Methodological Framework for the Comparative Evaluation of the Emission Footprint of Virtual Remote Work and Travel by Autonomous Electric Vehicle to the Workplace

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***Abstract* - The purpose and idea of the paper is to define a methodological framework for the comparative assessment of the carbon footprint of virtual remote work and the footprint of an autonomous electric vehicle for physical mobility to the workplace. The methodology is based on the remote work service, as a typical representative of information and communication solutions with potentially significant opportunities to reduce emissions in the area of physical mobility. On the other hand, autonomous electric vehicles cause less greenhouse gas emissions than diesel cars, even when powered by engines with lower carbon emissions, but we still don't know if it is more environmentally friendly to use digital teleworking services instead of electric autonomous vehicles for trips to the workplace. In the proposed methodology, special attention will be focused on the analysis of emission variables for existing consumption technologies of autonomous vehicles. The originality and value of the work consists in the fact that the results of the work offer an original comparative procedure for determining the value of emission footprint of the physical mobility of an autonomous electric vehicle in relation to the footprint of the virtual mobility of telecommuting.**

Key words - remote work; autonomous electric vehicles; emissions

I. Introduction

Virtual remote work (telecommuting) is a typical representative of information and communication services, which we define as a model of performing regular work from home, instead of traveling by car to work. In the literature, the terms tele-work or telepresence are also used for this kind of work. Telecommuting as a function of reducing the number of trips has been around for a long time, but the growth of this type of service has been relatively slow since then, except during the pandemic. The indicators of the reduction of traffic emissions from this period show the potential of the service in solving the problem of reducing direct traffic carbon emissions. Different strategies towards less intensive traffic are requiring consideration of potential for carbon reduction by introducing the measure of telecommuting.

On the other hand, vehicles with zero emissions during travel are rapidly developing with consequences for energy consumption and greenhouse gas emissions. Zero-emission vehicles (ZEVs) including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) are rapidly developing with varying effects on energy use and emissions. Electric vehicles (EVs) are widely regarded as a promising solution to reducing greenhouse gas emissions and key to the future of low-carbon mobility. It should be noted that BEV has the least amount emissions compared to internal combustion engine (ICE), HEV and PHEV. However, in the paper we focus on autonomous electric vehicles (AEV) 3,4, and 5 levels of autonomy, which have significantly higher efficiency and lower emissions compared to other levels. The vehicles themselves represent a new generation of vehicles that can move independently on roads, that is, with or without any human intervention. Four main drivers that include automated driving, electric powertrains, connectivity and shared mobility can provide a compelling transition to a low-carbon future. The vehicles function using a high-tech system that, among other things, consists of cameras, radar sensors and laser beams, with which the car recognizes the environment in which it is located, as well as other traffic participants. The vehicle continuously collects new amounts of information it receives from objective reality and reacts accordingly. By applying sensor and GPS technologies, vehicles follow road maps, including events, in order to safely reach the desired destination, and certain, more advanced systems have the ability to independently update and optimize the movement path with the help of sensor information. The main advantage of AEVs over conventional systems is the zero emission of harmful gases from the propulsion system during the trip. Also, on the electric vehicle there is no need to change the engine oil, which represents a great potential danger for environmental pollution.

The subject of research in the paper are emissions that can still appear in the process of electricity production in the case of non-carbonized power sources. A specific cause of the negative impact of these vehicles on the environment is the computer system that controls these vehicles and which indirectly generate large amounts of greenhouse gases, i.e. the autonomous driving mode consumes large amounts of energy for processing the autonomy and reliability information of the system. Data centers that house the computing infrastructure used to run applications are notorious for their large carbon footprint.

The methodological framework for researching the operational emissions of AEV computers requires a detailed analysis of the basic consumption factors (360° sensors, the power of the computer on the vehicle, driving hours of each vehicle and the amount of electricity emission that drives all equipment). In addition to the basic energy consumption of electric vehicles, the consumption manifests itself differently depending on additional factors: speed and driving style, topography, road geometry, weather and ambient conditions in the environment, and the electrical load of the vehicle. Achieving long-term energy efficiency of these vehicles means the application of more specialized and energy-efficient hardware designed to run specific driving algorithms as well as the possibility of simple application of new algorithms.

The purpose of this work, in the time of still incompletely decarbonized electricity production, is first of all to look at the indirect emissions of AEVs that are started and run using the energy stored in the battery. On the other hand, authors of the paper are fully aware that an additional trend in the traffic system is towards connected autonomous vehicles (CAEVs), which will play a key role in the new revolution in sustainable mobility with low emissions. Such vehicles can have great potential to operate with greater efficiency, only if they are charged from renewable energy sources that will significantly reduce emissions and dependence on fossil fuel sources. The fact is that such vehicles are complex automotive systems that combine the characteristics of connected vehicles (CV - a vehicle with technology that enables it to communicate with nearby vehicles, infrastructure and objects, but are not automated or electric), autonomous vehicles (AV - a vehicle that, in the broadest sense, capable of driving itself without human intervention) and electric vehicles (EVs).

II. STRUCTURE OF COMPONENTS OF AUTONOMOUS ELECTRIC VEHICLES

The core consumption components of autonomous electric vehicles are: electric motor, battery maintenance systems, various sensors and motor controllers with advanced communication and sensing capabilities and enhanced travel convenience. The system of an electric vehicle with an independent power source is based on the battery, which represents the only source of driving energy, and is charged via a connection from the power grid. E.g. the direct current from the battery through the amplifier and converter is increased and converted into alternating current and, if necessary, sent to electric motors that convert electrical energy into mechanical energy, which is then transferred to the wheels via transmission [1]. The controller manages the operation of the electric motor and the vehicle system through hardware components and software support and monitors the condition of the vehicle, coordinates work and reacts to changes in external driving conditions by issuing appropriate orders to the power unit and other system components. Other parts of electric vehicles are: analog-to-digital signal converter that provides the desired speed information, circuit breaker, fuse or switch, direct current (DC) voltage converter for driving the vehicle's built-in consumers (lights, direction indicators, wipers, sound signal, radio device, etc.), measuring instruments for vehicle management (battery remaining capacity indicator, voltage, current, power, speed), electric battery charger [2].

The energy management system in an electric vehicle aims to increase efficiency and reduce consumption so as to maximize the use of the battery and ensure efficient operation. These include the following control functions:

- *Power supply control:* the energy management system manages the supply of electricity from the battery according to the necessary electrical systems in the vehicle (engine, lights, air conditioning, etc.);
- *Engine speed regulation:* the energy management system controls engine speed to reduce energy consumption and increase energy efficiency;
- *Energy consumption optimization:* the energy management system applies various algorithms to optimize energy consumption, including energy recovery during braking and vehicle speed optimization;
- *Battery management:* the power management system also manages the battery, including its charging and status monitoring;
- *Integration with other systems:* the energy management system is often integrated with other electrical systems in the vehicle, such as the driving control system and air conditioning, to ensure the most efficient use of energy.

Modern user interface concepts of AEVs do not have standard elements such as steering wheel, pedals and gearbox, they are replaced by a large screen. E.g. the architecture of the control system of an autonomous vehicle of the fifth degree of autonomy according to the Society of Automotive Engineers (SAE) classification is divided into four parts consisting of sensor, client, action and user systems [3].

Sensor systems consist of several different sensors that have the task of collecting data from the vehicle's environment in real time. Short range sensors are ultrasonic sensors, capacitive sensors or infrared sensors while long range sensors are LIDAR, RADAR, computer vision and advanced GPS.

The client system has the task of processing a large amount of collected data and extracting the most important information in order to interpret the objective reality, determine the position of the vehicle in space, and thus decide on the next steps in driving.

Action systems represent the mechanical parts of AEV (e.g. steering, braking and drive systems) that actually execute the commands received from the client system and direct the autonomous electric vehicle.

User systems are a combination of hardware and software that allow the user of AEV to communicate with it in real time. The elements of the user system consist of pointers that provide information to the user about the optimal route of the vehicle or the actions he intends to perform.

III. ENVIRONMENTAL EFFECTS OF APPLICATION OF AUTONOMOUS ELECTRIC VEHICLES

The impacts of the AEVs can mainly be classified as indirect impacts that are a consequence of the current consumption of electricity, where the reasons and consequent connections of these impacts are mostly clear and well understood (Figure 1.).

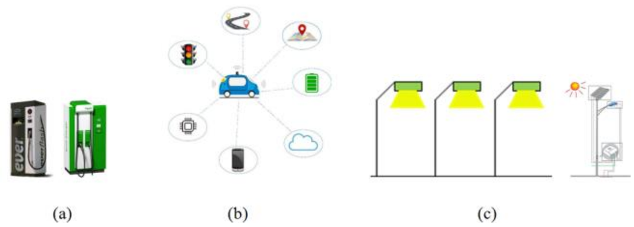

Figure 1. (a) Renewable and non-renewable energy sources, (b) consumers of AEVs and (c) secondary consumers

These impacts stem from the goal of using AEVs, i.e. energy efficiency and traffic development based on the energy sector of renewable sources. In this context, it is expected that by 2030, 55% of new vehicles in Europe will be fully electric, and 40% will be hybrids [4]. The introduction of electric vehicles causes the need for global planning of increased energy supply. The energy storage capacity of electric vehicles can be used to equalize demand and mitigate variations.

Other indirect impacts (secondary effects of the production of components for AEVs), which often have more severe consequences for the environment than the first impact, are the production processes and the availability of cobalt, lithium and other materials. In order to reduce this effect and avoid environmental pollution, the recycling of batteries must be encouraged [5].

The third type of impact is cumulative impacts that have additional, multiplying or synergistic effects of the type of construction of additional infrastructure required for AEVs.

The trend is for AEVs to increase the number of kilometers traveled per unit of time, which could contribute to significant environmental improvements given that they are electric and will drive more efficiently. AEVs produce zero emissions when in motion and are less noisy than classic fossil fuel vehicles. Indirect effects occur if the sources for powering the AEVs are non-renewable, e.g. autonomous electric vehicle level 3 does not emit CO_2 directly, but often uses electricity generated with indirect emissions in thermal power plants (Table I.).

TABLE I. EFFECTS OF APPLICATION OF AEVs

Category	Identified effects
Direct influences	None
Primary positive impacts	Reducing the use of diesel and gasoline vehicles.
Secondary positives impacts	Reduction of noise in the room.
	Reduced construction of facilities - pumps.
Primary negative impacts	Increased electricity consumption (from hydro and thermal power plants).
Secondary negative impacts	Expansion of the network of filling stations in the area.
	Increasing demand for batteries and specific materiales.

IV. ANALYSIS OF THE EFFECTS OF VIRTUAL WORK ON THE REDUCTION OF INDIRECT EMISSIONS OF AUTONOMOUS ELECTRIC VEHICLES

The methodology for assessing the effects of remote virtual work on the reduction of emissions of AEVs includes two domains: the first refers to the assessment of emissions that technologies directly cause, and the second to the quantification and valorization of the effects of reducing emissions that arise applying this measure. Both effects must be taken into account to assess the overall utility of the application. The methodological assessment procedure is based on the use of the life cycle approach [6].

In the first step, it is necessary to define the goal of the research, which is the basis for defining the indicator, and in the case of telecommuting, it could be defined as research into the possibility of applying services to reduce emissions in the commuting sector, bearing in mind the increased energy consumption in traffic. The analysis can be performed at the level of office or company, that is, of the employees. The scope of the research involves defining the components of the two systems. An alternative system usually contains a PC, a printer and the necessary infrastructure such as servers and networks. The components of the Baseline Assembly Unit (BAU) system are the components of the AEV defined in chapter II, a private garage and a public parking lot (Table II.).

TABLE II. BAU SYSTEM COMPONENTS

System	Description	System components	
ICT	Virtual remote work (telecommuting)	1. Computer 2. Printer 3. Data center	4. Servers 5. Networks
BAU	Autonomous electric vehicle (relation house - office)	1. Private vehicle 2. Public vehicle	3. Private garage 4. Equipment in the office 5.Public parking

In the next step, it is necessary to look at all positive and negative effects and then select only those that are considered to have a significant impact on the environment. If the effects that are expressed in a relatively short time and at a relatively small scale of implementation (company level) are chosen, the final list of processes that require evaluation is reduced. The reference BAU value is determined, in this case, on the basis of the potentially greatest effect that can be realized [7]. In the case of telecommuting, potential effects are given in Table III.

TABLE III. EFFECTS OF TELECOMMUTING

Category	Identified effects
Direct emission	Emission from telecommuting equipment
Primary positive impacts	Reducing the use of autonomous vehicles.
Secondary positive impacts	Reducing the use of autonomous public transport vehicles.
	Reduced use of public parking areas.
	Reduced construction of additional facilities.
	Reduction of construction of road infrastructure.
Primary negative impacts	Increased energy consumption in the house.
Secondary negative impacts	Expansion of cities in space.
	Increase in trips outside the commuting area.

This means that it is necessary to calculate the level of indirect emissions emitted by the use of a private or public

AEV powered by non-renewable sources per employee (data can be extrapolated for the number of employees in a company), in the house-office/factory relationship (Figure 2.).

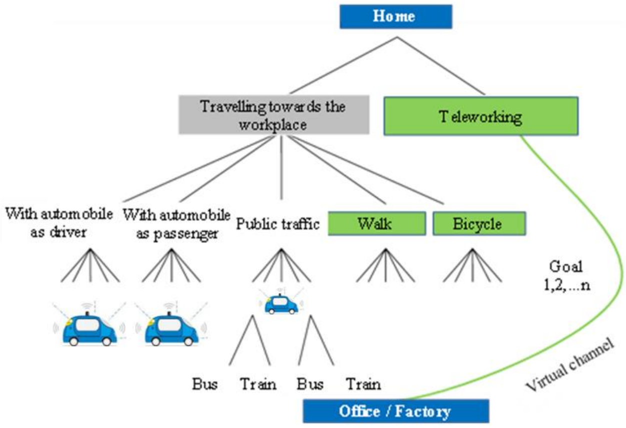

Figure 2. Structure of the physical travel model and the virtual channel of the home-work relationship

Variations in the emissions of the telecommuting components themselves are considered negligible for a shorter period of time, and the operation of some system components such as servers and computer centers are also unaffected because they work independently of where the employees are currently located. In addition, it is assumed that the employees already have the necessary equipment at home (Figure 3.), so the acquisition of new equipment for the needs of virtual work is partially unaffected by the emissions of component production.

The following effects were identified as significant: reduction in the number of trips by AEV, increase in household energy consumption and reduction in the use of equipment and energy in offices and lighting in closed parking lots. All of them represent processes that should be mathematically quantified in the use phase.

The next step is to determine the mean values of the distance from home to work, then determine the percentage of employees who use AVEs and those who use public electric transportation, and use the existing emission factors for the final calculation.

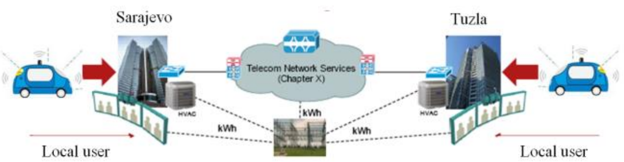

Figure 3. Structure of telecommuting system equipments

V. Model of the Indirect Footprint of Journey to Work by Autonomous Electric Vehicle

The emissions footprint parameter of an AEV commute is a combination of a set of characteristics sufficient to determine the behavior of emission values. In the practice of classic vehicles, there are four variables that have an impact on the emission value of the trip: A (total transport activity in the vehicle in km), S (participation of the mode of transport in the road), I (energy intensity) and F (CO_2 content in fuels). In our case, these variables need to be adapted to the AEV technology so that we have: P (drive energy consumption per 100 km traveled, i.e. consumption of AEV activities), D (range of certain AEV models with one charge in km - a higher number of charges causes losses energy), E (CO_2 emissions/km from the power source, with a note that AEVs do not emit CO_2 directly, but use electricity generated with emissions, e.g. in thermal power plants) and S (participation of secondary emissions, such as parking lighting). To determine the savings in CO_2 emissions by replacing travel with virtual work, not only the estimated CO_2 emissions of the vehicle are significant, but also the savings in secondary emissions (e.g. parking lot lighting, congestion in combined traffic, etc.).

To estimate the consumption of AEVs, it is necessary to take an average. With current technology, consumption ranges from 10 to 30 kWh/100 km, while the average consumption is around 17 kWh/100 km, depending on traffic conditions. If we multiply this value by the emission of the thermal power plant as a source of non-renewable energy, we get 9.978,515 gCO_2 for every 100 km. We divide the value by 100 and get a result of 99.78 gCO_2/km. This emission value would be relatively accurate if all the electricity needed for an autonomous vehicle was produced from a thermal power plant, and the emission would represent CO_2 emissions due to the production of electricity from non-renewable sources. If we take the second case that all the required energy is produced from renewable energy sources that generate emissions of up to 8 $gC0_2$/kWh, we would get the value that for every 100 km an AEV has 140 gCO_2. If we divide that value by 100, we get a result of 1.4 gCO_2/km, which is approximately 1.4% of the emissions in relation to the non-renewable source of electricity produced from the thermal power plant.

VI. Research of the Mathematical Model of Measuring Emission Savings of Journey to Work Using the Substitution Measure

For the calculation of emission savings, we propose the PDS (meaning is given below) procedures, as a method for quantifying the carbon emissions of AEVs. The procedure is adapted for the calculation of CO_2 emissions in passenger transport (private AEV, public AEV transport). The total CO_2 emissions of commuting are shown as the product of three factors: energy power consumption (P), travel distance (D) plus the factor of traffic congestion and secondary consumption (S). The elements are of essential importance for assessment and require the definition of the basic labels of their elements:

- E - total CO_2 emissions of all AEVs used by the user on the way from home to work;
- E_i - are the individual CO_2 emissions of the sight (private, public) of the AEV and used by the user;
- k_j - is the type of electrical power source (non-renewable, renewable source) in the form of i (public, private);

- A_i - total vehicle activity in *km* by type *i* (eg number of fillings AEV during the day);
- λ_j - participation of k_i energy sources in the form of *i* (%);
- *j* - energy source in form *i*;
- M_i - participation of type *i* in some area (%);
- I_i - energy intensity of type *i*; and
- E_{ij} - CO_2 emissions from electricity *j* in the form of transport *i* in gCO_2.

According to the proposed model, the emission savings measured by the substitution of an AEV to work can be calculated as:

$$\Delta CO_2 = [(P_{BAU}*D_{BAU}) + S_{BAU}] - (P_m + S_m) \quad (1)$$

where is:

- P_{BAU} - activity of indirect emissions of an AEVs under the BAU scenario,
- D_{BAU} - workplace distance corrected with the congestion factor,
- S_{BAU} - represents the activity of indirect secondary emissions,
- P_m - activity emissions if the measure is taken (virtual work),
- S_m - indirect emissions of work from home.

CO_2 savings from the impact of reducing the activity of AEV after *t* years are calculated as the difference between the annual base value of CO_2 emissions and the annual value of CO_2 emissions in the event in which the virtual remote work activity was undertaken. For each of the components of the PDS procedure, an individual set of defined factors is required to determine the carbon impact of the measure (e.g. with S, detailed data on the type of lighting in the parking lot is required). In the process of measuring CO_2 reduction, there are always secondary effects that influence the result.

Also, an undesirable effect of the application of teleworking is "induced traffic" due to better road conditions (less congestion), when people, in addition to the telecommuting option, want to use AEVs more, traffic is induced and congestion problems are not solved. If several measures are taken at the same time, estimates of the overall impact on emission reduction become difficult.

VII. PROPOSAL OF A GENERIC PROCEDURE OF COMPARATIVE ANALYSIS OF ENVIRONMENTAL IMPACT

The proposed comparative methodology is applicable to cases where telecommuting is used to avoid travel in the following areas: avoiding business trips by AEV, avoiding employe AEV trips to regular work, avoiding personal transportation and using virtual services. The proposed procedure for calculating telecommuting emissions is presented in several steps.

The general approach is to first calculate the direct emissions associated with the provision of data transmission, voice and video access as well as the secondary energy consumption of the end users of the equipment (telephone, video display, or laptop). End-user space includes an employee's home or remote office. After that, through the process, we compare the obtained (positive effects) values with emissions from indirect emissions of AEVs, and in the function of reducing the employee's physical journey to work.

In the paper, we propose a framework of eleven steps for the comparative evaluation and calculation of emissions, i.e. the justification of the application of the BAU alternative, namely:

Step 1: Create an inventory of existing equipment at the first telecommuting location. Then an inventory of endpoints, remote network ICT equipment and company infrastructure. Due to the application of telecommuting services, the company will increase traffic on the network;

Step 2a: Estimate the total energy consumption (phase of use) and related greenhouse emissions of all the company's ICT infrastructure solution and the company's shared network infrastructure;

Step 2b: Calculate the total electricity consumption (phases of use) and associated CO_2 emissions of the end-point telecommuting solution and remote network telecommuting equipment;

Step 3: Estimate the total invested emissions (non-use phase) from telecommuting solutions for enterprise infrastructure and network infrastructure;

Step 4a: Extraction of the total, phase of use, emissions from telecommuting solutions of the company's infrastructure and network infrastructure for the observed period;

Step 4b: Extracting the total, phase of use, CO_2 emissions from the telecommuting solution endpoints for virtual work for a certain period;

Step 5a: Allocation of built-in emissions for all enterprise ICT infrastructure solutions and enterprise network infrastructure above the number of scheduled / actual meetings for that same time;

Step 5b: Allocation of built-in emissions (non-use phase) of telecommuting endpoint solutions in relation to the number of actual working hours;

Step 6: Adjust emissions of one working day, endpoints with the average number of endpoints in the company. Then add the extracts from steps 3 and 4;

Step 7: Estimate the total emissions burden of the service provider for delivering the expected telecommuting solution bit rate for a period;

Step 8: Total emission for all network infrastructure, allocated to usage phases;

Step 9: Individual journey records of journeys for at least 90% of transport will be used to determine greenhouse gas emissions;

Step 10: Assessing how telecommuting solutions affect the reduction of AEV use for travel;

Step 11: Evaluation of alternative modes of travel instead of AEVs, e.g. by bike or by foot.

The results of the comparative analysis procedure between the application of the autonomous electric vehicle and the telecommuting system formally represent the difference in the environmental impact between the AEVs and the telecommuting system:

$$EI_{difference,i} = EI_{AEV,i} - EI_{telecomuting,i} \quad (2)$$

where is:

- *EI = environmental impact*
- *i = i-th comparative category*
- $EI_{difference,i}$ = *i-th secondary environmental impact*
- $EI_{AEV,i}$ = *i-th EI of the autonomous electric vehicle*
- $EI_{telecommuting,i}$ = *i-th EI of the telecommuting system*

By summing the total $EI_{difference}$, i we get the $EI_{difference}$ or the effect of the telecommuting system covered by AEV trips. The equation below shows the formula for calculating the total effect:

$$Total\ EI_{difference} = \sum EI_{difference,i} \quad (3)$$

A positive result (Total $EI_{difference}$ is positive) indicates a positive impact on the environment and a negative value (Total $EI_{difference}$ is negative) represents a negative impact on the environment. Positive secondary effects indicate a reduction in the environmental burden due to the introduction of telecommuting services. Negative secondary effects indicate the opposite.

On the other hand, the achieved effect (x) is expressed in the reduced value (kt) of CO_2 emissions. In the same units, the CO_2 emission that was reduced due to energy saving in commercial buildings/offices (y) is expressed, as well as the emissions caused by additional energy consumption in households (z). The total effect (x+y-z) gives a quantitative value, that is, an answer to the question of the potential usefulness of using telecommuting instead of autonomous electric vehicles to reduce emissions.

VIII. CONCLUSION

The research results are showing new approach of measuring the indirect emission footprint of travel in the electromobility system. In the paper, we determine the role and potential impact of virtual mobility on the reduction of physical electromobility emissions. The methodological framework for the comparative evaluation of the emission footprint of virtual remote work and travel by electric autonomous vehicle to the workplace includes a combination of characteristics of the two systems sufficient to determine a positive impact on the reduction of carbon emissions of commuting. We conclude that the previous comparative assessment methodologies, derived on the basis of positive effects, partially describe the conditions in the electromobility system, and do not include impacts the range of transport activities themselves. For a more comprehensive and detailed approach to this issue, wider research and the availability of field data are needed.

Based on all of the above, we can conclude that in order for autonomous electric vehicles to reach maximum utilization and affect emission reduction, quality integration into electrical energy systems, building of energy-efficient charging infrastructure, production of sustainable batteries and, most importantly, decarbonization of electricity production is necessary. The autonomous electric vehicle system is a very complex system and small changes within the environmental sustainability of one subsystem can have a large effect on the entire system. In order to preserve the overall positive ecological impact of telecommuting on the reduction of indirect emissions of electromobility commuting, it is necessary to have a policy of preferring decarbonized power sources. The increase in demand for electricity to power such cars will present a long-term challenge for electricity suppliers. For this reason, the positive effects on environmental protection could be canceled out by additional emissions from the individual energy sector, if the additional demand for energy is produced from coal-fired plants.

As in any scientific work, within the framework of time and space limitations, a number of additional questions were opened here, which should be treated below, such as the total losses of AEVs in the traffic flow, energy consumption in peak periods of traffic, problems of induced traffic of electromobility etc.

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