D3.3 CO2-Impact Estimation Methodology within the Planning for Autonomous Vehicles (PAV) Project

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1. Introduction

On the 9th of August 2021, the UN's climate panel, IPCC, presented the first [1] in a series of six assessment reports that deal with climate change and what can be done to slow it down. The climate panel points out that with the current emissions rate, within ten years, we will pass the Paris Agreement's goal of a 1.5-degree temperature rise, which is ten years earlier than researchers previously thought. "The annual global [greenhouse gas] (GHG) emissions have continued to grow and reached 49.5 billion tons (gigatons, Gt) of carbon dioxide equivalents (CO_2eq) in the year 2010" [2]. As a result of these GHG emissions, the Carbon dioxide (CO_2) concentrations (in parts per million) have increased substantially in the earth's atmosphere, from 280 ppm in 1750 to over 340 ppm in 2020. This increase in the concentration of CO_2 started because of the industrial revolution, of approx. 1750.

Today the transport sector alone is "responsible for one-quarter of total global energy-related CO_2 emissions" (7.0 Gt CO_2eq by 2010), and "80 % of this increase coming from road vehicles" [2]. The transport sector is crucial for international and national trade, enabling social activity and economic growth in the local society. The emissions increase results from the ever-increasing demand for mobility and movement of goods in a globalized world and economic development. "[The] demands for transport of people and goods … continue to increase over the next few decades": passenger air travel worldwide due to improved affordability; demand for mobility in non-OECD countries; and increases in freight movements [2]. The direct GHG emissions of the transport sector rose 250 % from 2.8 Gt CO_2eq worldwide in 1970 to 7.0 Gt CO_2eq in 2010, not including emissions from the production of fuels, vehicle manufacturing, and infrastructure construction [2].

According to the UN's climate panel, IPCC, the emerging challenge is to develop a sustainable global economy that the Earth can support indefinitely. A definition provided by Daly states that a sustainable economy is achieved when "rates of use of renewable resources do not exceed regeneration rates; rates of use of nonrenewable resources do not exceed rates of development of renewable substitutes; rates of pollution emission do not exceed assimilative capacities of the environment" [3]. An economic model by Dorf, Figure 1, reflects relationships between input resources as natural capital, intellectual capital, financial capital, and technology; and outputs entities as the desired benefits and the undesired waste [4].

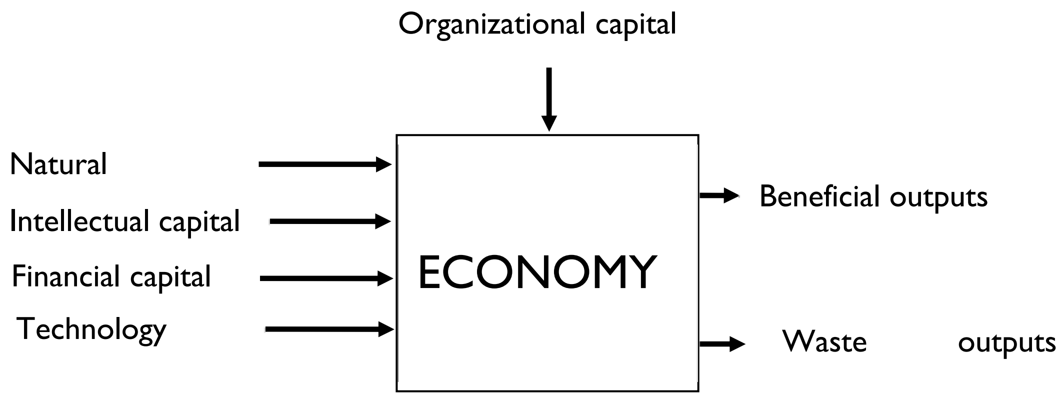

Figure 1: Economic model [4].

The two outputs of the economy model, Figure 1, impact the quality of life for humanity [4]. The problem is that beneficial outcomes often have a more direct effect on the quality of life than the indirect impact of waste outputs. Considering the waste output is crucial for developing a sustainable economy, i.e., innovative solutions that can improve resource efficiency, reduce greenhouse gas emissions, and address social and environmental challenges. There is a considerable CO_2 emission reduction potential in the transport sector at a low cost [4]. Efforts such as reduced transport activity, structural change, modal shift, and use of low-carbon energy sources can all substantially reduce CO_2 emissions. The world's sustainable development depends on the interaction between technological innovations, policy, economic activity, and the natural environment. The recombination of the invention is driven by the constant cycle of innovation and destruction of old economic structures. This cycle is inherent to capitalism and is necessary for sustained economic growth over time [5].

Innovations and investments in transportation have contributed significantly to economic growth throughout the 20th century. Innovation in transport and its infrastructure have "enabled households to optimize their residentials and workplace locations and their choice of employers; encourage firms to increase the size and scope of their markets, reduced their inventories, and expanded their choice of workers; and allowed consumers to benefit from greater competition among domestic and international firms and more product variety" [6]. Automation[1] has historically been the main driver of productivity, economic development, and wealth creation throughout the industrial age [7, 8] and continues to be in the present information age [9]. The path toward a promising economic future often drives technological innovation based on fundamental forces such as the benefits and risks of capitalizing on an invention.

Artificial Intelligence and complex autonomous systems are the "information age" versions of mechanization and automation that have driven productivity, economic growth, and wealth creation throughout the industrial age. Most vehicles today have some automated operation,

[1] Automation used as a synonym for earlier mechanization and lately digitalization.

and experimental vehicles with fully autonomous driving are tested worldwide. This development is going very fast and will most probably significantly impact society. Regulations, infrastructure, and the public and private sectors must adapt to the ongoing development. The continuous technological evolution of self-driving vehicles does not have a clear timeline. These developments evolved from specific automated tasks like cruise control, etc., toward fully autonomous vehicles. Society of Automotive Engineers (SAE) has provided the SAE 3016 standard [10] that gives a scale of vehicle autonomy, which ranges from level 0 (no autonomy) to level 5 (cars that do not need a steering wheel or pedals because they can perform the entire trip without human input). Exactly when we will see level 5 autonomous vehicles on the roads depends, as mentioned earlier, on many different things as regulations, infrastructure, and the public and private sectors must adapt to the technology development. "When developing low-carbon transport systems, behavioral change, and infrastructure investments are often as important as developing more efficient vehicle technologies and using lower-carbon fuels" [2]. The diffusion process [11] of innovation is sensitive to how it is communicated over time among the members of a social system. There is an ongoing discussion about the legal limitations of using AI, and autonomous vehicles will probably be questioned when they occupy our roads and streets. Historically has, innovations that automate work and remove professions been disputed and intensely debated. Introducing autonomous vehicles will remove professionals such as bus, truck, and taxi drivers.

Autonomous vehicles may introduce new transport modes [12], like shared rides and local pods for last-mile transportation, leading us from owned products to on-demand services. The factors that influence individuals' travel mode choices depend on many things [13] as age, car ownership, travel distance, ticket prices of public transport, public transport frequency, walking distance to access public transport and parking availability, etc. There are also cultural aspects that must be considered, Lomasky [14] suggests that the car symbolizes individual autonomy and self-determination, essential values in a free society. He argues that the car allows individuals to pursue their own interests rather than being constrained by the schedules and routes of public transportation. “Because we have cars to drive, we can, more than any other people in history, choose where we will live, where we will work, and separate these two choices from each other” [14].

2. Background

Reducing CO_2 emissions for personal transportation by introducing autonomous vehicles is complex. The plausible CO_2 reduction is dependent on many different things. First, we have the reduction/replacement of fossil-based fuels. The fuel consumption per 100 km for a standard car engine has been nearly cut in half over the last 40 years (1975 - 2015) due to more energy-efficient combustion engines [15]. The development and use of non-fossil fuels and fuels with less CO_2 footprint have reduced emissions. As a result of more efficient engines and the use of other fuel types, the CO_2 emissions in Sweden caused by transport have decreased by 21% since 1990. Despite increasing traffic, "As road transport is operated with an increasing share of biofuels and vehicles become more efficient, carbon dioxide emissions from cars and lorries are reduced" [15]. Notable is that vehicles for personal transport are responsible for two-thirds of the total CO_2 emissions in Sweden. If the global growth trend for passengers and freight transports continues, CO_2 emissions will increase by up to 50 % by 2035 and almost double by 2050 [IPCC 2014]. At the same time, the Swedish example, Table 1, gives that it is possible to reduce CO_2 and increase transport, but it requires new fuels and technologies. The Swedish car fleet is partly owned by private persons and partly owned by legal persons, in total, 5.7 million cars. Approximately 5.2 million use fossil fuels: 3.2 million are gasoline cars, and 2 million are diesel-fueled cars [15]. This amount indicates there is potential for reducing CO^2 emissions by replacing fossil-based fuels and reducing privately owned vehicles by introducing other modes of transportation like autonomous pods or buses.

Table 1: Number of cars in Sweden and number of km driven [15]

Fuel	Total driven 10 km		Number of vehicles		Average 10km per vehicle		
	Physical	Juridical	Physical	Juridical	Physical	Juridical	Total
Gasoline	2 174 256 892	464 369 986	2 563 632	598 826	848	775	834
Diesel	1 991 338 547	976 827 737	1 383 719	573 723	1 439	1 703	1 516
Electric	19 043 320	38 767 554	20 673	38 765	921	1 000	973
Electric/ hybrid	113 453 059	58 922 600	96 026	41 557	1 181	1 418	1 253
Ladd-hybrid	39 397 183	109 033 310	33 975	102 041	1 160	1 069	1 091
Ethanol	190 227 955	33 004 853	178 440	32 286	1 066	1 022	1 059
Gas	26 841 940	46 638 940	21 031	26 503	1 276	1 760	1 546
Misc	160 216	93 723	225	113	712	829	751
Total	**4 554 719 112**	**1 727 658 704**	**4 297 721**	**1 413 814**	**1 060**	**1 222**	**1 100**

There are many different fuel types, Table 2, that can replace traditional diesel combustion engines in buses, both renewable and fossil as natural gas. Only electricity of the mentioned fuel types has the potential of zero CO_2 emissions, which may have CO_2 emissions even if renewable production sources are used.

Table 2: Energy density [16]. Energy density is defined as the amount of energy stored per unit of volume. Therefore, the energy density concept does not apply to electricity with no volume. 2in MJ/Nm2 [17, 18].

Fuel type	**Energy density (MJ/lit)**	**Emissions (grCO₂/MJ)**	**Feedstock**
Biodiesel (FAME – fatty acid methyl ether)	33.2	47.6	Rapeseed oil (RME)
Biogas	34.9	22.5	Sewage sludge (39%), MSW(19%) and waste from food industry(19%)
Ethanol	21.1	28.7	Sugarcane, Maize, weath etc.
HVO	34.3	15.9	Vegetable oils and animal fats
Electricity	Not applicable	0	Certified electricity from renewable sources
Fossil diesel	35.13	86.4	Diesel low-blended with RME (5%)
Natural gas	39.96[2]	69.2	100% natural gas (EU data)

It is observable in Figure 2 that the total amount of million tons of CO_2 equivalents emitted by transport is decreasing over the last 30 years in Sweden. Buses are embedded in the group "other" in the graph in Figure 2.

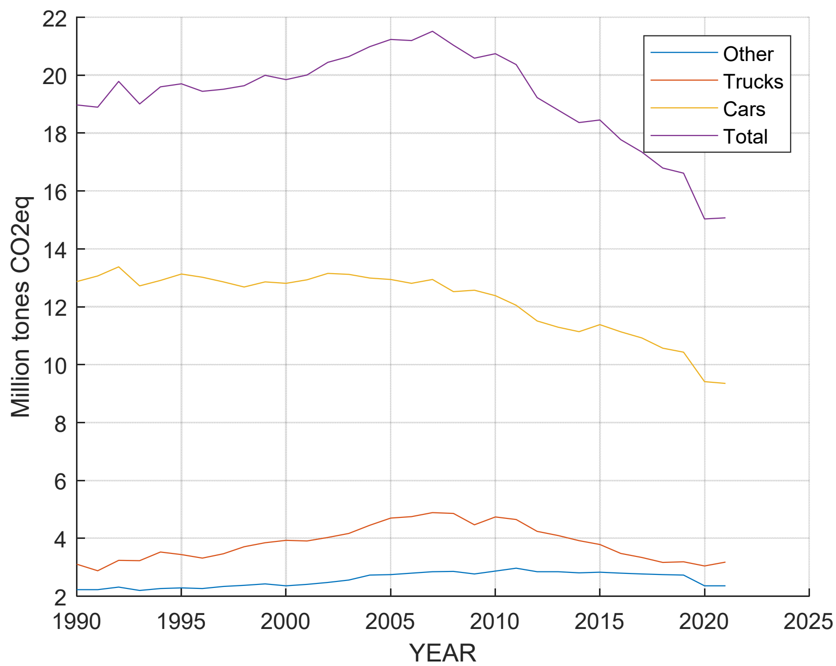

Figure 2. Million tons of CO2 equivalents by transport in Sweden [15].

When "buses" is extracted from "other", Figure 3, the amount of million tons of CO_2 equivalents emitted by buses is 0.25 of million tons today and is slowly going towards zero.

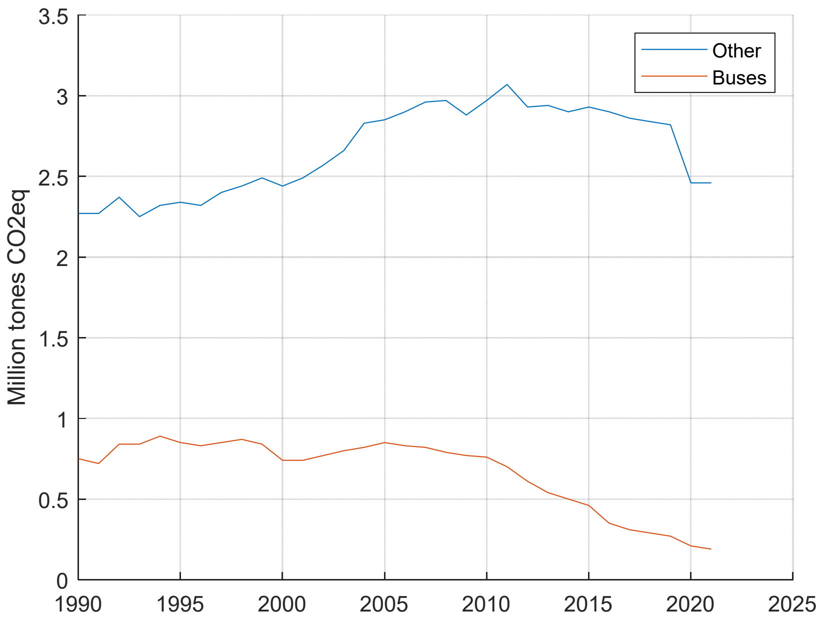

Figure 3: Million tons of CO2 equivalents by buses in Sweden, buses extracted from other [15].

As mentioned, only electric buses have the potential for zero CO_2 emissions. To achieve zero CO_2 emissions, the carbon intensity for the used electricity mix must be zero. Today no countries have zero carbon intensity in the electricity mix, Table 3; Nordic countries have a relatively low carbon intensity per produced KWh of electricity. Sweden and Norway have small CO_2 emissions per produced KWh of electricity.

Table 3: Carbon intensity for electricity mix in different regions [20].

Region	Carbon intensity (gr CO_2 eq/KWh)
Norway	19
Sweden	12
Denmark	209
Nordic Countries	75
Italy	327
Poland	846
EU avg.	294
US.avg.	432
China	555
Japan	506

Fossil diesel has an energy density of 35.13 MJ/Lit, and the emissions gram CO_2/MJ are 86.4 (assuming diesel low blended with RME 5%). A diesel bus (Volvo B7R and Volvo B7RLE chassis) typically consumes 4,2 liters per 10 km [19] in city traffic (33% idle and average speed of 19 km/h) and has a production CO_2 footprint of 100 CO_2 tons [20]. The average CO_2 emissions for a diesel engine bus are then 0.42 l/km * 35.13 MJ/lit*86.4 gr CO2/MJ =1274.8 g CO_2 emissions per km.

The GHG emissions versus distance are according to Figure 4. An electrical bus has an added battery production CO_2 cost of 50 tons [20]. An electric bus consumes, on average, 13 kWh/km [21]. Hybrid engines with smaller batteries have a smaller added CO2 production footprint, dependent on battery size, ranging from 10 tons of CO_2 and upwards (i.e., up to 50 tons). Considering the electricity mix in different regions, in Table 3, the outcome differs. Figure 4 shows diesel and the CO_2 emissions for four areas based on different electricity mixes, Sweden 12 gr CO_2/KWh, Nordic countries 75 CO_2/KWh, EU 294 CO_2/KWh, and Poland 846 CO_2/KWh.

In Figure 4 it can directly be seen that the CO_2 footprint of an electrical bus depends on the specific area's electrical mix. The black dotted line is a Diesel bus and an electric bus charged in areas with electric mixes, as in Poland, Denmark, and the average EU has a higher CO_2 footprint than a diesel bus. The dotted yellow line shows that the average of Nordic countries is reducing precisely below the diesel bus when run for more than approx. 160.000 kilometers.

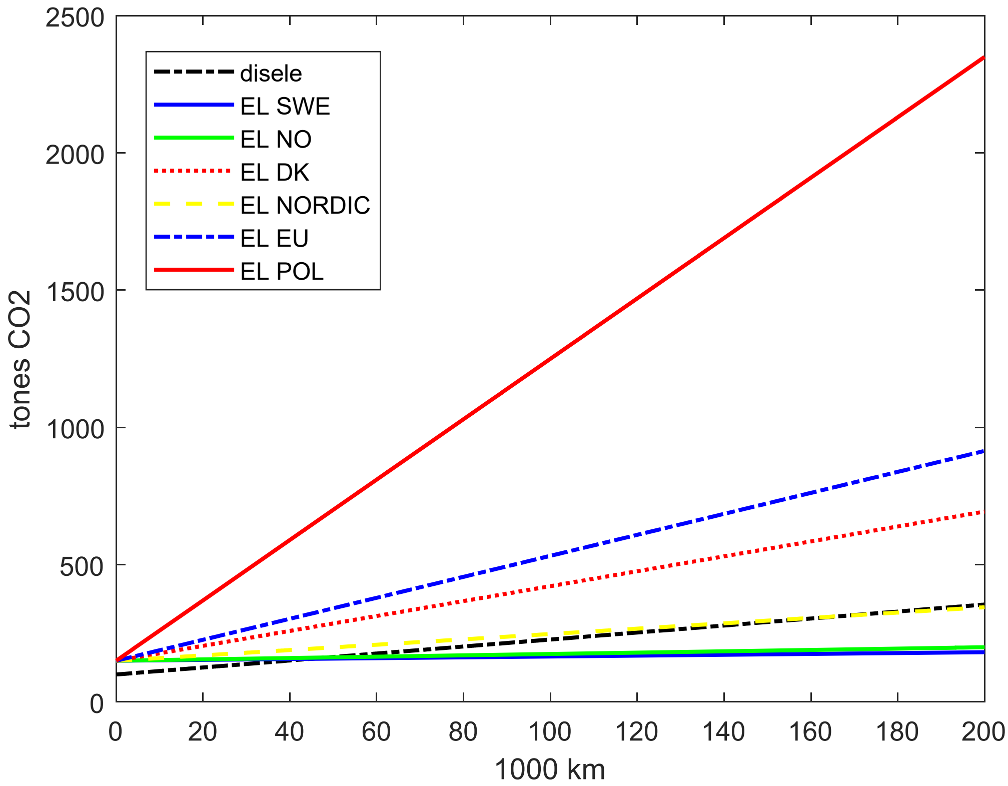

Figure 4: Tones CO2 versus 1000 kilometers, for Diesel and electrical busses with an electrical mix from areas such as Sweden, Norway, Denmark, average Nordic countries, average European Union, and Poland based on [19], [20] and [21].

3. Models for calculating CO_2 emission reductions

A flowchart is applicable when evaluating the CO_2 footprint, and plausible emission reduction by introducing autonomous vehicles is given in Figure 5. This report does not consider the three boxes circumferenced by a red dotted box: changing bus routes or operations, combining services provided by different transport operators, and modal shift use of public or shared transport. The project considers these aspects in other reports [22, 23, and 24]. The emission calculator is provided in the following section.

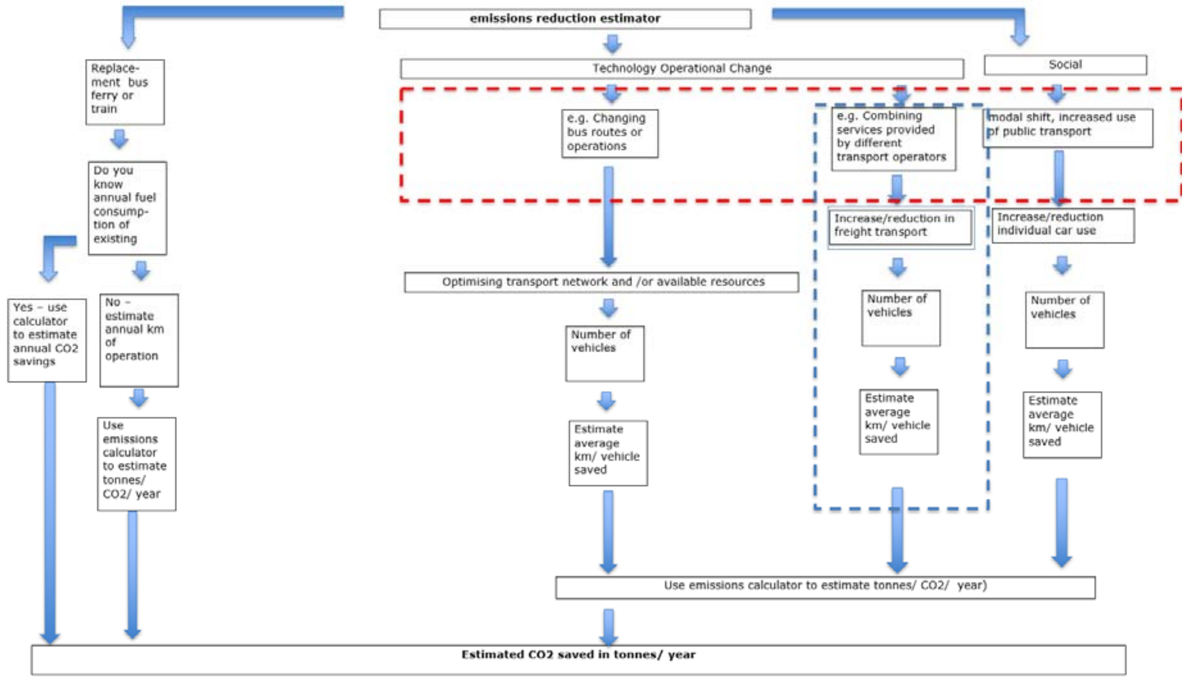

Figure 5: Flow charts for the emission reduction estimator.

The emission calculator in Figure 5 calculates the reduction in emissions by replacing a fossil-based AV with a non-fossil-based AV. According to equation 1, the reduction in CO_2 per year, R, by replacing fossil-based engines with electrical engines using green electricity is calculated, with the following input parameters: assumed CO_2 emission per km fossil-based engine, *G*. CO_2 emission per km for electrical engine, *E*, can be set zero if thought as negligible. The average number of runs per day, *N,* and distance per run (km), *D*.

$$R = 365 \cdot (G - E) \cdot N \cdot D \tag{1}$$

For an upscaled version, the total CO_2 reduction, R, of a fleet of vehicles adds the contribution from each AV, equation 2. We are introducing the following input parameters: Number of vehicles in a fleet, *K*, CO_2 emission per km if gas instead, G_i, $1 \le i \le K$. CO_2 emission per km for electrical AV, E_i, $1 \le i \le K$. Number of runs per day on average, N_i, $1 \le i \le K$; *and* distance per run on average (km), D_i, $1 \le i \le K$.

$$R = 365 \cdot \sum_{1 \le i \le K} \left((G_i - E_i) \cdot (N_i \cdot D_i) \right) \tag{2}$$

If we have several different classes of AVs in the fleet, the total CO_2 reduction, R, of a fleet of various categories of vehicles are according to equation 3. For this calculation, we are introducing the following updates of input parameters: number of classes of vehicle type, C, CO_2 emission per km if gas instead, G_j , $1 \leq j \leq C$ *for that class and* CO_2 emission per km for electrical AV, E_j , $1 \leq j \leq C$. Number of vehicles of each class, K_j, $1 \leq j \leq C$. Number of runs per day on average, N_i, $1 \leq i \leq K_j$; and distance per run on average (km), D_i, $1 \leq i \leq K_j$

$$R = 365 \sum_{1 \leq j \leq C} \left(\left(G_j - E_j \right) \cdot \sum_{1 \leq i \leq K_j} (N_i \cdot D_i) \right) \quad (3)$$

4. Discussion/conclusion

Autonomous Vehicles (AV), or self-driving vehicles, promise widely available, low-cost, clean, door-to-door transport for people and goods [25]. The convergence of autonomous transport systems and urban development and design (from street to district- and regional development) is a promising development "to overcome the challenges of urbanization such as congestion and greenhouse gas (GHG) emissions" [25]. Cities are currently home to 50% of the world's population, and by 2050 about 70% of the world's population is expected to live in urban areas. Today cities are responsible for 70% of global CO_2 emissions, and transport is responsible for about one-third of total urban greenhouse gas emissions in major cities [27]. It is challenging to harmonize sustainable urban development considering the need for job opportunities, good living conditions, and preserving the environment [28]. The introduction of autonomous vehicles has the potential to reduce global CO2 emissions substantially. Understanding how tightly entangled this is with energy policy and the development of non-fossil fuels and energy sources is essential.

There are many more aspects of the emission reduction effect for autonomous vehicles than replacing fossil fuels with non-fossil fuels. Some examples are [26], where autonomous cooperating vehicles can save fuel/energy by improving traffic flow. Intelligent traffic control can save fuel/energy by avoiding/reducing congestion. Possible energy savings if reaching a higher fraction of shared transport by autonomous vehicles. Platooning, where autonomous vehicles drive close to each other, can save fuel/energy. Innovation in smart mobility is an essential part of the sustainable development of smart cities characterized [26] by the integration of sustainable vehicular technologies and cooperative intelligent transport systems (ITS) and tightly related to sustainable thinking [4]. A too-technocentric approach can lead to "solutions that fail to achieve sustainable goals due to lack of comprehensive thinking" [29], and technology lock-in can cause rebound effects that may keep development on the present carbon-based pathway [30]. The "absence of proper policy measures, [the introduction of autonomous vehicles] may generate more demand in terms of car ownership and miles traveled" [29].

As part of the Interreg project Planning for Autonomous Vehicles, this report presents a model that can be applied as a CO_2-Impact Estimation Methodology when planning for autonomous vehicles. The flowchart emission reduction estimator points out important aspects that need to be considered and provides calculations for CO_2-Impact Estimation. The automobile is one of the most important innovations in the modern world, and planning for autonomous is very hard since its evolution depends on many aspects of possible, probable, and preferable futures. The CO_2-Impact Estimation Methodology is a small part of the handbook Planning for Autonomous Vehicles, which is the outcome of the project and a source of help for planning and decision-making in today's chaotic, complex, and rapidly changing world.

5. Acknowledgement

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