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GREEN CITY DEALS

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Green City Deals –

A study on the global warming potential of alternative urban transportation systems

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Abstract: *The population is growing constantly in urban areas. This results in an increasing demand for mobility solutions while it is also worldwide aimed to reduce greenhouse gas emissions. This paper summarizes the results of a comparative study concerning the greenhouse gas emissions (based on carbon footprint) caused by alternative urban passenger transportation systems. The emissions for the vehicles and their infrastructure are analyzed over the entire life cycle from manufacturing up to their end of life. An existing cable car system in La Paz, Bolivia was analysed and evaluated in comparison to other modes of transportation such as small busses, large busses and a tram. According to the system definitions and the considered balance framework the study shows that beside the use of the systems the materials and the manufacturing as well as the infrastructure have a significant impact on the total emissions over the life cycle. To put focus on the „true and real" impacts to the society it is preferable to consider the measurement results in total absolute emissions.*

Keywords: Carbon footprint, life cycle, urban mobility, cable car, bus, tram, transport planning, city planning

1. Introduction

July 29th, 2019 - Earth Overshoot Day "With Earth Overshoot Day occurring ever earlier in the year, and big part of it being the growing amounts of CO_2 emissions, the importance of decisive action is becoming ever more evident. For this reason, we are working with all parties to find effective approaches." [1]

The „Earth Overshoot Day" describes the point in a year when the natural resources available to mankind as an annual budget on earth are used up. This deficit is caused by the depletion of ecological resources and by waste, mainly carbon dioxide (CO_2). [2] Since 1970, earth overload day has moved five months forward from the end of December to July. According to this, we are currently "over-exploiting" our natural resources to such an extent that the ecosystems can no longer sustainably regenerate. [3]

The need to act is obvious. Climate protection is given top priority in the global climate agreements, such as the Paris Climate Agreement and the climate agreement of the European Union. The main focus is on a reduction of harmful carbon dioxide emissions (CO_2 emissions) as one of the most important greenhouse gas emissions. [4]
The use of clean technologies is crucial here. In this context, the EU has defined the energy and transport sectors as central fields of action. [5] The transport sector is a major contributor to global greenhouse gas emissions due to the burning of fossil fuels. Transport emissions — which primarily involve road, rail, air and marine transportation — accounted 2016 for over 24% of global CO_2 emissions. A growing world population simultaneously leads to an increased need for mobility and growing traffic volume. [6,7]

2. Goal, scope and research methodology

2.1 Goal of the study

The present study compares the global warming potential (GWP) of different passenger transport systems in urban areas. Using the cable car installation in La Paz, Bolivia as a reference, the greenhouse gas emissions for three alternative transport systems, a large bus, a small bus and a fictitious tram line, were determined under the primacy of the same transport and operating times between two defined transport hubs. The GWP of the different systems over their entire life cycle is to be recorded and analyzed in order to determine not only the actual time of usage but also to take into account e.g. the phases of system creation, construction and disposal in the evaluation.
In the study, a standardized balance sheet framework with key figures was defined in which the considered systems were examined and compared. Furthermore, according to literature research a staged life cycle model (according to DIN EN 14040/14044) was applied for a detailed analysis. [8,9]

2.2 Scope of the study

In accordance with relevant standards a reference scenario had to be created that was used as a basis for the comparison of all alternative options. [8,9,,10,11]

2.2.1 Life Cycle Stages

To compare the passenger transport systems, all phases of the life cycle need to be considered to include emissions generated before and after operation. Therefore, based on literature, the balance framework comprises the five phases: Material phase, production phase, distribution phase including assembly, operating phase including maintenance and end of life phase. [10,11,12] Without a functioning infrastructure the systems are unable to operate. Therefore, the provision of this infrastructure is also included in this assessment. The individual life cycle phases include the following services and functions:

- Material phase: The delivery of the materials, including, if available, the pre-processing steps of the suppliers as well as the transport from the supplier to the manufacturer's production facility
- Production phase: The auxiliary materials that are required for production and the energy expenditure, from factory gate to factory gate.
- Distribution phase including assembly: The transport emissions from the manufacturer's factory gate to the place of use, including installation and assembly emissions.
- Operating phase including maintenance: the amount of energy required for operation including maintenance.
- End of life phase: decommissioning of the plant and the associated transports and treatments (differentiation between landfills, incineration and recycling)

2.2.2 Definition of the functional unit

ISO 14040 and ISO 14044 (2006) define the functional unit is a "quantified description for the performance of a product system for use as a reference unit." [8,9] Essentially it specifies the function to which all results are referenced. VDMA 34160 states that the defined "load spectrum" are the "minimum requirements to be met [...] Added value due to exceeded minimum requirements, e.g. higher availability, is disregarded.“ [11] This is especially important when attempting to place results into context.

The definition of the balance frame limits for the comparative investigation of different urban transport systems was based on a specific scenario of a cable car-based passenger transport system in the city of La Paz, Bolivia.

Therefore, the functional unit is defined in this study as “The transport of 3,000 passengers per hour from station 16 de Julio to Estación Central in La Paz, Bolivia, over a total service period of 30 years, operating for 6,049 hours per year. “

The system technology used there, as well as the required system performance and topography should serve as a basis/benchmark for the comparison with alternative urban transport solutions.

2.2.3 Transportation scenarios and reference flow

Based on the definition of the functional unit, the following scenarios result for the alternative transport systems bus and tram for the required 3,000 passengers per hour and per direction of travel over the desired service life of 30 years.

The reference flow for the cable car comprises the provision and operation of the stations, the track between the stations and 109 cabins operating simultaneously over a period of 30 years. [13]

Since these two passenger transport systems cannot transport passengers above ground with the cable car line, they have to cover a distance of 12,4 km to reach the same stations as the cable car system. To transport the same number of passengers within one hour, in total 175 large buses or 753 small buses or 75 trams would be required at an average speed of 41,3 km / h. [14]

The reference flow for the buses includes the provision and operation of the infrastructure, covering the depots and the road between the stations (just the share of the busses). The reference flow for the tram is the provision and operation of the infrastructure, covering the depots, the stations and the track between the stations.

Using existing databases and values from literature, emissions generated by passenger transport have to be calculated for all life cycle stages. As measured variables the units tCO_2eq and gCO_2eq/p_ckm (CO_2eq = CO_2 equivalent, p_ckm = passenger capacity kilometers) were defined. For the presentation of results in gCO_2eq/p_ckm, total emissions are divided by passenger capacity kilometers (p_ckm). Comparisons in the transport sector are usually made in passenger kilometers (pkm). Passenger kilometers are calculated by multiplying the number of passengers carried by the distance travelled in kilometers. [15]

2.2.4 Research methodology and data integration

The research results presented below are based on the combination of various data sources from literature and practice. The material and consumption data found were then converted in a second step in order to determine the respective global warming potential via the database ecoinvent. [16] The calculation is based on the system model APOS (Allocation at the point of substitution). APOS is an allocation approach that uses expansion of product systems to avoid allocating within treatment systems.

The basic data for the evaluation of the cable car were made available by Doppelmayr Seilbahnen GmbH. The primary data provided covers all life cycle phases for both the vehicles and the infrastructure for the cable car. [13]

For the bus and tram, primary data were extracted from literature and combined with assumptions to build appropriate models for the case study, with reference to the functional unit. The distribution of the vehicles to the place of operation and the needed number of busses has been calculated according to the scenario in La Paz and extrapolated over the considered service period of 30 years. The emissions of the busses in the usage phase were extracted from literature according to the defined functional unit and reference flow. [17] These factors include the fuel used for operation as well as estimates for maintenance, repair, and tire wear in a public transport scenario. [18]

For the tram, the average electricity consumption per vehicle km was extracted from literature. [19] The consumption has been scaled linearly to the total vehicle km service and multiplied by the country specific emission factor for Bolivia to place the results into the correct geographical context. A list of foreground data can be found in the annex.

3. Research results

3.1 Overall emissions of compared passenger transport systems

In the research study two different scenarios have been modeled: On the one hand a (fictious) scenario assuming a permanent utilization of 100% of all vehicles. In the second scenario the (actual) utilization of 69% of the La Paz business case has been applied.

3.1.1 Carbon footprint of the 100% utilization scenario

The emissions in tCO_2eq of the passenger transport systems over the life cycle are shown in figure 1 below. In addition to the total emissions over the entire life cycle, the graphic also shows a breakdown of the emissions related to the vehicle and infrastructure system components. In the box above the respective bar there is also a breakdown of the emissions related to the life cycle phase use and the remaining phases (as a total). The operating phase including maintenance takes up the largest share of life cycle phases for all four passenger transport systems. The large and small bus with 388.987 tCO_2eq and 348.142 tCO_2eq and the tram with 272.004 tCO_2eq have a much larger share than the cable car with 64.974 tCO_2eq. [12]

But the provision and maintenance of the infrastructure also generates a large proportion of emissions. The infrastructure for the busses includes the the proportional allocation of the emissions for the maintenance of the road induced by the bus operation and for the construction and operation of the bus depots. In the case of the cable car, it must be taken into account that the one-time transport from Europe to the La Paz location and the on-site installation as the main emissions factor for the infrastructure is included in the calculation.

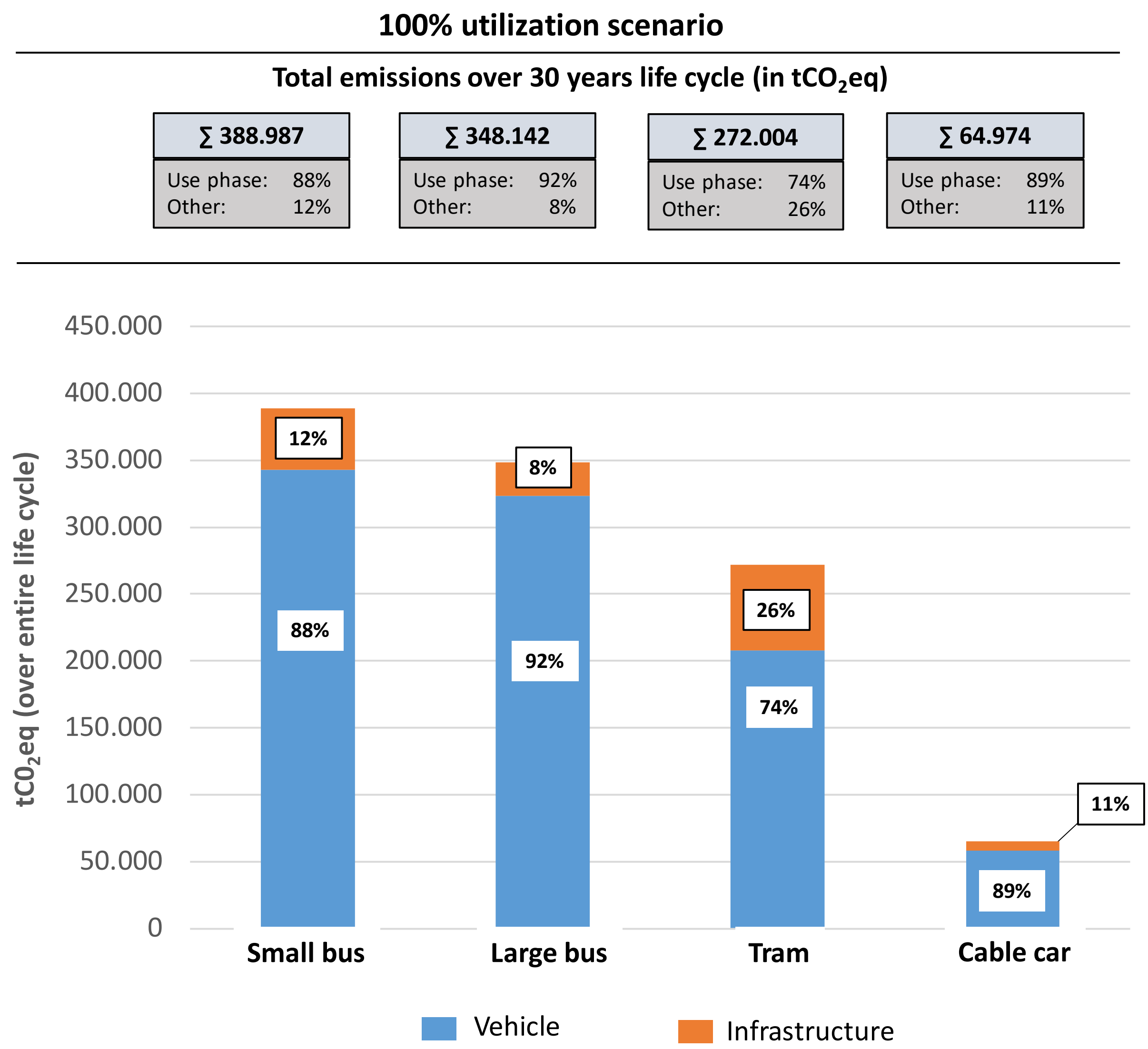

Figure 1: Comparison of passenger transportation systems (100% utilization scenario)

During operation, the infrastructure is only responsible for around 1% of emissions. [12] The absolute emissions from the provision and maintenance of the tram option alone, for example, are higher than the total emissions caused by the cable car (including manufacturing, transport, erection, operation and maintenance etc.) over the entire life cycle.

In total, the results show that the impact from the construction, upkeep and maintenance of this infrastructure can make a substantial contribution to the overall life cycle emissions. These findings comply with existing literature. [17, 20]

Relating the calculated emissions to the performed passenger capacity kilometers of the vehicles (see annex, $p_c$km) the large bus and the small have the highest emission rate with 28,7 gCO_2eq/p_ckm and 25,2 gCO_2eq/ p_ckm. The cable car with 22,7 gCO_2eq/p_ckm follows the tram with 19,6 gCO_2eq/ p_ckm.

But this quotient might be misleading, because according to the goals and the defined functional unit, it is not decisive what the theoretical system performance would be. The integration of this consideration would - if at all - possibly be useful for investigations of extended system flexibility or differentiated utilization analyses. However, this would also mean including these requirements accordingly in the definition of the functional unit.

Secondly, the total emissions of the actually installed system solution are ultimately relevant, especially for the local impact and to the community. A ratio related to passenger capacity kilometres as an indicator might be easily manipulated by increasing the length of the tracks (e.g. by absurd or even intended detours).

3.1.2 Carbon footprint of the 69% utilization scenario

For comparison, the real business case from La Paz was analyzed in a further scenario. The actual occupancy rate of the system on site is ca. 69% (=2.059 passengers per hour) which corresponds to a reduction of 31% in comparison to the baseline scenario.

As a result, the studies show that the total emissions of all transport systems examined correspond largely proportional. This is mainly due to the fact that most of the emissions are caused by the use of the vehicle, which is accordingly reduced in this scenario. This linear dependency is particularly evident in the case of buses. Nevertheless, some changes can also be seen.

Especially for the tram the decline in emissions is only disproportionately low at 21%. This is due to the fact that a comparatively large portion of the emissions is caused by the production, erection and maintenance of the infrastructure.

This is already indicated in figure 1 and confirmed in figure 2, in which the percentage of emissions induced by the infrastructure has increased to 30% compared to the baseline scenario.

The same applies to the changes in the analysis of the cable car. Here, overall emissions are falling slightly disproportionately despite lower capacity utilization.

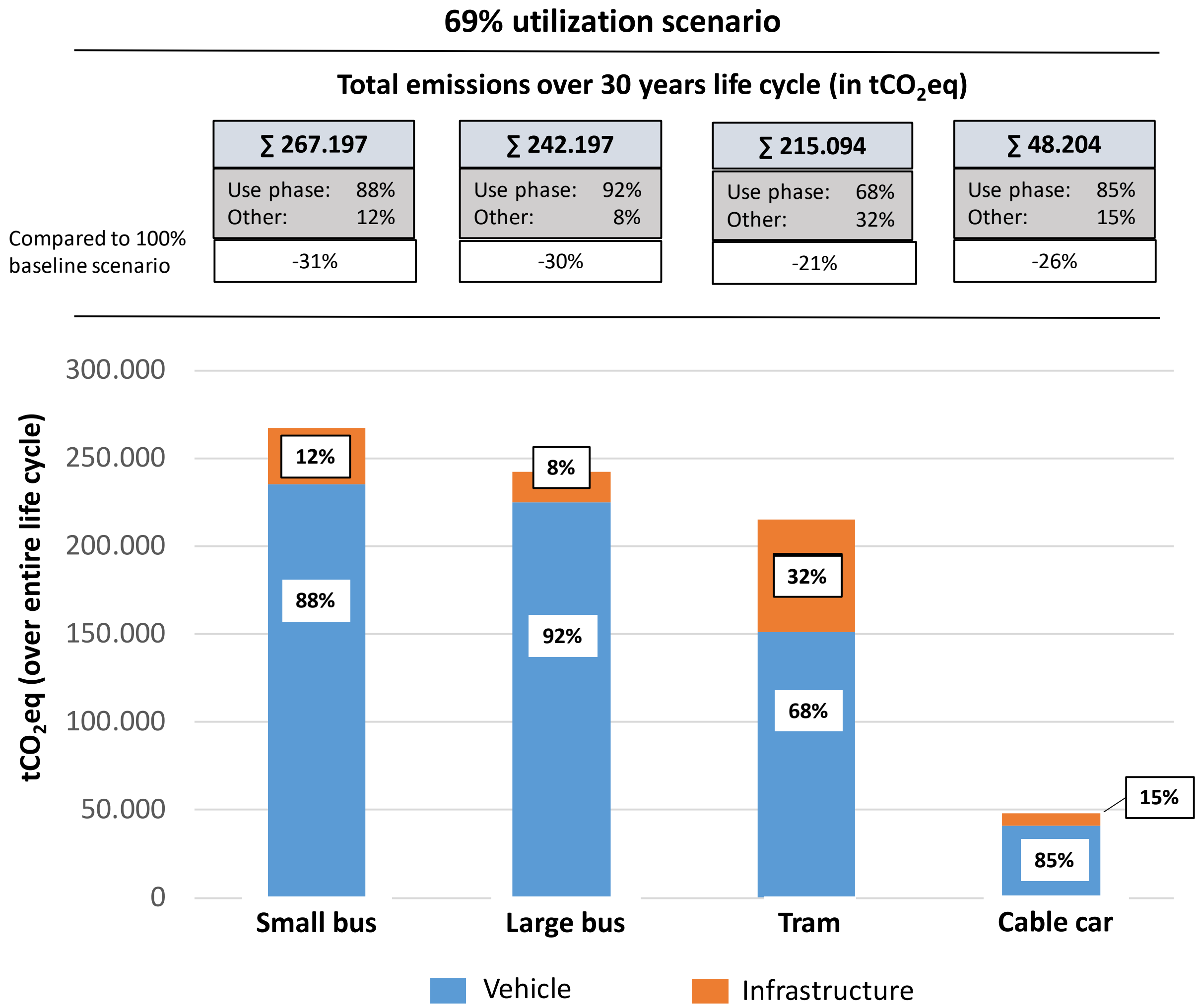

Figure 2: Comparison of passenger transportation systems (69% utilization scenario)

Compared to the baseline scenario, an almost unchanged infrastructure has to be erected and maintained, although it is designed to generate significantly lower emissions than the tram.

3.2 Sensitivity Analysis

The analysis of the individual stages of the life cycle shows that the emissions for the alternatives examined mainly arise in the use phase. Therefore, the main influencing factors of the emissions were identified in a sensitivity analysis in order to determine potentials and influences for future studies. In addition, the study was carried out on the basis of given framework parameters in accordance with the definition of the functional unit (see chapter 2.2.2). Figure 3 shows some factors that have a strong influence on the result of the investigation.

Factor	Small bus	Large bus	Tram	Cable car
Utilisation	Load profile in combination with location routing	Load profile in combination with location routing	Load profile in combination with location routing	Directional utilisation profile over day
Location routing	Length of transport distance	Length of transport distance	Length of transport distance	N/A
Energy	Fleet efficiency	Fleet efficiency	Grid mix and electricity consumption	Grid mix/ electricity mix

Figure 3: Sensitivity analysis of core factors for emissions

It can be seen that the utilization of the various systems used throughout the day has a strong influence on emissions. In the case of cable cars, for example, unevenly distributed use in one direction has a particularly strong effect on energy demand (e.g. in the morning and evening hours). In connection with the specific topography of the place La Paz, Bolivia, the considerably longer routes (tracks) for buses and trams compared to cable cars are significant.

Ultimately, however, the energy requirement of the alternatives examined is particularly decisive. The cable car and the tram have to use the existing energy mix of the grid in Bolivia. This analysis shows that the total impact of the transport system over the lifetime can be greatly reduced through by either the amount of electricity consumption itself or by the choice of the electricity generation mix. A change towards the use of renewable energies or at least more energy-efficient drives would have a major impact on the overall emissions balance for the transport systems. For the buses e.g. more energy-efficient fleets (e.g. lower consumption, lower maintenance costs, etc.) lead to different results over the long period under consideration. In the case of the tram and the cable car, this could be achieved by changing the grid mix with a significantly higher proportion of electricity from renewable sources.

4. Summary and outlook

The investigation focuses on determining a life-span footprint for different urban modes of transportation. The research study is based on a specific scenario defined in the functional unit around the transport from one fixed point to another. This service definition was derived from the actual installation of the cable car. In accordance with literature additional service options (e.g. more stops, partial transport of passengers along the route etc.) of the buses and trams are not taken into account.

The largest share of total emissions is being generated in the operating phase including maintenance. This is due to the fact that the operating phase also accounts for the longest period during the 30-year period. In addition to a changed initial scenario, changes in the factors identified in the sensitivity analysis in particular represent opportunities to influence the results obtained with regard to emissions.

The assessment clearly shows that an assessment of the emissions on the basis of passenger km (or per passenger capacity km) is not a reliable parameter for comparing alternative urban transport systems; the actual overall impact of the compared modes of transportation in operation is more meaningful.

In the study, the carbon footprint respectively the global warming potential of various modes of transport were determined and compared. Investigation thus provides one component of an ecological life cycle assessment. For a comprehensive sustainability study, economic and social factors would have had to be included in the investigation. This wasn't done for this study. [21]

Since the decision in favour or against a transport system usually means a long term commitment, the consequences of such a decision must be carefully analyzed and evaluated. This must be reflected in the initial definition of the functional unit in the planning phase.

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References

[1] Earth Overshoot Day: Earth Overshoot Day 2019. Available at: https://www.overshootday.org/ (Accessed 2020/08/09)

[2] Earth Overshoot Day: About Earth Overshoot Day 2019. Available at: https://www.overshootday.org/aboutearth-overshoot-day/ (Accessed 2020/08/09)

[3] Earth Overshoot Day: Past Earth Overshoot Days 2020, https://www.overshootday.org/newsroom/past-earth-overshoot-days/ (Accessed 2020/08/09)

[4] Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit: Internationale Klimapolitik 2020. Available at: https://www.bmu.de/themen/klima-energie/klimaschutz/ internationale-klimapolitik/ (Accessed 2020/08/09)

[5] Bargende, M.: Erdgas und erneuerbares Methan für den Fahrzeugantrieb: Wege zur klimaneutralen Mobilität. In: Basshuysen, R. van: Erdgas und erneuerbares Methan für den Fahrzeugantrieb- Wege zur klimaneutralen Mobilität, p.233-463, Springer Viehweg, Wiesbaden, 2015

[6] Wang, S.; Ge, M.: Everything You Need to Know About the Fastest-Growing Source of Global Emissions: Transport. World Resources Institute, 2019. Available at: https://www.wri.org/blog/2019/10/everything-you-need-know-about-fastest-growing-source-global-emissions-transport. (Accessed 2020/08/09)

[7] Deutsche Gesellschaft für die Vereinten Nationen e. V.: Eine-Welt-Presse: Nachhaltige Stadtentwicklung- Wie Metropolen mithilfe der UN gegen Kollpas kämpfen, 2015. Available at: https://nachhaltig-entwickeln.dgvn.de/ fileadmin/publications/PDFs/Eine_Welt_Presse/Eine-Welt-Presse_2015_WEB. pdf. (Accessed 2020/08/09)

[8] DIN Deutsches Institut für Normung e. V. (Ed.): DIN EN ISO 14040: Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006), Beuth –Verlag Deutsche und Englische Fassung EN ISO 14040:2006, 2006

[9] DIN Deutsches Institut für Normung e. V. (Ed.). Environmental management - Life cycle assessment - Requirements and guidelines. ISO 14044:2006, Beuth-Verlag, 2006

[10] Niemann, J.; Tichkiewitch, S.; Westkämper, E.: Design of Sustainable Product Life Cycles, Springer Verlag, Heidelberg Berlin, 2009

[11] o.V: Calculating Lifecycle costs in the capital goods industry. Version 98.0d, VDMA, 2012. Available at: https://www.vdma.org/v2viewer/-/v2article/render/15237352. (Accessed 2020/08/09)

[12] Krautzer, F.; Stoll, K.: Carbon Footprint of a Doppelmayr Cable Car in La Paz, Placed in the Context of Select Alternative Transport Systems, denkstatt GmbH, 2019

[13] Doppelmayr Seilbahnen GmbH (Ed.): Aerial cable cars. Available at: https://www.doppelmayr.com/en/aerial-cable-cars/ (Accessed 2020/08/09)

[14] Spielmann, M. et al.: Transport Services Data v2.0 - ecoinvent report No. 14. Villigen and Uster, 2007

[15] Wilke, S.; Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Ed.): Fahrleistungen, Verkehrsaufwand und „Modal Split." Umweltbundesamt, 2019.
Available at: https://www.umweltbundesamt.de/daten/verkehr/fahrleistungen-verkehrs- aufwand-modal-split (Accessed 2020/08/09)

[16] Wernet, G. et al.: The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment,21(9), pp. 1218–1230, 2016. Available at: http://link.springer.com/10.1007/s11367-016-1087-8. (Accessed 2020/08/09)

[17] Chester, M.; Life-cycle Environmental Inventory of Passenger Transportation in the United States, Berkeley: University of California, 2008

[18] Cuéllar, Y. Et al.;,: Life cycle emissions from a bus rapid transit system and comparision with other modes of passenger transportation. ciencia, technologia futuro 6(3), pp. 123-133, 2016.

[19] Stolz, P. et al.; Life Cycle Inventories of Road and Non-Road Transport Services. Uster: SBB AG, BFE, BAFU, Swisscom AG, Öbu., 2016

[20] Chester M. et al.: Parking infrastructure: energy, emissions, and automobile life-cycle environmental accounting. Environmental Research Letters 5(3) 0340012010

[21] Kogel, B.; Pfeifer, A.: VDI Status Report – Urbane Seilschwebebahnen, VDI Gesellschaft für Fahrzeugtechnik, VDI-Verlag, 2020

Annex

List of foreground data

	Route length (single direction)	Lap length	Time per direction	Vehicle capacity	Average speed	Number of vehicles simultan-eously	Service lifetime per vehicle	Total number of vehicles over service life	Number of laps per vehicles per day	Distance travelled per vehicle per day	Total distance travelled by all (simultan-eous) vehicles per day	Total distance travelled by all vehicles over service life	Total transport capacity over service period
Unit	km/ direction	km	min	pax	km/h	# of vehicles	years	# of vehicles	# of laps	km/day	km/day	Million km	billion p_ckm*
Small bus	12,4	24,8	18	18	41,3	99	3,95	753	28	694	68,764	752,8	13,5
Large bus	12,4	24,8	18	79	41,3	23	3,95	175	28	694	15,971	174,9	13,8
Tram	12,4	24,8	18	166	41,3	11	4,42	75	28	694	7,638	83,6	13,9
Cable car	2,3	4,6	8	10	18,0	109	undisclosed		N/A				2,6

* In the comparison the unit p_ckm is used, where 'c' stands for person capacity. The 'c' relates to a potential 100 % occupancy rate of all vehicles over the time.

	Operating time	Operating days	Service time	Required service capacity per direction	Mass (net vehicle weight)	Average passenger weight	Gross vehicle weight	Footprint of the vehicle (incl. 20% maneouvering space in depot)	Transport distance of vehicle from production to operation site	Transport freight from production to operation site	Concrete used in tram station con-struction	Electricity use per tram station per year
Unit	hours/ day	days/ year	years	pax/h	t	kg/pax	t	m^2	km	tkm	m^3/ station	kwh/ station*year
Small bus	16,57	365	30	3000	4,600	75	5,950	18	3.000	13.800	N/A	N/A
Large bus	16,57	365	30	3000	11,340	75	17,265	36	3.000	34020	N/A	N/A
Tram	16,57	365	30	3000	20,992	75	33,442	108	3.000	62.976	255	2.600
Cable car	16,57	365	30	3000	0,495	75	1,245	N/A	14.400	7.128	N/A	