uniform vehicle movement, ensuring optimal following conditions.

$R_v(t)$ < 1, the second vehicle moves slower, increasing the overall time vehicles spend at the intersection and contributing to network congestion.

$R_v(t)$ >1, the second vehicle moves faster, increasing the risk of traffic accidents.

3. Time Shift:

Since the second vehicle starts with a delay of Δt, the time ratio can be expressed as:

$$\Delta t = tstart, Car2 - tstart, Car1 \quad (3)$$

tstart, Car2 – The start time of the first vehicle's movement,

tstart, Car1 – The start time of the second vehicle's movement.

4. Distance increment ratio over a time interval:

To compare the rate of distance accumulation over a specific interval Δt:

$$\mathrm{R\Delta s(t)} = \frac{s_2(t)}{s_1(t)} = \frac{[s_2(t+\Delta t)-s_2(t)]}{[s_1(t+\Delta t)-s_1(t)]} \quad (4)$$

RΔs (t) – The coefficient of the distance increment ratio between the second and the first vehicle over the time interval Δt. It indicates how the distance between the two vehicles changes during this period.

Δs_2 (t), Δs_1(t) – The distance increments of the second and first vehicles, respectively. They determine how much the distance traveled by each vehicle has changed over the time interval Δt.

s_2 (t+Δt)−s_2 (t) – The change in the distance traveled by the second vehicle over the time interval Δt. This means comparing the distance at time t+Δt with the distance at time t.

s_1 (t+Δt)−s_1 (t) – The change in the distance traveled by the first vehicle over the same time interval Δt.

If RΔs (t)>1 – The second vehicle accumulates distance faster than the first, meaning it is catching up with the first vehicle.

If RΔs (t)<1 – The first vehicle moves away faster than the second, increasing the gap.

If RΔs (t)=1 – Both vehicles accumulate distance at the same rate, meaning their relative position remains unchanged.

5. Acceleration Ratio:

$$R_a(t) = \frac{a_2(t)}{a_1(t)} = \frac{\left[\frac{dv_2(t)}{dt}\right]}{\left[\frac{dv_1(t)}{dt}\right]} \quad (5)$$

Ra (t) – The acceleration ratio coefficient, which indicates how the acceleration of the second vehicle changes relative to the first.

a_2 (t), a1(t) – The instantaneous accelerations of the second and first vehicles, respectively, at a given moment in time t.

dv_2 (t)/dt – The derivative of the second vehicle's speed over time, which represents its acceleration.

dv_1 (t)/dt – The derivative of the first vehicle's speed over time, which represents its acceleration.

If Ra(t) > 1 – The second vehicle has greater acceleration than the first, meaning it begins to catch up with the first vehicle.

If Ra(t) < 1 – The first vehicle accelerates faster than the second, increasing the gap between them.

If Ra(t) = 1 – Both vehicles have the same acceleration, meaning their speed changes at the same rate.

The conducted analysis provides valuable insights into various aspects of traffic dynamics at intersections. It enables a comprehensive assessment of traffic efficiency, helping to determine how effectively vehicles move through intersections under different conditions. Additionally, it facilitates the study of the impact of driver reaction time on intersection capacity, allowing for a better understanding of how human factors influence traffic flow and congestion levels [12 – 15].

Furthermore, the findings contribute to the optimization of algorithms for adaptive traffic signal control systems, improving real-time signal adjustments based on traffic demand. These optimizations can enhance road network efficiency, reduce vehicle delays, minimize fuel consumption, and lower emissions by ensuring smoother traffic flow [16]. The results of this study can be applied to develop intelligent transportation solutions aimed at increasing road safety, improving intersection throughput, and supporting the implementation of advanced traffic management strategies.

Conclusion. This study analyzes the dynamics of vehicle movement when starting at a green traffic light. The primary focus is on the impact of the reaction time of the driver of the first vehicle on the subsequent movement of the vehicle queue. Key parameters characterizing this interaction have been identified, and appropriate mathematical models have been proposed.

This study describes the interaction of a pair of vehicles starting at a green traffic light and provides an analysis of the relevant ratio indicators. A decrease in these indicators affects traffic safety, whereas an increase contributes to optimizing traffic flow and reducing road network congestion. When the ratio value equals 1, uniform vehicle movement allows for optimizing traffic through the implementation of intelligent transport systems.

The obtained results can be used for: Assessing the efficiency of traffic at intersections: studying the impact of driver reaction time on intersection throughput; **o**ptimizing algorithms for adaptive traffic signal control systems, developing recommendations for improving road safety and traffic flow management.

Further research will focus on analyzing vehicle arrivals at intersections and constructing a graphical model, allowing for a more detailed examination of traffic organization and regulation efficiency.

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Conflicts of interest/ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Polishuk, V., Popov, S., Vyhovska, I., Yanishevskiy, S., & Nahrebelna, L. (2024). Energy-based approach to the assessment of traffic flow. Transport Technologies, 5(2). https://doi.org/10.23939/tt2024.02.023.

2. Boikiv, M. V., & Zherebetskyi, N. V. (2024). Study of traffic conditions at intersection with a heavy traffic flow in the main direction. *Scientific Notes of Vernadsky TNU*, *35*(6). https://doi.org/10.32782/2663-5941/2024.6.2/35.

3. Polishchuk, V. P., Nahrebelna, L. P., Vyhovska, I. A., & Popov, S. Y. (2024). Applying energy principles to the assessment of road traffic safety. *Journal of Transport Systems and Traffic Safety*, *1*(58), 133-141. https://doi.org/10.33744/2308-6645-2024-1-58-133-141.

4. Vieira, M., Galvão, G., Vieira, M., Louro, P., Véstias, M. & Vieira, P. (2024). Enhancing Urban Intersection Efficiency: Visible Light Communication and Learning-Based Control for Traffic Signal Optimization and Vehicle Management. *Symmetry, 16*. https://doi.org/10.3390/sym16020240

5. Vieira, M., Vieira, M., Galvão, G. M., Louro, P., Véstias, M. P. & Vieira, P. (2024). Enhancing Urban Intersection Efficiency: Utilizing Visible Light Communication and Learning-Driven Control for Improved Traffic Signal Performance. *Vehicles*. https://doi.org/10.3390/vehicles6020031

6. Simões, M., Milheiro-Oliveira, P. & Costa, A. P. (2010). Modeling and Simulation of Traffic Movements at Semiactuated Signalized Intersections. . https://doi.org/10.1061/(asce)te.1943-5436.0000124.

7. Bai, Z., Hao, P., Shangguan, W., Cai, B. & Barth, M. (2022). Hybrid Reinforcement Learning-Based Eco-Driving Strategy for Connected and Automated Vehicles at Signalized Intersections. *IEEE transactions on intelligent transportation systems (Print), 23*. https://doi.org/10.1109/tits.2022.3145798.

8. Aoki, S. and Rajkumar, R. (2022). Cyber Traffic Light: Safe Cooperation for Autonomous Vehicles at Dynamic Intersections. *IEEE transactions on intelligent transportation systems (Print)*. https://doi.org/10.1109/tits.2022.3146457.

9. Wang, Z., Wu, G. & Barth, M. (2020). Cooperative Eco-Driving at Signalized Intersections in a Partially Connected and Automated Vehicle Environment. *IEEE transactions on intelligent transportation systems (Print), 21*. https://doi.org/10.1109/tits.2019.2911607.

10. Eom, M. and Kim, B. (2020). The traffic signal control problem for intersections: a review. *European Transport Research Review, 12*. https://doi.org/10.1186/s12544-020-00440-8.

11. Horbachov, P., & Liubyi, Y. (2022). Method of estimating the time required to ensure the uniform motion of vehicle platoon progression on the coordinated section of the city arterial road. *Vehicle and Electronics. Innovative Technologies*, 22. https://doi.org/10.30977/VEIT.2022.22.0.2.

12. Zhou, M., Yu, Y. & Qu, X. (2020). Development of an Efficient Driving Strategy for Connected and Automated Vehicles at Signalized Intersections: A Reinforcement Learning Approach. *IEEE transactions on intelligent transportation systems (Print)*. https://doi.org/10.1109/tits.2019.2942014.

13. Wu, W., Huang, L. & Du, R. (2019). Simultaneous Optimization of Vehicle Arrival Time and Signal Timings within a Connected Vehicle Environment. *Italian National Conference on Sensors, 20*. https://doi.org/10.3390/s20010191.

14. Rakha, H. A., El-Shawarby, I. & Setti, J. (2007). Characterizing Driver Behavior on Signalized Intersection Approaches at the Onset of a Yellow-Phase Trigger. *IEEE Transactions on Intelligent Transportation Systems*. https://doi.org/10.1109/tits.2007.908146.

15. Lin, Q., Li, S., Xu, S., Du, X., Yang, D. & Li, K. (2021). Eco-Driving Operation of Connected Vehicle With V2I Communication Among Multiple Signalized Intersections. *IEEE Intelligent Transportation Systems Magazine*. https://doi.org/10.1109/mits.2020.3014113.

16. Katsaros, K., Kernchen, R., Dianati, M. & Rieck, D. (2011). Performance study of a Green Light Optimized Speed Advisory (GLOSA) application using an integrated cooperative ITS simulation platform. *International Wireless Communications & Mobile Computing Conference*. https://doi.org/10.1109/iwcmc.2011.5982524.

ВЗАЄМОДІЯ ТРАНСПОРТНИХ ЗАСОБІВ НА РЕГУЛЬОВАНОМУ ПЕРЕХРЕСТІ ПРИ ВМИКАННІ ЗЕЛЕНОГО СИГНАЛУ

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Анотація. Організація та ефективність роботи світлофорного регулювання на перехрестях є ключовими факторами, що впливають на пропускну здатність та рівень заторів у міських вулично-дорожніх мережах. Неправильна робота світлофорів може призводити до додаткових затримок, зниження ефективності руху транспорту та підвищення ризику виникнення ДТП. Актуальність даного дослідження полягає у вивченні впливу характеристик старту транспортних засобів на динаміку руху через регульовані перехрестя та оцінці їхнього впливу на оптимізацію транспортних потоків. У роботі проаналізовано рух двох транспортних засобів, що послідовно перетинають регульоване перехрестя під час увімкнення зеленого сигналу світлофора. Основна увага приділяється дослідженню таких параметрів, як співвідношення відстаней, пройдених транспортними засобами, співвідношення їхніх швидкостей, затримка старту другого транспортного засобу відносно першого та зміна цих показників у процесі руху. Оцінювання взаємозв'язку зазначених параметрів дозволяє визначити оптимальність організації потоку та рівень його безпеки. Описані характеристики є важливими для аналізу умов руху як на самому перехресті, так і на підходах до нього. Виявлення закономірностей між співвідношеннями швидкостей, відстаней та затримками старту дозволяє оцінити вплив світлофорного регулювання на динаміку руху. Це, у свою чергу, дає можливість запропонувати оптимальні параметри для підвищення пропускної здатності перехрестя та зниження заторів у вулично-дорожній мережі. Отримані результати можуть бути використані для удосконалення транспортного моделювання та розробки адаптивних алгоритмів управління рухом. Оптимізація параметрів старту транспортних засобів сприятиме підвищенню загальної ефективності дорожньої мережі, зменшенню затримок та підвищенню рівня безпеки на перехрестях. Запропонований підхід може застосовуватись в міському плануванні та при розробці інтелектуальних транспортних систем, що забезпечують ефективне управління транспортними потоками.

Ключові слова: світлофорне регулювання, регульоване перехрестя, динаміка транспортних засобів, затримка старту, співвідношення швидкостей, оптимізація транспортних потоків, затори дорожньої мережі, адаптивне управління рухом, інтелектуальні транспортні системи, ефективність перехрестя, взаємодія транспортних засобів.

Перелік посилань

1. Polishuk, V., Popov, S., Vyhovska, I., Yanishevskiy, S., & Nahrebelna, L. (2024). Energy-based approach to the assessment of traffic flow. Transport Technologies, 5(2). https://doi.org/10.23939/tt2024.02.023.

2. Boikiv, M. V., & Zherebetskyi, N. V. (2024). Study of traffic conditions at intersection with a heavy traffic flow in the main direction. *Scientific Notes of Vernadsky TNU*, *35*(6). https://doi.org/10.32782/2663-5941/2024.6.2/35.

3. Polishchuk, V. P., Nahrebelna, L. P., Vyhovska, I. A., & Popov, S. Y. (2024). Applying energy principles to the assessment of road traffic safety. *Journal of Transport Systems and Traffic Safety*, *1*(58), 133-141. https://doi.org/10.33744/2308-6645-2024-1-58-133-141.

4. Vieira, M., Galvão, G., Vieira, M., Louro, P., Véstias, M. & Vieira, P. (2024). Enhancing Urban Intersection Efficiency: Visible Light Communication and Learning-Based Control for Traffic Signal Optimization and Vehicle Management. *Symmetry, 16*. https://doi.org/10.3390/sym16020240

5. Vieira, M., Vieira, M., Galvão, G. M., Louro, P., Véstias, M. P. & Vieira, P. (2024). Enhancing Urban Intersection Efficiency: Utilizing Visible Light Communication and Learning-Driven Control for Improved Traffic Signal Performance. *Vehicles*. https://doi.org/10.3390/vehicles6020031

6. Simões, M., Milheiro-Oliveira, P. & Costa, A. P. (2010). Modeling and Simulation of Traffic Movements at Semiactuated Signalized Intersections. . https://doi.org/10.1061/(asce)te.1943-5436.0000124.

7. Bai, Z., Hao, P., Shangguan, W., Cai, B. & Barth, M. (2022). Hybrid Reinforcement Learning-Based Eco-Driving Strategy for Connected and Automated Vehicles at Signalized Intersections. *IEEE transactions on intelligent transportation systems (Print), 23*. https://doi.org/10.1109/tits.2022.3145798.

8. Aoki, S. and Rajkumar, R. (2022). Cyber Traffic Light: Safe Cooperation for Autonomous Vehicles at Dynamic Intersections. *IEEE transactions on intelligent transportation systems (Print)*. https://doi.org/10.1109/tits.2022.3146457.

9. Wang, Z., Wu, G. & Barth, M. (2020). Cooperative Eco-Driving at Signalized Intersections in a Partially Connected and Automated Vehicle Environment. *IEEE transactions on intelligent transportation systems (Print), 21*. https://doi.org/10.1109/tits.2019.2911607.

10. Eom, M. and Kim, B. (2020). The traffic signal control problem for intersections: a review. *European Transport Research Review, 12*. https://doi.org/10.1186/s12544-020-00440-8.

11. Horbachov, P., & Liubyi, Y. (2022). Method of estimating the time required to ensure the uniform motion of vehicle platoon progression on the coordinated section of the city arterial road. *Vehicle and Electronics. Innovative Technologies*, 22. https://doi.org/10.30977/VEIT.2022.22.0.2.

12. Zhou, M., Yu, Y. & Qu, X. (2020). Development of an Efficient Driving Strategy for Connected and Automated Vehicles at Signalized Intersections: A Reinforcement Learning Approach. *IEEE transactions on intelligent transportation systems (Print)*. https://doi.org/10.1109/tits.2019.2942014.

13. Wu, W., Huang, L. & Du, R. (2019). Simultaneous Optimization of Vehicle Arrival Time and Signal Timings within a Connected Vehicle Environment. *Italian National Conference on Sensors, 20*. https://doi.org/10.3390/s20010191.

14. Rakha, H. A., El-Shawarby, I. & Setti, J. (2007). Characterizing Driver Behavior on Signalized Intersection Approaches at the Onset of a Yellow-Phase Trigger. *IEEE Transactions on Intelligent Transportation Systems*. https://doi.org/10.1109/tits.2007.908146.

15. Popov, S., Vyhovska, I. (2025). Digital Control Tower Model for Public Transport City Network. In: Slavinska, O., Danchuk, V., Kunytska, O., Hulchak, O. (eds) *Intelligent Transport Systems: Ecology, Safety, Quality, Comfort. ITSESQC 2024. Lecture Notes in Networks and Systems*, vol 1335. Springer, Cham. https://doi.org/10.1007/978-3-031-87376-8_34.

16. Katsaros, K., Kernchen, R., Dianati, M. & Rieck, D. (2011). Performance study of a Green Light Optimized Speed Advisory (GLOSA) application using an integrated cooperative ITS simulation platform. *International Wireless Communications & Mobile Computing Conference*. https://doi.org/10.1109/iwcmc.2011.5982524.

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