ARCHIVES OF TRANSPORT
Volume 73, Issue 1, 2025

ISSN (print): *0866-9546*
e-ISSN (online): *2300-8830*
DOI: *10.61089/aot2025.5dtybt57*

ANALYSIS OF REAL-TIME ENERGY TRANSFER POSSIBILITIES AT INTERSECTIONS WITH CONSIDERATION OF ENERGY STORAGE AND REDUCTION OF TRANSPORT IMPACT ON THE ENVIRONMENT

Marcin KONIAK[1], Piotr JASKOWSKI[1], Radovan MADLEŇÁK[2], Jurijus ZARANKA[3]

[1,2] *Faculty of Transport, Warsaw University of Technology, Warsaw, Poland*

[3] *Faculty of Operation and Economics of Transport and Telecomunications, University of Zilina, Zilina, Slovakia*

[4] *Department of Automotive Engineering, Vilnius Gediminas Technical University, Vilnius, Lithuania*

Abstract:

Issues related to braking and acceleration in vehicles represent both technical and environmental challenges, regardless of the type of drive, whether combustion or electric. In conventional vehicles, the emission of particulate matter is a problem associated with the friction between brake pads and discs, leading to air pollution and health hazards. Brake dust contributes to up to 55% of particulate matter in urban environments. In electric vehicles, the processes of braking and rapid acceleration affect battery wear; however, thanks to energy recovery technology, it is possible to recuperate up to 70% of the kinetic energy. This paper proposes a solution involving the placement of induction loops before intersections with traffic lights to enable the recovery and storage of energy, which could be used to power vehicles waiting at intersections, as well as placement behind intersections to supply power to vehicles accelerating when leaving the intersection. The study considers the application of various energy storage technologies, such as flow batteries, supercapacitors, and flywheels. Each of these technologies offers unique benefits and limitations, such as long operational life, a high number of charge/discharge cycles, and environmental friendliness. Simulations performed using AIMSUN.Next software made it possible to analyze energy consumption and pollutant emissions in various scenarios, indicating the potential benefits of traffic optimization, the use of electric vehicles, and energy recovery. The research results highlight the importance of traffic smoothness and the use of energy storage technologies to reduce pollutant emissions (possible reduction: CO2 by over 40%, NOx by 48%, PM by 73%, and VOC by 40%) and energy consumption (lack of smooth traffic flow leads to approximately 159% higher energy use). The proposed use of energy storage technologies at intersections may significantly decrease particulate and carbon dioxide emissions. The final choice of energy storage technology will depend on local conditions, such as space availability, investment costs, and market availability.

Keywords: *braking emissions, regenerative braking, energy storage, traffic optimization, decarbonization*

To cite this article:

Koniak, M., Jaskowski, P., Madleňák, R., Zaranka, J., (2025). Analysis of real-time energy transfer possibilities at intersections with consideration of energy storage. Archives of Transport, 73(1), 195-206. https://doi.org/10.61089/aot2025.5dtybt57

Contact:
1) marcin.koniak@pw.edu.pl [https://orcid.org/0000-0003-0556-2814] – corresponding author; 2) piotr.jaskowski@pw.edu.pl [https://orcid.org/0000-0002-6563-1917], 3) radovan.madlenak@uniza.sk [https://orcid.org/0000-0002-4376-0830], 4) jurijus.zaranka@vilniustech.lt [https://orcid.org/0000-0002-7642-5705]

1. Introduction

The topic of braking and acceleration is the focus of intensive research and remains a source of analysis and further development. Regardless of the technology—whether it is combustion or electric—it continues to pose both technical and environmental challenges. For conventional vehicles, the primary issues are the emission of particulate matter and the consumption of vehicle components (Wieser et al., 2022). In areas where braking occurs with increased intensity, air pollution from brake dust can be observed. This is due to the generation of fine solid particles during braking resulting from friction between brake pads and discs. Such dust contains metals and other compounds, which significantly contribute to air pollution. These particles can infiltrate the lungs, posing health risks and contributing to respiratory and cardiovascular diseases. In fact, brake dust accounts for between 16% and 55% of non-exhaust particulate emissions in urban environments (Men et al., 2022). This type of pollution can persist in the environment for decades, contributing to long-term contamination. From an operational perspective, friction braking accelerates the wear of brake pads and discs, leading to higher maintenance costs. The intersection with traffic lights analyzed by the authors in this article, by virtue of its function, forces vehicles to stop and then accelerate according to the traffic signal cycle. This operational mode leads to increased emissions of greenhouse gases such as CO_2, NOx, and CO (Cristescu et al., 2011; Salek et al., 2020). Emissions of particulate matter during aggressive acceleration can increase by more than 500%, deteriorating air quality.

In electric vehicles as well, the processes of braking and rapid acceleration are not negligible. Thanks to regenerative braking, as much as 70% of kinetic energy can be recovered and stored in the battery (Anbumani et al., 2023). This allows for a significant reduction in the use of friction brakes, decreasing their utilization and wear. Analyzing the braking process in terms of battery wear, it can be concluded that the advantages of energy recovery outweigh the negative aspect, such as premature wear. The process of rapid acceleration can be analyzed in terms of its impact on battery lifespan. During acceleration, greater current is drawn from the battery, which can affect its service life. This is associated with the generation of additional heat, which accelerates degradation (M. Li et al., 2016).

In this article, the authors analyze one of the potential solutions to the aforementioned problems through the recovery and storage of energy. The proposed concept assumes the installation of induction loops adapted for energy reception and vehicle charging within the structure of the roadway lanes before the intersection, allowing the capture of energy generated during braking (Amin et al., 2023). Additionally, vehicles stopped at intersections could replenish their batteries. Upon moving off, vehicles would receive stored energy, thus reducing the use of their own batteries and contributing to lower battery degradation.

2. Literature review

2.1. Energy storage

To properly implement the concept discussed here, the use of energy storage is essential. However, for this to be economically and ecologically justified, it is necessary to select the appropriate technology. This technology must meet operational requirements, such as the highest possible number of charge/discharge cycles, a service life of 20 years or more, and minimal environmental impact. These characteristics constitute very stringent criteria and significantly limit the energy storage options that can be utilized. Fortunately, there are commercially developed and available solutions that can be deployed. The first among them is flow batteries. Their operating principle is based on storing energy in chemical form within two tanks containing liquid electrolytes (Choi et al., 2017). In order to charge or discharge the storage, the electrolytes are pumped through an electrochemical cell, where reduction and oxidation reactions occur. A key element of the electrochemical cell is a membrane that enables ion exchange but prevents the mixing of fluids. The main advantage is their long service life, reported as more than 10,000 cycles. This is due to the absence of degradation of electrode materials, since solid-state phase changes are avoided, and the electrolyte is resistant to wear, provided it is properly protected (Yu, 2024). These parameters allow for an operational life of up to 20 years. After this period, it may be necessary to replace the accompanying infrastructure, such as hydraulics, pumps, containers, and other mechanical components; however, the electrolyte itself remains functional and can still be reused. From a system design perspective, this technology enables scalability of capacity by increasing the

volume of electrolyte tanks and scalability of power output by adding more electrochemical cells. The efficiency of flow batteries is approximately 75% (Viswanathan et al., 2023). Safety must also be considered, as these systems do not exhibit thermal runaway and use non-flammable electrolytes. The possibility of full recycling of vanadium, on which the most popular solutions of this type are based, makes flow batteries highly competitive with lithium-ion cells in this aspect (Whitehead, 2023).
Another technology to mention in terms of long-life energy storage capable of performing hundreds of thousands of cycles is supercapacitor technology (Afif et al., 2019). Energy is stored in these devices by the separation of charge in the Helmholtz double layer at the interface between the conductive electrode surface and the electrolyte (Czagany et al., 2024). Such capacitors can achieve cycle numbers approaching one million without significant capacity loss. They enable charging within one minute and can deliver current of several kiloamperes. Like flow batteries, there is no risk of explosion or fire caused by thermal runaway. Additionally, supercapacitors offer a wide operating temperature range from −40°C to +60°C and an efficiency of about 95% (Z. Xu et al., 2022). With regard to the considered application, their main limitation—relatively low energy density, on the order of several tens of Wh/kg—does not constitute a major disqualifying factor. It should be noted that supercapacitors are a more expensive technology than lithium-ion batteries. However, because they have an indisputable advantage in the number of cycles, a properly designed system that efficiently uses available capacity can perform hundreds of times more cycles at a much lower capacity (Simon et al., 2014). This will lead to significant economic benefits for supercapacitors when calculated per operating cycle.
In the analyzed application, energy storage can also be implemented by storing energy in the form of rotational kinetic energy (K. Xu et al., 2023). This is possible through the use of a flywheel with an electric machine serving as both a motor and a generator (X. Li & Palazzolo, 2022). This technology is often analyzed for stabilizing energy processes and short-term power buffering (Ji et al., 2024). Its principle of operation consists in increasing the rotational speed of the wheel when surplus energy needs to be stored and releasing this energy from rotation when needed. This technology is particularly desirable in locations where short-term energy storage is required, in such cases achieving efficiencies in the range of 85–90% (Amiryar & Pullen, 2020). A properly constructed and maintained storage system based on this technology can achieve long service life reaching even hundreds of thousands of charge and discharge cycles (Haidl et al., 2019). Such installations can absorb and deliver large amounts of power in a short time, ranging from seconds, which makes them interesting for the application analyzed in this article. It should also be mentioned that they do not contain toxic chemicals or heavy metals, reducing their environmental impact, making them a better choice in this respect than lithium-ion cells (Esparcia et al., 2022). Their advantages over previously mentioned technologies also include significant robustness and operational reliability across a wide range of temperatures. As noted earlier, these storage units are dedicated to applications requiring short-term energy storage due to the fact that they have significant self-discharge losses, which can reach 3% to even 10% per hour (K. Yao et al., 2024).

2.2. Simulation Methods

Traffic modeling enables verification of pollutant emissions resulting from the number and structure of vehicle types within a road network. The AIMSUN.Next software (version 24.0.2) allows for the analysis of energy consumption in vehicle traffic, combined with the characterization of driver behavior patterns. Studies indicate that a vehicle's energy consumption is correlated with the driver's driving style (Merkisz et al., 2014), which is significant—30% of greenhouse gas emissions generated by road transport are attributed to this factor (Xiaotong et al., 2024). Aggressive driving, mainly characterized by frequent acceleration (Lárusdóttir & Úlfarsson, 2014) and braking, results in up to 32% higher energy consumption required for vehicle movement (Yan & FAN, 2017). These data emphasize the significant potential for energy savings through interventions aimed at modifying driver behavior (Lárusdóttir & Úlfarsson, 2014), as well as through energy recovery. Infrastructure construction that optimizes the energy efficiency of transport can also yield benefits. This can be determined on a global scale using simulation environments or through precise studies related to verification of vehicle power profiles correlated with driving methods, which are the basis for individual (vehicle/driver-specific) eco-driving techniques (E. Yao et al., 2013; Zhang et al., 2022). Research shows that so-called eco-driving—progressive acceleration and deceleration—allows for about 30% energy savings for a vehicle (Bingham et al., 2012; Szumska & Jurecki, 2020). The problems of intense acceleration and braking mainly pertain to specific elements of the road network, especially urban driving (Wu et al., 2010), which should be considered by infrastructure managers in the context of control and management.

Studies confirm that microsimulations using software tools can serve as a means to determine potential energy savings in transportation (Gołda et al., 2017; Jacyna et al., 2014). The cited software allows for the analysis of various research scenarios, including driver behaviors in the context of their impact on fuel consumption (Bennaya & Kilani, 2024; Muzir et al., 2023). Simulation methods are now widely used for controlling and optimizing road traffic (Jacyna & Merkisz, 2014; Sippel et al., 2024), and enable the inclusion of both conventional and electric vehicles in a given simulation scenario (Jacyna et al., 2021; Muzir et al., 2023). An important aspect is the ability to verify the implementation of advanced driver assistance systems (Muzir et al., 2023; Wang et al., 2017), whose purpose is to increase the energy efficiency of vehicle movement. There is also notable potential for autonomous vehicles (Tumminello et al., 2023) to significantly improve traffic flow and energy efficiency, benefitting even traditional road users (Chen et al., 2023; Su et al., 2023), thereby significantly reducing energy consumption due to optimization and the reduction of unnecessary vehicle maneuvers (Jahangard et al., 2023). Simulation techniques thus provide an opportunity to verify the application of clean transport zones in the context of energy consumption for transport purposes and pollutant emissions (Hasan et al., 2022; Mintsis et al., 2016).

In this article, simulation techniques were used to verify transport-related emissions and determine energy consumption for vehicle movement. This approach enables the development of conceptual assumptions for infrastructure expansion with solutions that enable energy recovery and its distribution for charging vehicles waiting for a green signal at intersections equipped with traffic lights.

3. Methods

3.1. Study Area

For the purpose of this analysis, the intersection of Grójecka Street – Wawelska Street – Kopińska Street (City of Warsaw) (Fig. 1) was selected and subsequently reconstructed within the simulation environment. Real measurement data collected by the infrastructure manager on September 20, 2023 (Wednesday, no precipitation, sunny day) were used for this purpose.

The traffic control at the intersection is implemented via traffic lights, operating according to three signal programs depending on the time of day (Table 1).

The daily vehicle type structure at the analyzed intersection is as follows: 88.0% passenger cars, 5.3% delivery vans, 2.7% motorcycles, 2.4% buses, and 1.6% trucks. Based on the conducted measurements, the traffic volumes for reference vehicles are as follows: during the morning peak—4,656 vehicles (8:00–9:00), off-peak—3,873 vehicles (12:00–13:00), and afternoon peak—4,332 vehicles (16:00–17:00). To illustrate the traffic characteristics of individual approaches, cartograms for the morning and afternoon peak periods are presented below (Fig. 2).

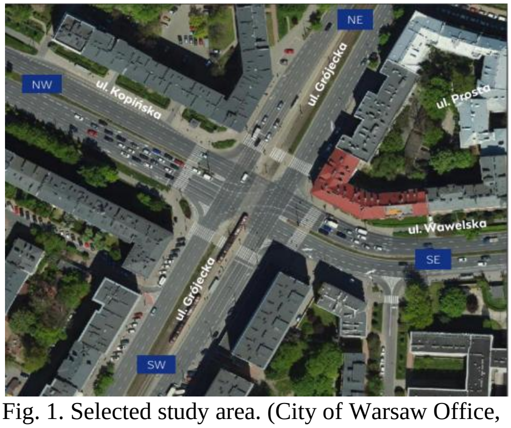

Fig. 1. Selected study area. (City of Warsaw Office, 2024)

Table 1. Traffic Signal Control Programs (Urząd m.st. Warszawy, 2024)

Program	Cycle [s]	OFFSET [s]	Working hour
1	110	96	5:00-9:00
2	102	84	9:00-12:00
3	96	94	12:00-5:00

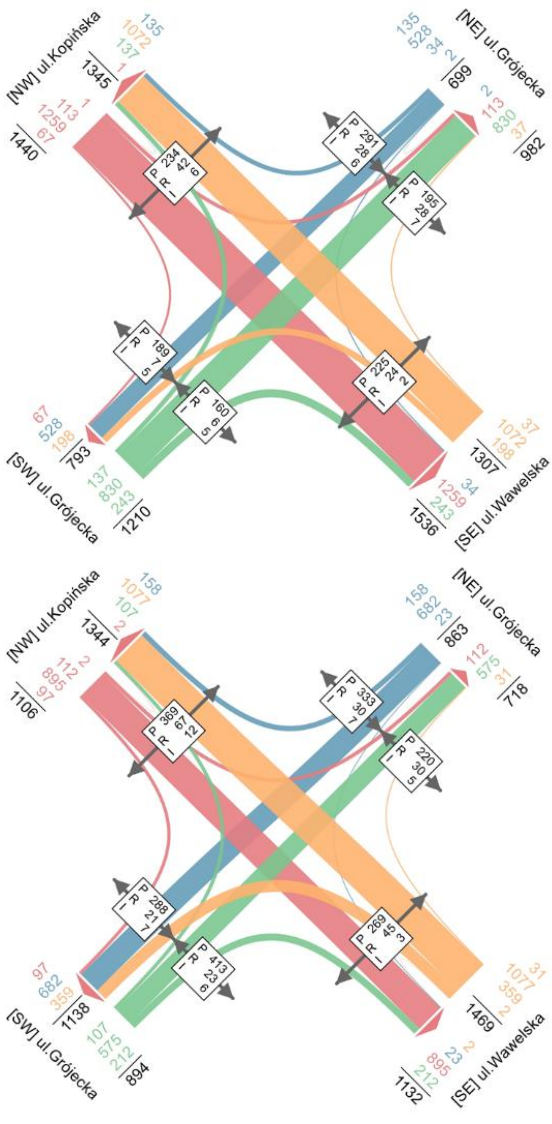

Fig. 2 Morning peak (on the left), afternoon peak (on the right). (City of Warsaw Office, 2024)

Additionally, on the approach to the intersection, there are dedicated lanes for buses and electric vehicles, which will be considered in the context of vehicle charging infrastructure. These include the far-right lane of Wawelska Street, designated for straight and right-turn movements, as well as the far-right lane for straight-ahead traffic on Kopińska Street.

3.2. Energy Storage

In the analyzed case, there are several methods to reduce emissions of pollutants and greenhouse gases. One can examine the impact of traffic light cycle settings and strive to optimize this parameter from an environmental perspective. Another approach involves reconstructing the intersection so that traffic flows unimpeded in one direction, for example, via an overpass. Introducing speed limit zones, increasing the number of trees, and promoting alternative forms of transport are also viable strategies.

In this publication, however, the authors focus on considering energy storage technologies that could both recover braking energy and supply accelerating vehicles. Additionally, it would be possible to charge vehicles while they are stationary at the intersection. As previously mentioned, there are technologies that meet the criteria required for a system implementing the analyzed functionality. These technologies must ensure long operational life, fast charging capability, and environmental friendliness, as described in the literature review section. The energy storage system must also be sized appropriately, with a capacity that matches the energy to be recovered from vehicles braking at the intersection and the ability to deliver this energy when vehicles start and accelerate.

The construction of the analyzed system is presented in the diagram below, which shows the main elements—including the inductive section integrated with the roadway, energy converters, and the energy storage unit (Fig. 3).

Figure 4 below presents the arrangement of inductive elements according to the conducted simulation. The green elements indicate components that receive energy during the braking process, while the red elements represent the energy transfer system supplying vehicles during acceleration.

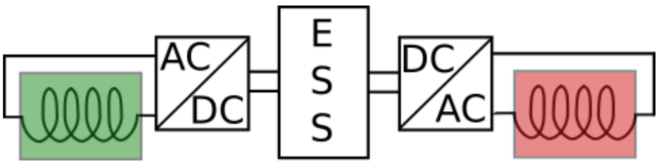

Fig. 3. Block diagram of the analyzed energy storage solution

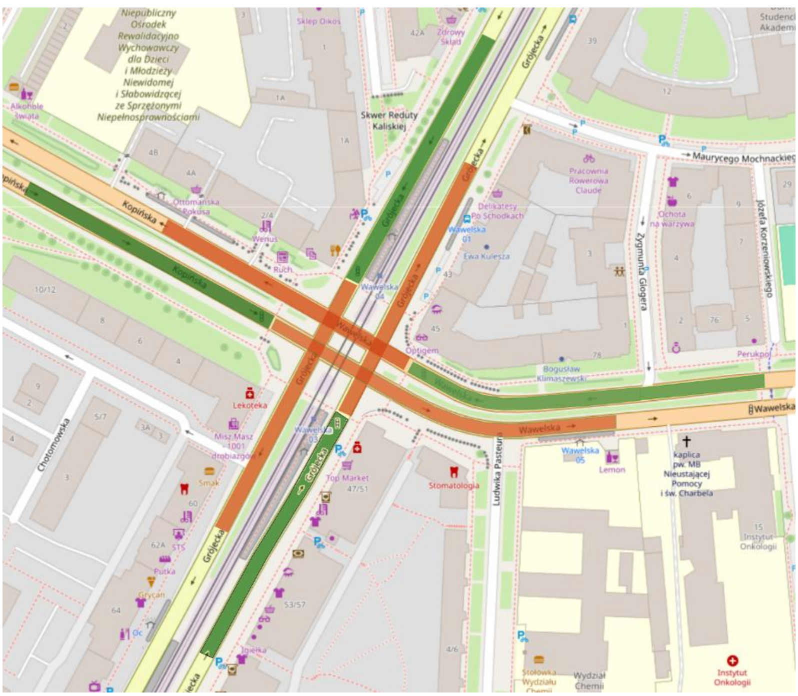

Fig. 4. Arrangement of inductive elements according to the presented method

3.3. Simulation Assumptions

Based on the intersection geometry, traffic data, and the assumed traffic signal cycle, a digital model of the study area was developed in the AIMSUN environment (Fig. 5).

For the simulation, scenarios were developed for the morning peak period, which is characterized by the highest infrastructure load. The following four research scenario variants were assumed: a) Autonomous vehicle movement at the intersection without traffic light control, with the following vehicle powertrain distribution: diesel 40%, petrol 50%, and electric 10%. b) Scenario a) with 100% electric vehicles. c) Intersection controlled by a traffic signal program with a 110-second cycle and the vehicle powertrain distribution from scenario a). d) Scenario c) with 100% electric vehicles. e) No electric vehicles in scenario c).

For the purposes of the simulation, the default vehicle mix was assumed, considering emission classes representing varying levels of energy efficiency, while also using the standard driver behavior model built into the software.

AIMSUN software features built-in transport environmental impact assessment modules. To verify the impact of road transport on environmental pollution, models embedded in AIMSUN will be used. Within the scope of microsimulation, five models can be used:

- the Fuel Consumption Model – assigns total traveled distance (in km) and total fuel consumption (in liters) for the entire network, a specified section, or route;
- the Battery Consumption Model – assigns total traveled distance (in km) and total battery energy consumption (in kWh) for the entire network, a specified section, or route;
- the QUARTET Pollutant Emission Model – assigns total traveled distance (in km) and determines the mass (in kilograms) of each type of emitted pollutant for the entire network, a specified section, or route;
- the Panis et al.'s Pollutant Emission Model – provides two time series for each type of pollutant (CO_2, NOx, VOC, and PM), reporting their values in grams and in g/km (labeled as "interurban");
- the London Emissions Model (LEM) – two time series for CO_2 and NOx are added to sections (g/km), links (g/h), and replication (g).

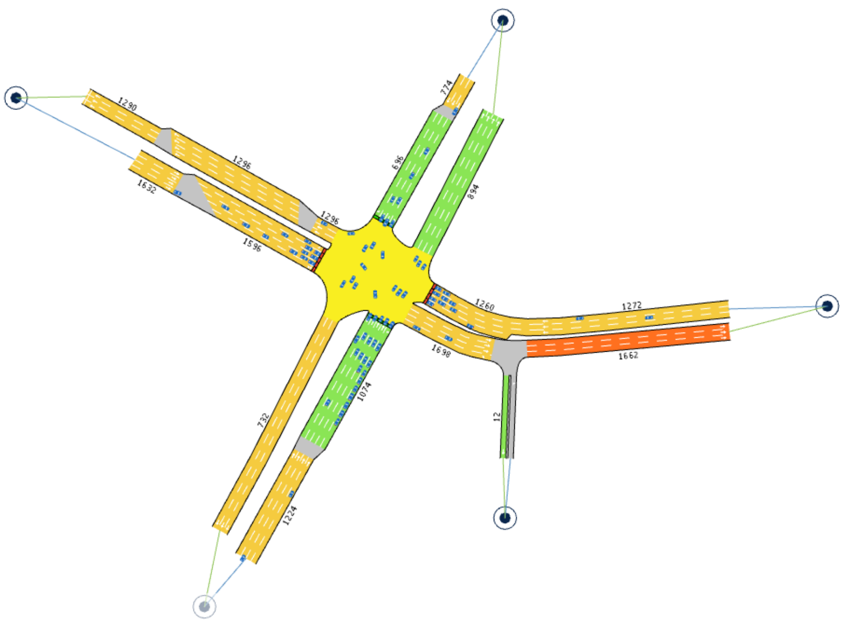

Fig. 5. Digital twin of the analyzed intersection

In the article, the instantaneous emission models (IEM) were used, which are particularly based on parameters such as vehicle speed, acceleration and deceleration, and engine load. The analysis focused on changes in emissions parameters: carbon dioxide (CO2), nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOC), also indicating indices relating to pollutant amounts per kilometer of road. This will allow for an environmental assessment of the selected study area and the potential for decarbonizing the intersection. An important parameter is the energy consumption for transportation in relation to electrification, which will constitute the basis for assessing the potential use of infrastructure for energy redistribution.

4. Results and Discussion

Based on the simulations conducted for the defined research scenarios, the results obtained are presented in Table 2.

The results indicate the importance of smooth traffic flow and electric vehicles in the context of transport decarbonization. Smooth autonomous vehicle traffic, based on self-regulation, enables a reduction of CO2 emissions by over 40% at the intersection compared to real-life traffic conditions. For other pollutant emission parameters, the possibility of reduction was as follows: NOx by 48%, PM by 73%, and VOC by 40%. It is important to emphasize that, in the case of electric vehicle traffic, traffic lights—which result in more frequent stops and the associated accelerations and decelerations—cause an increase in the energy consumption required for vehicle movement by about 159%. This highlights the significance of traffic management and control optimization, with the necessity to incorporate energy efficiency issues into control algorithms.

The above data directly provide information about the differences between ideal conditions in variant B, where there is no traffic signal cycle and every car is autonomous, positioned and controlled through V2G and V2E systems, and the operation of electric vehicles driven by humans, where the flow is regulated by the traffic light cycle—variant D. Comparing the energy consumption results for these two cases, we obtain a difference of 102.51 kWh in a one-hour window. According to the data, there are 32.72 light changes per hour. This translates to energy consumption of 3.13 kWh per light change cycle. Each cycle lasts about 1 minute and 50 seconds. The braking process for a vehicle traveling at 50 km/h with a deceleration of 1 m/s² lasts approximately 13 seconds, covering a distance of about 96 meters, which fits within the experiment radius of 150 meters from the intersection axis. It can be assumed that this time is twice as long for all vehicles from the analyzed traffic segment.

Therefore, the energy amount of 3.13 kWh must be stored within 26 seconds. Using equation (1), we obtain a power output of 433.384 kW.

$$P = \frac{E}{t} \tag{1}$$

where:
P – power,
E – energy,
t – time.

Table 2. Results for individual variants

Variant	A	B	C	D	E
Traffic signal control	No	No	Yes	Yes	Yes
Share of electric vehicles [%]	10	100	10	100	0
Battery Consumption - Car [kWh]	17,95	170,92	28,51	273,43	0
IEM Emission - Car - CO_2 [g]	269970,17	0	452876,44	0	509289,7
IEM Emission - Car - Nox [g]	618,8	0	1198,82	0	1136,05
IEM Emission - Car - PM [g]	60,54	0	226,85	0	208,56
IEM Emission - Car - VOC [g]	237,19	0	396,01	0	660,17
IEM Emission - Car - CO_2 - Interurban [g/km]	162034,59	0	271813,91	0	305672,84
IEM Emission - Car - NOx - Interurban [g/km]	371,4	0	719,52	0	681,85
IEM Emission - Car - PM - Interurban [g/km]	36,33	0	136,15	0	125,18
IEM Emission - Car - VOC - Interurban [g/km]	142,36	0	237,69	0	396,23

It is precisely this high power requirement that will be the main challenge for the energy storage technology. As can be seen, the system will be characterized by very unique parameters, where the power output represents over 100 times the storage capacity. In typical grid applications, such as energy storage for capacity markets, these are usually four-hour solutions—meaning the entire stored energy is released over a period of four hours. In the analyzed case, however, the entire energy storage must be both absorbed and released within less than half a minute. This clearly demonstrates how specific and unique this solution is. Given the limited space, safety concerns, and functional requirements, the choice is limited to supercapacitor and flywheel technologies. The main parameters of both technologies are summarized below (Table 3).

Table 3. Main parameters of flywheel and supercapacitors

Parameter	Flywheel	Supercapacitors
Number of cycles	500000	500000
Service life	>20 year	>20 year
Storage volume	~1m3	12m3
Efficiency	85-90%	85-90%

At this point, it is worth mentioning the expected amount of stored energy. Although the assumed capacity of the storage unit is relatively small—3.13 kWh—the fact that there are almost 728 light changes per day means the total energy processed can reach almost 2.5 MWh. This is a significant value in terms of both the energy that would be reused (thus saving its primary source) and environmental benefits, as it would reduce particulate matter and carbon dioxide emissions by more than 2 tons.
The final decision regarding the preferred technology at a given location will depend on commercial conditions, the amount of space available for installation, market availability of the solution, and the proposed service and maintenance arrangements.
The comparative analysis of traffic scenarios allows for the evaluation in a predictive way of the best strategy to be adopted in infrastructure management and urban planning policies of cities (Mądziel et al., 2021).

5. Conslusion

Contemporary analyses highlight the necessity of integrating energy efficiency and emission indicators into urban traffic control algorithms. Such optimization is crucial for improving air quality and reducing the carbon footprint of transportation, especially in cities where frequent braking and acceleration are unavoidable. Research and simulations indicate that the use of energy recovery and storage technologies, such as supercapacitors and flywheels, has a significant impact on reducing emissions of carbon dioxide, nitrogen oxides, particulate matter, and volatile organic compounds.
Autonomous vehicles, through optimized road maneuvers, can substantially reduce energy consumption and CO_2 emissions. With energy storage and recovery systems from braking, it is possible to further increase the efficiency of urban transport, which may positively impact the quality of life for residents of large metropolitan areas. It is proposed to develop systems based on inductive loops, enabling energy redistribution to and from electric vehicles.
The integration of energy recovery systems and V2G (vehicle-to-grid) technologies in public transport vehicles could further decrease pollutant emissions. Economic analysis should take into account the costs of installation and maintenance of these solutions as well as the potential savings resulting from reduced energy consumption.
Further research should address variable traffic conditions, such as intensity at different times of day and weather conditions, to allow for more precise modeling and optimization of energy systems in transportation. The current study includes models related to passenger vehicle traffic and will be expanded in the future to include public transportation flows.
In summary, advanced technologies and traffic control algorithms supported by a developed decarbonization infrastructure offer significant environmental and operational benefits. Collaboration with institutions responsible for road infrastructure will enable the broad implementation of such solutions. The development of energy recovery technologies in urban transport carries considerable potential for reducing its environmental impact, making it a key area for future investment in sustainable mobility.

References

1. Afif, A., Rahman, S. M., Tasfiah Azad, A., Zaini, J., Islan, M. A., & Azad, A. K. (2019). Advanced materials and technologies for hybrid supercapacitors for energy storage – A review. *Journal of Energy Storage*, *25*, 100852. https://doi.org/10.1016/j.est.2019.100852
2. Amin, I. K., Islam, Md. N., Hasan, Md. K., Jaman, A., & Uddin, M. N. (2023). Design and Analysis of a Bidirectional Wireless Power Transfer System for Dynamic Charging of Electric Vehicles. *2023 IEEE Industry Applications Society Annual Meeting (IAS)*, 1–8. https://doi.org/10.1109/IAS54024.2023.10406996
3. Amiryar, M. E., & Pullen, K. R. (2020). Analysis of Standby Losses and Charging Cycles in Flywheel Energy Storage Systems. *Energies*, *13*(17), 4441. https://doi.org/10.3390/en13174441
4. Anbumani, K., Janani S, M., J, P., M, S., & B, D. (2023). Integrating Regenerative Braking with Advanced Battery Management for Sustainable Transportation. *2023 Intelligent Computing and Control for Engineering and Business Systems (ICCEBS)*, 1–7. https://doi.org/10.1109/ICCEBS58601.2023.10449122
5. Bennaya, S., & Kilani, M. (2024). Evaluating the Benefits of Promoting Intermodality and Active Modes in Urban Transportation: A Microsimulation Approach. In F. Belaïd & A. Arora (Eds.), *Smart Cities* (pp. 279–294). Springer International Publishing. https://doi.org/10.1007/978-3-031-35664-3_15
6. Bingham, C., Walsh, C., & Carroll, S. (2012). Impact of Driving Characteristics on Electric Vehicle Energy Consumption and Range. *Iet Intelligent Transport Systems*, *6*(1), 29–35. https://doi.org/10.1049/iet-its.2010.0137
7. Chen, B., Chen, Y., Wu, Y., Xiu, Y., Fu, X., & Zhang, K. (2023). The Effects of Autonomous Vehicles on Traffic Efficiency and Energy Consumption. *Systems*, *11*(7), 347. https://doi.org/10.3390/systems11070347
8. Choi, C., Kim, S., Kim, R., Choi, Y., Kim, S., Jung, H., Yang, J. H., & Kim, H.-T. (2017). A review of vanadium electrolytes for vanadium redox flow batteries. *Renewable and Sustainable Energy Reviews*, *69*, 263–274. https://doi.org/10.1016/j.rser.2016.11.188
9. Cristescu, C., Drumea, P., Ion, D., Dumitrescu, C., & Chirit, C. (2011). Mechatronic Systems for Kinetic Energy Recovery at the Braking of Motor Vehicles. In H. Martinez-Alfaro (Ed.), *Advances in Mechatronics*. InTech. https://doi.org/10.5772/24420
10. Czagany, M., Hompoth, S., Keshri, A. K., Pandit, N., Galambos, I., Gacsi, Z., & Baumli, P. (2024). Supercapacitors: An Efficient Way for Energy Storage Application. *Materials*, *17*(3), 702. https://doi.org/10.3390/ma17030702
11. Esparcia, E. A., Castro, M. T., Odulio, C. M. F., & Ocon, J. D. (2022). A stochastic techno-economic comparison of generation-integrated long duration flywheel, lithium-ion battery, and lead-acid battery energy storage technologies for isolated microgrid applications. *Journal of Energy Storage*, *52*, 104681. https://doi.org/10.1016/j.est.2022.104681
12. Gołda, I. J., Gołębiowski, P., Izdebski, M., Kłodawski, M., Jachimowski, R., & Szczepański, E. (2017). The evaluation of the sustainable transport system development with the scenario analyses procedure. *Journal of Vibroengineering*, *19*(7), 5627–5638. https://doi.org/10.21595/jve.2017.19275
13. Haidl, P., Buchroithner, A., Schweighofer, B., Bader, M., & Wegleiter, H. (2019). Lifetime Analysis of Energy Storage Systems for Sustainable Transportation. *Sustainability*, *11*(23), 6731. https://doi.org/10.3390/su11236731
14. Hasan, U., Whyte, A., & AlJassmi, H. (2022). A Microsimulation Modelling Approach to Quantify Environmental Footprint of Autonomous Buses. *Sustainability*, *14*(23), 15657. https://doi.org/10.3390/su142315657
15. Jacyna, M., & Merkisz, J. (2014). PROECOLOGICAL APPROACH TO MODELLING TRAFFIC ORGANIZATION IN NATIONAL TRANSPORT SYSTEM. *Archives of Transport*, *30*(2), 31–41. https://doi.org/10.5604/08669546.1146975

16. Jacyna, M., Wasiak, M., Kłodawski, M., & Lewczuk, K. (2014). SIMULATION MODEL OF TRANSPORT SYSTEM OF POLAND AS A TOOL FOR DEVELOPING SUSTAINABLE TRANSPORT. *Archives of Transport*, *31*(3), 23–35. https://doi.org/10.5604/08669546.1146982
17. Jacyna, M., Żochowska, R., Sobota, A., & Wasiak, M. (2021). Scenario Analyses of Exhaust Emissions Reduction through the Introduction of Electric Vehicles into the City. *Energies*, *14*(7), 2030. https://doi.org/10.3390/en14072030
18. Jahangard, M., Madarshahian, M., Sabur, H., Rezvani, R., Mohammadzadeh Moghaddam, A., & Huynh, N. (2023). Illegal Maneuver Effect on Traffic Operations at Signalized Intersections: An Observational Simulation-Based Before-After Study Using Response Surface Methodology. *Journal of Advanced Transportation*, *2023*, 1–19. https://doi.org/10.1155/2023/2038167
19. Ji, W., Hong, F., Zhao, Y., Liang, L., Du, H., Hao, J., Fang, F., & Liu, J. (2024). Applications of flywheel energy storage system on load frequency regulation combined with various power generations: A review. *Renewable Energy*, *223*, 119975. https://doi.org/10.1016/j.renene.2024.119975
20. Lárusdóttir, E. B., & Úlfarsson, G. F. (2014). Effect of Driving Behavior and Vehicle Characteristics on Energy Consumption of Road Vehicles Running on Alternative Energy Sources. *International Journal of Sustainable Transportation*, *9*(8), 592–601. https://doi.org/10.1080/15568318.2013.843737
21. Li, M., Qiu, C., & Zheng, Z. (2016). Thermal Analysis on Power Battery of Intermittent Discharging under Sample Function. *DEStech Transactions on Environment, Energy and Earth Science*, *peee*. https://doi.org/10.12783/dteees/peee2016/3803
22. Li, X., & Palazzolo, A. (2022). A review of flywheel energy storage systems: State of the art and opportunities. *Journal of Energy Storage*, *46*, 103576. https://doi.org/10.1016/j.est.2021.103576
23. *Mądziel, M., Campisi, T., Jaworski, A., & Tesoriere, G. (2021). The Development of Strategies to Reduce Exhaust Emissions from Passenger Cars in Rzeszow City—Poland. A Preliminary Assessment of the Results Produced by the Increase of E-Fleet. Energies, 14(4), 1046. https://doi.org/10.3390/en14041046*
24. Men, Z., Zhang, X., Peng, J., Zhang, J., Fang, T., Guo, Q., Wei, N., Zhang, Q., Wang, T., Wu, L., & Mao, H. (2022). Determining factors and parameterization of brake wear particle emission. *Journal of Hazardous Materials*, *434*, 128856. https://doi.org/10.1016/j.jhazmat.2022.128856
25. Merkisz, J., Andrzejewski, M., Merkisz-Guranowska, A., & Jacyna-Gołda, I. (2014). THE INFLUENCE OF THE DRIVING STYLE ON THE CO2 EMISSIONS FROM A PASSENGER CAR. *Journal of KONES. Powertrain and Transport*, *21*(3), 219–226. https://doi.org/10.5604/12314005.1133212
26. Mintsis, E., Belibassakis, M., Mintsis, G., Basbas, S., & Pitsiava-Latinopoulou, M. (2016). The use of a transport simulation system (AIMSUN) to determine the environmental effects of pedestrianization and traffic management in the center of Thessaloniki. *EUROPEAN JOURNAL OF ENVIRONMENTAL SCIENCES*, *6*(1), 25–29. https://doi.org/10.14712/23361964.2016.5
27. Muzir, N. A. Q., Hasanuzzaman, Md., & Selvaraj, J. (2023). Modeling and Analyzing the Impact of Different Operating Conditions for Electric and Conventional Vehicles in Malaysia on Energy, Economic, and the Environment. *Energies*, *16*(13), 5048. https://doi.org/10.3390/en16135048
28. Salek, F., Babaie, M., Redel-Macias, M. D., Ghodsi, A., Hosseini, S. V., Nourian, A., Burby, M. L., & Zare, A. (2020). The Effects of Port Water Injection on Spark Ignition Engine Performance and Emissions Fueled by Pure Gasoline, E5 and E10. *Processes*, *8*(10), 1214. https://doi.org/10.3390/pr8101214
29. Simon, P., Gogotsi, Y., & Dunn, B. (2014). Where Do Batteries End and Supercapacitors Begin? *Science*, *343*(6176), 1210–1211. https://doi.org/10.1126/science.1249625
30. Sippel, I., Magdin, K., & Evtyukov, S. (2024). Simulation modeling as a decision support system tool for improving the environmental safety of road transport. In A. Gibadullin & K. Eshankulov (Eds.), *Third International Conference on Digital Technologies, Optics, and Materials Science (DTIEE 2024)* (p. 21). SPIE. https://doi.org/10.1117/12.3035765
31. Su, Z., Liu, Q., & Gong, L. (2023). Energy Consumption Optimization of Connected and Autonomous Vehicles Based on Cooperative Perception in Ramp Overflow Scene. *Journal of Circuits, Systems and Computers*, *32*(16), 2350282. https://doi.org/10.1142/S0218126623502821

32. Szumska, E., & Jurecki, R. (2020). The Effect of Aggressive Driving on Vehicle Parameters. *Energies*, *13*(24), 6675. https://doi.org/10.3390/en13246675
33. Tumminello, M. L., Macioszek, E., Granà, A., & Giuffrè, T. (2023). Evaluating Traffic-Calming-Based Urban Road Design Solutions Featuring Cooperative Driving Technologies in Energy Efficiency Transition for Smart Cities. *Energies*, *16*(21), 7325. https://doi.org/10.3390/en16217325
34. Urząd m.st. Warszawy. (2024, April 11). *UM Warszawa*. https://um.warszawa.pl/
35. Viswanathan, V. V., Crawford, A. J., Thomsen, E. C., Shamim, N., Li, G., Huang, Q., & Reed, D. M. (2023). An Overview of the Design and Optimized Operation of Vanadium Redox Flow Batteries for Durations in the Range of 4–24 Hours. *Batteries*, *9*(4), 221. https://doi.org/10.3390/batteries9040221
36. Wang, J., Besselink, I., & Nijmeijer, H. (2017). Battery Electric Vehicle Energy Consumption Prediction for a Trip Based on Route Information. *Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering*, *232*(11), 1528–1542. https://doi.org/10.1177/0954407017729938
37. Whitehead, A. H. (2023). Safety Considerations of the Vanadium Flow Battery. In C. Roth, J. Noack, & M. Skyllas-Kazacos (Eds.), *Flow Batteries* (1st ed., pp. 175–191). Wiley. https://doi.org/10.1002/9783527832767.ch8
38. Wieser, S., Reiland, S., Bondorf, L., Lober, M., Schripp, T., & Philipps, F. (2022). Development and Testing of a Zero Emission Drive Unit for Battery Electric Vehicles. *2022 Second International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART)*, 1–6. https://doi.org/10.1109/SMART55236.2022.9990033
39. Wu, G., Boriboonsomsin, K., Zhang, W.-B., Li, M., & Barth, M. (2010). Energy and Emission Benefit Comparison of Stationary and in-Vehicle Advanced Driving Alert Systems. *Transportation Research Record Journal of the Transportation Research Board*, *2189*(1), 98–106. https://doi.org/10.3141/2189-11
40. Xiaotong, Y., Zheng, S., Shi, T., Chen, G.-Y., & Yadong, H. (2024). *Research on Influencing Factors of Driving Behavior Energy Consumption Based on Multi-Driving Conditions*. 84. https://doi.org/10.1117/12.3015786
41. Xu, K., Guo, Y., Lei, G., & Zhu, J. (2023). A Review of Flywheel Energy Storage System Technologies. *Energies*, *16*(18), 6462. https://doi.org/10.3390/en16186462
42. Xu, Z., Ma, R., & Wang, X. (2022). Ultrafast, long-life, high-loading, and wide-temperature zinc ion supercapacitors. *Energy Storage Materials*, *46*, 233–242. https://doi.org/10.1016/j.ensm.2022.01.011
43. Yan, Y., & FAN, Y. (2017). *Influence of the Driver Style Difference in the Acceleration Process on the Energy Consumption of the EV Bus*. https://doi.org/10.2991/iceat-16.2017.39
44. Yao, E., Yang, Z., Song, Y., & Zuo, T. (2013). Comparison of Electric Vehicle's Energy Consumption Factors for Different Road Types. *Discrete Dynamics in Nature and Society*, *2013*, 1–7. https://doi.org/10.1155/2013/328757
45. Yao, K., Ye, C., Liu, Y., Yang, M., & Zhao, Y. (2024). Loss and Vibration Analysis of Flywheel Energy Storage Motor for UPS System. *2024 IEEE China International Youth Conference on Electrical Engineering (CIYCEE)*, 1–6. https://doi.org/10.1109/CIYCEE63099.2024.10846487
46. Yu, Y. (2024). Vanadium redox flow battery: Characteristics and application. *Applied and Computational Engineering*, *58*(1), 267–273. https://doi.org/10.54254/2755-2721/58/20240732
47. Zhang, L., Song, G., & Zhang, Z. (2022). Heterogeneity Analysis of Operating Mode Distribution for Modeling Energy Consumption of Light-Duty Vehicles. *Transportation Research Record Journal of the Transportation Research Board*, *2677*(1), 93–109. https://doi.org/10.1177/03611981221098397