Traffic & Transport
Anna van Buerenplein 1
2595 DA Den Haag
P.O. Box 96800
2509 JE The Hague
The Netherlands

www.tno.nl

T +31 88 866 00 00

TNO report

TNO 2021 P11077

Great circle distance as the optimal distance metric for CO_2 allocation in freight transport

Date	14 June 2021
Author(s)	I.Y. Davydenko, R.T.M. Smokers, W.M.M. Hopman, H. Wagter
Copy no	2021-STL-RAP-100340209
Number of pages	24 (incl. appendices)
Sponsor	Connekt, namens het ministerie van Infrastructuur en Waterstaat als uitvoerende organisatie van het Meerjarenprogramma Topsector Logistiek
Project name	Connekt ISO-CF vervolg
Project number	060.46177

Summary

Carbon footprinting is an important method for computation, reporting and reduction of CO_2 and other greenhouse gas emissions from freight transport and logistics. Carbon footprinting is a means for analysis of greenhouse gas (GHG) emissions, attribution of these emissions to the activities that cause them, and ex-ante and ex-post evaluation of emissions resulting from transport and logistics. The currently under development ISO 14083 standard on quantification of GHG emissions aims at harmonization of different methodological approaches for carbon footprinting. It is very important that the to be standardized methodology is a proper one: an inconsistent methodology may do more harm than good with respect to real world CO_2 emissions. Therefore, in this report we analyze four distance metrics, which are at the core of currently used different GHG emission computation methods, for their suitability in the future ISO 14083 standard.

The emission intensity factor, kg CO_{2e}[1] per tonne-kilometre shipped, is the most important key performance indicator for a carbon footprinting methodology.
For a given flow of goods, the emission intensity factor fully determines the amount of greenhouse gases emitted by transport activities, provided it is computed on primary real world data. The emission intensity factor consists of two components: the quantity of the emissions in the nominator and the quantity of transport activity in the denominator. Quantification of the transport activity, the denominator, and even more specific the distance component in the tonne-kilometres is the primary focus of this paper.

This paper analyzes four distance metrics for computing transport activity: the great circle distance (GCD), the actually driven distance (ADD), the planned distance (PD) and the shortest feasible distance (SFD). The paper presents a framework consisting of eight criteria to analyze suitability of each of the four distance metrics for carbon footprinting. The table below summarizes the outcome of the analysis.

Table 1: Suitability of distance metrics for different purposes: summary of comparative analysis.

Criterion / Distance Metric	**GCD**	**ADD**	**PD**	**SFD**
1: Adequacy for estimation of fuel used	--	++	+	+/-
2: Adequacy for allocation of emission to individual shipments and customers	++	--	-	+/-
3: Adequacy and ease of auditing results by accountants	++	-	--	+/-
4: Data requirements and ease of data gathering for calculations	++	-	--	+/-
5: Use for comparison of different networks and / or modalities	++	-	--	-
6: Use for analysis of potential improvement measures and for GHG optimization	++	+	+	+/-
7: Use for combining data from multiple subcontractors	++	-	--	-
8: Commercially sensitive information shared	+/-	-	-	+/-

---

[1] CO_{2e} denotes carbon dioxide equivalent: an amount of a GHG whose atmospheric impact has been standardized to that of one unit mass of carbon dioxide

On the basis of this analysis, the great circle distance is the distance metric that should be used for determining transport activity as denominator in the emission intensity factor. We strongly recommend the GCD distance metric to be standardized in the ISO 14083 standard for the purpose of transport activity computation, and for the emission allocation to shipments and entities that cause the emissions. The use of other distance metrics should be discouraged as it will result in a weaker method at best, and in a harmful method at worst, possibly discouraging measures that do reduce real-world CO_2 emissions or even stimulating measures that increase real world CO_2 emissions instead of reducing them.

Contents

1 Introduction

The challenge of decarbonization of transport and logistics is huge. Previously the EU has agreed to a 40% cut in greenhouse gas (GHG) emissions (from 1990 levels)[2]. With the 2030 Climate Target Plan, the Commission proposes to raise the EU's ambition on reducing greenhouse gas emissions to at least 55% below 1990 levels by 2030. This is a substantial increase compared to the existing target[3].

On a national level, individual countries set their own goals for emission reduction, as for instance the Netherlands aims to raise the EU ambition for 2030 from 49% to 55% emission reduction compared to 1990 levels and to translate this to a robust and effective legislative framework. Although EU's and national targets are ambitious, both the EU and national action plans confirm that for the medium term (action 2030), a complete decarbonization seems to be unfeasible due to a number of reasons, such as technological immaturity and market unavailability of zero emission vehicles, insufficiently decarbonized generation of electricity, and lack of infrastructure. However, for the long term (action 2050) the European countries aim to achieve effectively a climate neutrality with at least 95% cuts of GHG emissions to the atmosphere compared to the 1990 emission level.

This means that for the medium term horizon, substantial efforts need to be made by all sectors in the society including users of transport and transport service providers to substantially cut the emissions[4]. The midterm targets (action 2030) for emission reductions can be achieved through operational improvements that can be realized short term, as well as by efforts related to investments in zero emission techniques and a different and more efficient organization of logistics, which may require substantial investment and longer term payoff periods. When decisions on decarbonization are made, a carbon footprinting method can be used to assess the current level of emissions, estimate the expected impact of the decarbonization measures, and compute in a verifiable manner the outcome (i.e. the new state of the system) of improvement measures.

Carbon footprinting is an important method for promoting and monitoring the reduction of CO_2 and other GHG emissions from Freight Transport and Logistics (Davydenko and Smokers, 2017). Carbon footprinting is an analysis of GHG emissions and attribution of these emissions to the activities that cause them. It feeds the decarbonization process with the data on actual emissions (ex-post) and expected emissions (ex-ante) related to the proposed improvements. Applications of carbon footprinting generate insights into the impact of the activities on the GHG emissions and their intensities with the possibility of subsequent actions to reduce them. It is the underlying method for carbon reporting and carbon accountancy. Carbon footprinting can be performed at different levels, such as at macro (national or regional), meso (collaborative structures, ports, corridors), micro (company or department) and nano levels (specific activities, journeys, shipments).

---

[2] https://ec.europa.eu/clima/policies/strategies/2030_en

[3] https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en

[4] Specific targets for the transport sector have not yet been set at the moment of writing.

Carbon footprinting always includes decomposition of complex transport and logistics chains into transport chain elements or transport service categories, which can be further supplemented with in-depth analyses (Davydenko et al., 2019).

The most important criteria for an appropriate carbon footprinting methodology are directional correctness, verifiability, consistency, accountability and fairness of allocation. With respect to allocation of emissions there is always some degree of arbitrariness present in all carbon footprinting methodologies. A minimum requirement is that all emissions associated with a logistic operation are attributed to all transport activities that cause them with the same method. The directional correctness requirement for carbon footprinting relates to the property of a computation method such that a decrease (or an increase) in computed emissions, corresponds to a decrease (or an increase) in real world emissions. In other words, if decisions are made based on computed emissions, a reduction in computed emissions must translate into a real world emission reduction. The fairness of a carbon footprinting method is required for support by the users such that their real world decarbonization actions are reflected in computed results, and such that there is a general agreement on a proper allocation of emissions to the activities or entities that cause them. Implementation of a carbon footprinting procedure provides for a positive decarbonization loop, see Figure 1 (Davydenko et al., 2019). A carbon footprinting procedure almost always results in unexpected findings of reduction potential (McKinnon, 2018).

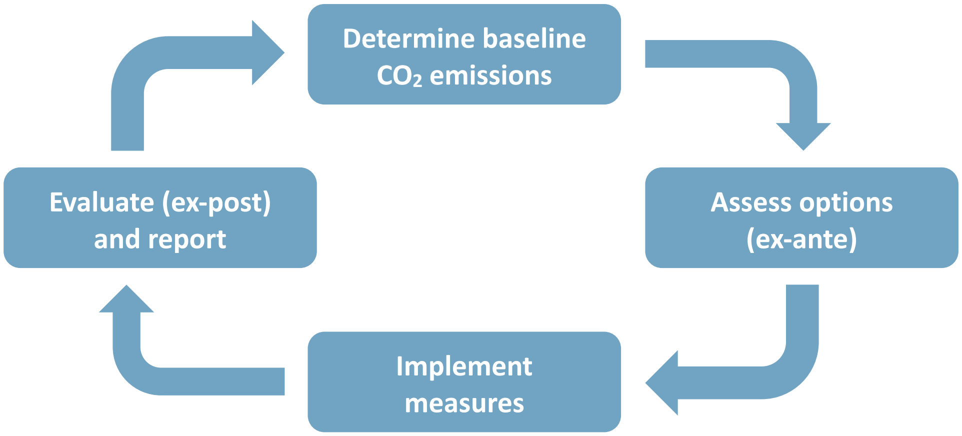

Figure 1: Positive emission reduction loop through complete visibility of emissions.

Carbon footprinting allows for decarbonization through redesign of supply and transport chains (decisions on location of logistics facilities, service and speed requirements, transport modes involved and routing of the material flow, frequency of delivery, batch sizes), and through selection of the most environmentally friendly services and energy providers once design decisions are firmed.

Due to the fact that carbon footprinting is a powerful instrument in decarbonization, a standardized carbon footprinting method is necessary: a proper standard ensures that computations performed by different entities are consistent, and can serve, among other, as a basis for reporting, optimization and accounting.

The first harmonized carbon footprinting methodology for transport and logistics is the European EN 16258 standard. The EN 16258 has been the first serious step towards building a consensus about how carbon footprinting is to be done (Davydenko et al., 2019). The EN 16258 has some issues with ambiguity of computation methods and fairness of emission allocation, which led to suggestions for methodological improvements as identified in the EU FP7 COFRET project (Davydenko et al., 2014). The ambiguity of the EN 16258 standard is partly responsible for the creation of different carbon footprinting methods and frameworks, such as the GLEC Framework, Objectif CO_2, EPA SmartWay and others[5]. These are different examples of carbon footprinting methods, which serve the same purposes of emission computation and emission allocation. However, due to the fact that these methods make slightly different choices with respect to computational algorithms, the outcomes of the computations cannot be directly compared or used without a harmonization layer.

Carbon footprinting has been already incorporated into operations of many companies (see for example LEARN project deliverables D3.2 and D4.4; Bewustbezorgd carbon footprinting of parcel deliveries in the Netherlands).
From the practice, two functionalities of carbon footprinting efforts become apparent: modelling and accounting. In case of modelling, missing data is estimated using certain algorithms; accounting is based on the operational data. Both approaches can serve two purposes, namely operational improvements with respect to GHG emissions and reporting on the emissions. In the context of reporting, there strong parallels appear with financial reporting, with respect to both the quality of reporting and quality to the reported data. As the policy is shifting into the direction of a mandatory carbon pricing mechanism, requirements for the reporting will become more stringent and in line with the financial reporting. This implies that default emission factors will be of limited use in the future, modelling and GHG emission minimization will become more important as the GHG pricing will directly influence operational costs. The standardized method on emission computation and reporting will become the underlying basis for all data, reporting and pricing mechanisms.

The ongoing ISO effort to standardize a carbon footprinting method intends to overcome the problem of lack of harmonization. The future ISO 14083 standard “Greenhouse gases — Quantification and reporting of greenhouse gas emissions arising from operations of transport chains” is expected to be published in June 2022. The standard will provide for a universal, harmonized and broadly accepted carbon footprinting method. This paper intends to facilitate discussion on specific methodological choices that will be implemented in the ISO standard. The report is structured as follows: Chapter 2 explains basic technical aspects of carbon footprinting together with KPIs that the methods compute. Chapter 3 provides an assessment framework for different types of distance metrics that is one of the core variables in carbon footprinting methods. The chapter assesses suitability of different metrics for the purpose of emission estimation and emission allocation to activities and entities. Chapter 4 presents some fictive examples that corroborate outcomes of the assessment framework application in Chapter 3. Chapter 5 concludes the paper with conclusions and recommendations.

---

[5] Carbon footprint methodology implementations, such as BigMile, EcoTransIT, TK Blue, etc., implement different methodological choices as well, which can be traced back to the ambiguity of the EN 16258 standard.

2 Carbon footprinting KPIs for users of transport and transport providers

Carbon footprint KPIs quantitatively represent GHG emissions associated with a certain amount of useful activity.

In general, all transport-related carbon footprint KPIs can be divided into two classes:

1. Carbon efficiency of a network of a carrier or an LSP. This is measured as kg CO_2-equivalent emissions resulting from a unit of transport activity, which is typically defined as a unit of goods carried over a unit of distance. The most common unit of transport activity is one tonne-kilometre (tkm) and in that case, the carbon efficiency of a carrier is expressed in kg of CO_2-equivalent per tonne-kilometre transported. Another common measure of transport activity as in, for example parcel distribution, is m^3-kilometre, since in that logistic segment vehicles are more often capacity-limited by volume as opposed to weight.

2. Carbon efficiency of a supply chain of a shipper or consignee. This is measured as kg CO_2-equivalent emissions resulting from one tonne (or other capacity unit like m^3) shipped. Note that a shipper's KPI does not include distance, nonetheless, some shippers are interested in the GHG emission intensity of their LSPs[6], thus may request their normalized indicators, such as kg CO_2-equivalent emissions per unit of transport activity. Although the most preferred way is when the shipper's KPI is computed and reported by the LSP, the shipper's KPI can be computed by multiplying the carrier's KPI (provided by the LSP) by the distance. The latter way of computation is used when the carrier does not provide such a service, or when the shipper considers its own computations to be more reliable than those of the service provider.

Computing these KPIs requires two classes of data: greenhouse gas emissions and transport activity. In the carbon network efficiency KPI (kg CO_2e / tkm) the greenhouse gas emissions determine the nominator and the transport activity determines the denominator. The greenhouse gas data is expressed as a carbon dioxide equivalent or CO_2-equivalent, abbreviated as CO_2-eq or CO_{2e}. It is a metric measure used to compare and add the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. The carbon dioxide equivalent allows taking into account greenhouse gasses other than CO_2 without the need for explicit reference to them. In this paper for the purpose of simplicity and if it is not otherwise specified, CO_2-equivalent emissions are understood under CO_2 emissions. The CO_2 emissions can be computed based on fuel use or electricity use by application of an appropriate emission factor that converts, for example, liters of fuel into corresponding CO_2 emissions when burned.

---

[6] The LSP can also be referred to as carrier.

There are essentially two types of emission factors: 1) Tank-To-Wheel (TTW) -- emissions of the GHGs that are a direct consequence of burning fuel and 2) Well-To-Wheel (WTW) emissions that sum up TTW emissions and GHG emissions that result from production of the fuels and include emissions from fossil oil and gas extraction, transport of raw materials, refining, storage and distribution. In the field of carbon footprinting, the general convention is to use Well-To-Wheel emission factors to include Scope 3 emissions related to production and distribution of fuels. The WTW approach allows to adequately include the effect of electricity generation, and the climate impacts associated with the production of e.g. biofuels or synthetic fuels. The CO_2-emissions can be derived from a measurement of the consumed fuel, but can also be estimated by multiplying the actually driven distance with a CO_2 emission factor that is representative for the type of vehicle and transport mode that is used. This indicates that CO_2 emissions scale with the actually driven distance.

The second data class relates to transport activity. Transport activity is measured per transport leg within a transport service category. The most common measure of transport activity is tonne-kilometre, which is obtained by multiplying the quantity of goods by the distance over which the goods are displaced. Some methodologies allow using m^3 and other measures for the quantity of goods. The distance unit (kilometres) can be measured as great circle distance (GCD), actually driven distance (ADD), planned distance (PD) and shortest feasible distance (SFD). Independently of the specific units chosen, transport activity is measured as a multiplication of shipment size (possible dimensions are weight, volume, other) by the distance over which the shipment is displaced.

A crucial component for computation of transport activity thus is the distance over which the shipment is displaced.
The following four distance measure definitions are commonly used in the context of carbon footprinting:

1. **Great Circle Distance (GCD).** The great circle distance is the shortest distance between two points on the surface of the Earth, measured along the surface of the Earth. It is also known as the “as the crow flies” distance: this distance does not consider any infrastructure, so two points are connected directly, as if there is a straight road between them.
   The GCD is the most suitable measure for distance for the purpose of carbon footprinting as it looks at the net transport work independent of the chosen modality, infrastructure density and routing of the goods flow.
   It is the only measure that leads to a correct calculation of the impact of changes in routing or modalities on the carbon footprint. It is also the “easiest” distance measure from an administration and data requirements point of view, as there is no need to keep track of the routes that the vehicles travelled.

2. **Actually Driven Distance (ADD).** The actual driven distance is the distance travelled by the vehicle. This distance can be measured by the vehicle’s odometer. The ADD is the most intuitively understandable distance: for this reason it has deep usage roots. For instance, transport statistics is expressed in tonne-kilometres actually driven and the companies are used to reporting to the statistics bureaus in this manner. Also, some transport companies charge their clients based on travelled distances.

3. **Planned Distance (PD).** The planned distance is the distance that a shipment will be following in a vehicle as the route of the vehicle is optimized by the planning software. The software optimizes the vehicle route, for instance, by minimizing total kilometres driven and / or making sure that time-related constraints are satisfied. The PD is therefore not the shortest distance for a shipment, but a distance that the shipment is planned to travel. The advantage of the PD is that it is an ex-ante estimation of distance to be travelled, it can be computed and stored in a database. The PD can be later revoked from the database.

4. **Shortest Feasible Distance (SFD).** The shortest feasible distance is the shortest distance between two places on a mode-specific network. The SFD may not be the best route as it may include slow moving streets, or toll roads. The advantage of the SFD is that it is easily understood, that it can be computed ex-ante and that under certain conditions it is the same for all users that use the same software to compute it. Computation of SFD depends on the software implementation, state of infrastructure, implicit assumptions, such as avoidance of city centers while the shortest route often goes directly through such places, and mutability of infrastructure.

In current practice different types of distance metrics are used in carbon footprinting methodologies for the calculation of transport activity and/or the estimation of energy use. Historically, a number of distance metrics dominated the computation of transport activity, as for instance, the actually driven kilometers metric.
The ADD forms the cost basis of transport on the one hand, and on the other hand it was used by statistics to reflect on the volume of the transport market and for infrastructure decisions. However, for the purpose of carbon footprinting and subsequent use of the results for GHG reporting and GHG emission minimization not all distance metrics are equally useful.

The following chapter considers the suitability of each of these four distance metrics for carbon footprinting.

3 Assessment framework for different types of distance

In this chapter we formulate an assessment framework to analyze suitability of different distance metrics for eight criteria. Subsequently we provide a comparative analysis using the framework to draw the conclusions per criterion per distance metric.

3.1 Assessment framework

The framework assesses usefulness of the four distance metrices for calculating both the nominator (i.e. the volume of GHG emissions) and the denominator (i.e. emission allocation to the activities and entities) of the carbon footprinting network emission intensity KPI (kg CO_2e/tkm), which is discussed in the previous chapter. Although GHG emissions (the nominator) should in the ideal case be computed based on the amount of energy used (i.e. fuel, electricity), in many cases this data is not available so that distance is often used to estimate energy use and hence derive GHG emissions.

The framework assesses each distance metric for the following purposes:

1) **Adequacy for estimation of fuel used**. In case fuel or energy use is unknown, distance, in combination with a vehicle or mode-specific fuel consumption or emission factor (in gCO_2/km), can be used for estimation of fuel use and hence resulting GHG emissions. Although not ideal, the use of distance is a wide spread practice to estimate the unknown fuel quantities and corresponding GHG emissions.

2) **Adequacy for allocation of emissions to individual shipments and customers**. Emission allocation results in individual shipments or entities (e.g. customers) getting a certain portion of the total trip emissions assigned to them. In case of a more aggregated fleet and period emissions, the allocation is done proportionally to the shipment's or entity's share in the total transport activity.

3) **Adequacy and ease of auditing results by accountants.** The GHG emissions computed by an entity (e.g. a carrier) can be required to be validated by an (independent) accountant. The accountant should be able to verify correctness of the data and applied method. It implies that the data and method used should be reproducible in order to trace back the computations and certify their correctness.

4) **Data requirements and ease of data gathering for calculations**. The less data requirements and the easier it is to gather them, the better. Certain data elements can be obtained automatically without human labor, some other require meticulous data recording and human supervision. This criterion assess distance metrics for carbon footprinting from the data gathering point of view.

5) **Use for comparison of different networks and/or modalities.** Comparison between networks and modalities is a quick and easy way for making transport choice decisions.

However, direct comparison of emission intensities may be complicated by some factors, such as by different mode-specific network densities and network distances. Some distance metrics are better than other for this purpose.

6) **Use for analysis of potential improvement measures and for GHG optimization.** One of the major applications of carbon footprinting is to evaluate ex-ante and ex-post carbon optimization and decarbonization measures. Do optimization algorithms based on different distance metrics result in a directionally correct outcome and do resulting implementations lead to better operations and real world impact?

7) **Use for combining data from multiple subcontractors.** In many instances transport involves outsourcing and subcontracting. In these cases, emissions are not directly produced by the (reporting) entity, but are made on their behalf, so-called GHG protocol scope 3 emissions. For the purposes of optimization and reporting, the GHG emission data needs to be collected from the subcontracted parties. In this case it is important that the data is consistent and unambiguous.

8) **Commercially sensitive information shared.** The amount of GHG emitted can be directly linked to the fuel and energy use, especially it is the case in conventional transport solutions based on the use of fossil fuels. Once the quantity of fuel is estimated, the fuel costs can be estimated too. These data may be commercially sensitive as they possibly provide some insights into operational cost structures of the service providers. This property of carbon footprinting may be perceived as a disadvantage by certain categories of service providers. Therefore, from the acceptability point of view, distance metrics that disclose less sensitive information may be preferred.

3.2 Comparative analysis

The comparative analysis assesses the suitability of each of the four distance metrics for the eight criteria presented in the previous section. The summary of the analysis is presented in Table 2, where we denote “++” as the most suitable, “+” as suitable, “+/-” as neutral, “-” as unsuitable, and “--” as the most unsuitable.

Table 2: Suitability of distance metrics for different purposes: summary of comparative analysis.

Criterion / Distance Metric	**GCD**	**ADD**	**PD**	**SFD**
1: Adequacy for estimation of fuel used	--	++	+	+/-
2: Adequacy for allocation of emission to individual shipments and customers	++	--	-	+/-
3: Adequacy and ease of auditing results by accountants	++	-	--	+/-
4: Data requirements and ease of data gathering for calculations	++	-	--	+/-
5: Use for comparison of different networks and / or modalities	++	-	--	-
6: Use for analysis of potential improvement measures and for GHG optimization	++	+	+	+/-
7: Use for combining data from multiple subcontractors	++	-	--	-
8: Commercially sensitive information shared	+/-	-	-	+/-

Below we explain the most important reasons that lead to the conclusions with respect to the eight analysis criteria.

1. **Adequacy for estimation of fuel used[7].** This criterion relates to the nominator of the network emission intensity KPI. In an ideal situation, the primary data on fuel or energy use should be used. Moreover, as fuel is one of the main cost components of transport, the fuel data is generally well collected and stored, and thus actual fuel data must be used when available. However, in the absence of these data, the actually driven distance, combined with a default fuel consumption or emission factor, can be used to estimate fuel use[8]. Of the four distance metrics, the ADD is the most suitable for this purpose as it leads to the most accurate estimate of fuel consumption. If coupled together with an accurate vehicle-specific consumption factor, information on the load (weight of the vehicle has an impact on per-kilometer fuel use) and empty segments related to pre- and post- positioning, fuel or energy use can be estimated quite accurately. PD and SFD may also be used for this purpose, where PD is generally closer to the ADD, but does not account for possible deviations in ADD from the planned route. SFD is usable in case of point-to-point transport, but it becomes unusable if a journey involves multiple stops, therefore caution in application of the SFD should be exercised. The GCD is not suitable for the purpose of estimation of fuel use as it takes no account of actual network distances.

2. **Adequacy for allocation of emissions to individual shipments and customers.** This criterion relates to the process of emission allocation (also known as emission assignment) to the shipments, customers/entities that cause them or are responsible for them. The GCD is the most suitable one for this purpose: it allocates emissions proportional to the geographic displacement and is independent of operational details, while truly reflecting on the overall carbon efficiency within the scope of computation. The KPIs based on GCD can be communicated with the customers such they can compute absolute emissions related to their shipments. It is the most objective indicator of the total network efficiency. The SFD is the second best choice and can be used in case of unimodal transport, but it also has a number of disadvantages compared to the GCD, of which the most important one is ambiguity in SFD computation.
   An SFD computation depends on the software used and its network definition database, it also depends on the state of infrastructure and infrastructure evolution over the time, which may result in different SFD distances between the same locations computed using different software or at different moments. The PD metric is not suitable for allocation[9] as it is problematic in distribution (such as milk runs, groupage networks or LTL operations) as results vary a lot depending on assumptions. The PD also hides information on network efficiency.

---

[7] The adequacy for estimation of fuel use is the single criterion that relates to the nominator of the carbon footprinting GHG intensity KPI. Criteria 2-8 relate to the denominator of this KPI, namely transport activity measured as a unit of freight displaced over a unit of distance (e.g. tonne-kilometers).

[8] The use of ADD to estimate fuel use is applicable for the road vehicles. Other modalities have a weaker relationship between (projected on the Earth surface) distance driven and fuel use.

[9] Note that the PD is not the shortest distance for a shipment, but a distance that the shipment is planned to travel within a vehicle.

The ADD is not suitable metric, in distribution rounds or other routes with multiples stops allocation becomes arbitrary depending on the sequence of stops, require assumptions to carry out, and can often lead to directionally wrong results. This is illustrated in the example in Section 4.2.

3. **Adequacy and ease of auditing results by accountants**. The GCD distance metric used for determining of transport activity is the most suitable one for accountancy as it is immutable and can always be verified. Coupled with shipment data, the GCD metric presents easy to verify data on transport activity. The SFD is less suitable for this purpose as it requires additional information to be stored, such as routing software and network definitions. Furthermore the SFD can change over time, which leads to irreproducible results. The ADD is not suitable, as it requires a lot of detailed information to be supplied. Theoretically it is possible that the driven routes are collected and stored, but the amount of data, data consistency and complexity of the checks make auditing very difficult (i.e. more detailed information means more work). The PD is the least suitable, as auditing will require access to the software by which the planning was made, which is not realistic to expect, as software can be embedded, proprietary and evolve over time.

4. **Data requirements and ease of data gathering data for calculations**. Similarly to the auditing requirements, GCD requires least data gathering requirements and efforts, can be computed for any given two addresses using the Haversine formula[10] implemented in any software, leading to exactly the same results. The SFD will require using network definitions and applications of the Dijkstra algorithm (Dijkstra, 1959). As network definitions evolve over time (e.g. due to software updates and infrastructure changes), the use of SFD will require more data storage, making it less suitable from the data gathering point of view. The ADD at the level of shipments is difficult to collect as it requires complete logging of the routes travelled by the individual shipments[11]. The PD is the least suitable metrics requiring logging of the plans and inaccessibility of these data to the 3rd parties – for the 3rd parties access to the planning data is in most cases impossible.

5. **Use for comparison of different networks and/or modalities**. The GCD as distance metric in the denominator is suitable for comparison of network GHG efficiencies and between different modalities. As the GCD distance is the same for all transport options, GHG intensity based on transport performance calculation using GCD provides a sound basis for comparison of networks and across different modalities. All other types of distance metrics are mode-specific and do not provide any basis for comparison across modalities, see example in the Section 4.1 illustrating the problem. Within the same modality, the PD does not provide any basis for comparison as it is vehicle-level journey specific and cannot be reproduced by a third party to have a meaningful comparison between networks. The ADD-based comparison of the emission intensity KPIs only reflects on the load and vehicle efficiency, while overall network organization efficiency in not reflected when ADD is used to determine transport activity.

---

[10] The Haversine formula is known from the beginning of the 19th century in the context of navigation, e.g. Robusto (1957)

[11] The ADD at the level of road vehicle is easy to collect, as it is equal to the odometer data.

The SFD metric is possible to use for emission intensity comparison within the same modality, but it is not problem-free, as the example in section 4.3 illustrates.

6. **Use for analysis of potential improvement measures and for GHG optimization.** The GCD provides a very good basis for optimization: minimizing GHG emissions per tonne-km GCD will result in the best real world result for a given flow of goods. The minimization of kilometers driven (ADD) is an often used optimization strategy, but it is limited to one modality. The ADD minimization results in an optimal PD, such that for a given goods flow an optimal planned route is determined, so in essence these two are equivalent. The minimization of emissions per tonne-km SFD is similar to the GCD-based optimization, but it is only possible within one modality and is more difficult or cumbersome to implement.

7. **Use for combining data from multiple subcontractors.** There are different ways of collecting data from the subcontractors. In case GHG data is provided in absolute volumes by the subcontractors, specifically for the information exchange, the distance metric used for information exchange does not matter. However, it matters for verifiability and auditing, see point 3. If the data is shared in the form of network GHG intensity[12], the distance metric matters a lot, making analysis for this criterion similar to the one conducted for point 2 on emission allocation. If emissions are computed on the basis of GHG intensity, both the transport service provider and the user of transport services must be using the same distance metric and the same tool to calculate it in case of SFD and PD. Therefore, GCD is an ideal metric in this situation. The SFD is the second best, but much less preferable due to the fact that it cannot be defined unambiguously. In the majority of cases, SFD computation discrepancy between the parties is probably not large, but in some cases as, for instance, when infrastructure status may play a role, there could be substantial discrepancies rendering the SFD unsuitable. Based on these arguments, it is deemed generally to be unsuitable, as the example in Chapter 4 shows. The PD is utterly unsuitable as this distance is not known to the party who receives the GHG intensity data and cannot be independently assessed. The ADD can only be used if complete data on driving routes is shared, which is not practical and given availability of better options is not necessary.

8. **Commercially sensitive information shared.** Sharing carbon footprint data or GHG network intensity data leads to a degree of commercial information sharing. For conventional transport solutions based on fossil fuels, GHG data can be directly converted into fuel use and thus monetary expense. However, some distance metrics can only be used for general derivative data on network cost efficiency, such as GCD and SFD, while the ADD and PD based data reveal more information about network organization and distances travelled for specific customers.

---

[12] Sharing of network GHG intensity is not the preferred way to provide carbon footprint data by the carrier to the user of transport. In an ideal situation the absolute footprint information should be provided. But in case the user of transport requires this data or for the purpose of verification, the network GHG intensity data can be an important element.

If audited, the ADD and PD based computation will require network disclosure to the auditor, making them less attractive from this point of view[13]. If part of the operations is carried out using (near) zero emission technology or fuels, the GCD and SFD based computations better hide away (or aggregate) the sensitive properties of the network organization than it is the case for ADD and PD.

This leads to the following conclusions on the suitability of the four analyzed distance metrics for carbon footprinting:

- The ADD is a clear winner for estimation of fuel use and GHG emissions in case primary fuel consumption data is not available.
- For all other purposes, and especially for determining of the transport activity, transport performance and for emission allocation as well as for the goals of sharing emission intensity data, minimum data requirements and auditing, the GCD distance metric is the only fundamentally correct option among the analyzed distance metrics. For these purposes the SFD metric is a second-best choice, when used for calculating and comparing carbon footprints within one transport modality. However, as we show in the example in the following chapter, the SFD metric is mutable, software-dependent and can lead to directionally incorrect decisions. This makes it generally less suitable compared to the GCD.

---

[13] The accountant can be obliged to keep the audited source data confidential

4 Examples to illustrate the advantage of using GCD as a distance metric

The comparative analysis of chapter 3 has shown that the GCD metric performs better than the other considered distance metrics for all considered analysis criteria except estimation of fuel used. The GCD is the optimal distance metric to determine the transport activity in a carbon footprinting methodology. This chapter substantiates the analysis by three examples where the properties of GCD and other distance metrics are analyzed in the context of transport modes, roundtrips and planning software.

4.1 Comparing different transport modes

A CO_2 network intensity indicator in the form of CO_2/tkm that uses the ADD or SFD to determine the transport activity cannot be used for comparison of mode-specific emissions since it does not always meet the requirement of being directionally correct when comparing different transport modes.

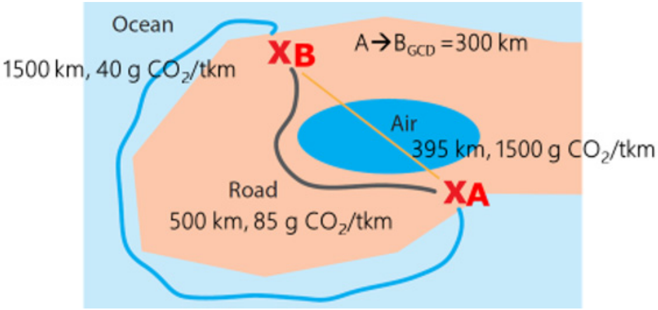

Figure 2: A shipper can choose from three transport modes (ocean, road and air) to transport goods from A to B.

Suppose that a shipper wants to send 1 ton of goods from A to B and there are three possible transport modes: ocean, road and air (Figure 2). In situation 1 the shipper receives the CO_2-intensity for all three options based on ADD (or SFD that is equal to ADD for the simplicity in this example), which is 40, 85 and 1500 gCO_2/tkm for ocean, road and air respectively. In situation 2 the CO_2-intensity is based on GCD and is 200, 143 and 1977 gCO_2/tkm_{GCD} for ocean, road and air respectively. Based on these CO_2-intensities, the naïve choice of the shipper would be the ocean transport solution in situation 1 and the road transport solution in situation 2.

One of the basic principles of carbon footprinting is that the method should be directionally correct and thus lead to the choice with the least amount of real-world CO_2-emissions. The real world CO_2-emissions are 60, 43 and 593 kg CO_2 for ocean, road and air respectively to transport 1 ton of goods from A to B (Table 3). Based on the real world CO_2-emissions the right choice would be to use road transport in this case, which is equal to the naïve choice of the shipper in situation 2 (GCD).

This example illustrates that naïve use of the CO_2-intensity indicator based on ADD (or SFD) does not result in a directionally correct CF method, and hence decisions taken based on this indicator will likely lead to a real world increase of emissions[14]. Furthermore, calculating real world CO_2-emissions based on the CO_2-intensity requires additional information on the mode and the route in situation 1. In situation 2 the only required information is the network CO_2 intensity and the locations A and B that are needed and sufficient to calculate the GCD.

Table 3: Using ADD or SFD is not always directionally correct when comparing different transport modes.

	Situation 1: ADD or SFD		**Situation 2: GCD**		**Situation 1 and 2**
	Distance (km)	CO_2-intensity (gCO_2/tkm)	Distance (km_{GCD})	CO_2-intensity (gCO_2/tkm_{GCD})	Real-world CO_2 ($kgCO_2/ton$)
Ocean	1500	40	300	200	60
Road	500	85	300	143	43
Air	395	1500	300	1977	593

4.2 Choosing the direction in a roundtrip

A CF method that uses the ADD to determine the transport activity does not always meet the requirement of being directionally correct when choosing the direction in a roundtrips.

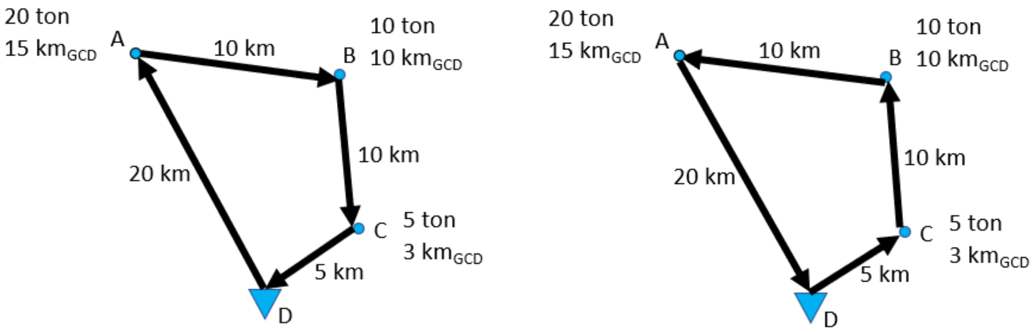

Figure 3: A transport operator can do a roundtrip clockwise (option 1) or counterclockwise (option 2).

The effect of a roundtrip direction on the carbon footprinting KPIs was first noted by Swahn and Peterson (2013). A transport operator delivers goods at three locations A, B and C in one roundtrip starting and ending at depot location D. The transport operator has to choose in which order to visit these locations: clockwise or counterclockwise (Figure 3). These two options result in different trip-level emissions due to the fact that fuel consumption and resulting GHG emissions depend on the distance travelled (the same for both options) and the weight of the vehicle, which is differently distributed in these two options: in option 2 (counterclockwise) a heavier load makes more kilometers.

---

[14] This is an example of a CF method application where it is likely to do more harm than good.

In situation 1 the transport operator makes a decision using the CO_2-intensity based on ADD and in situation 2 the transport operator uses the CO_2-intensity based on GCD. Since both options (clockwise and counterclockwise) are part of the same road network, the CO_2-intensity factor of a proper CF method could be used for decision support. Table 4 provides an overview of situation 1 for both options (clockwise and counterclockwise) and shows that the ADD-based CO_2-intensity is lower for a clockwise roundtrip, while the real world CO_2-emission is lower for a counterclockwise roundtrip. In situation 2 the GCD is used to determine the CO_2-intensity and as is shown in Table 5. This leads to a choice for a counterclockwise roundtrip. Table 6 summarizes situation 1 and 2 to show that using the ADD is not always directionally correct when choosing the direction in a roundtrip.

Table 4: Situation 1: TA is based on ADD for the two roundtrip options (clockwise and counterclockwise).

	Option 1: clockwise				**Option 2: counterclockwise**				
Route	Distance (km)	TA (tkm)	EF ($kgCO_2/km$)	CO_2 (kg)	Route	Distance (km)	TA (tkm)	EF ($kgCO_2/km$)	CO_2 (kg)
DA	20	700	0.90	18	DC	5	175	0.90	4.5
AB	10	150	0.70	7	CB	10	300	0.85	8.5
BC	10	50	0.55	5.5	BA	10	200	0.70	7
CD	5	0	0.50	2.5	AD	20	0	0.50	10
Total	45	900		33	Total	45	675		30
CO_2-intensity (gCO_2/tkm)				37	CO_2-intensity (gCO_2/tkm)				44

Table 5: Situation 2: TA is based on GCD for the two roundtrip options (clockwise and counterclockwise).

			Option 1: clockwise		**Option 2: counterclockwise**	
	Distance (km_{GCD})	TA (tkm_{GCD})	CO_2 (kg)	CO_2-intensity (gCO_2/tkmGCD)	CO_2 (kg)	CO_2-intensity (gCO_2/tkmGCD)
A	15	300				
B	10	100				
C	3	15				
Total		415	33	80	30	72

Table 6: Using ADD is not always directionally correct in the case of roundtrips.

	Situation 1: ADD	**Situation 1 and 2**	**Situation 2: GCD**
	CO_2-intensity (gCO_2/tkm)	Real-world CO_2 ($kgCO_2$)	CO_2-intensity (gCO_2/tkm_{GCD})
Clockwise	37	33	80
Counterclockwise	44	30	72

4.3 The state of the infrastructure and planning software

A CF method that uses the SFD relies on possibly inconsistent data and is not verifiable by others (e.g. accountants).

The SFD is not a consistent and verifiable distance measure, which makes it unsuitable[15] for use in a CF method. First of all, the SFD has an ambiguous definition: it can be defined as the route with the least amount of kilometers or which takes the least amount of time. Driving through a city center might be shorter in kilometers, but longer in time, so the question which route is the 'shortest' is a moot point, as well as related to different perceptions and software implementations. It has to be clear to all users which definition of SFD is applied in the CF method, but even then it is possible that inconsistencies occur, since the SFD is also dependent on the maps and the algorithms used in planning software. Other causes of possible inconsistencies in the data are the state of the infrastructure (e.g. due to road works, state of the tunnels) and the fact that infrastructure networks evolve over time, which can result in different measurements of SFD. Figure 4 shows an example of inconsistent data when using the SFD as distance measure. In case the SFD is defined as 'shortest time' the vehicle would take a route of 701 kilometers in the left situation and a route of 810 kilometers in the right situation. In case the SFD is defined as 'shortest distance' the vehicle would take a route of 701 kilometers in the left situation and a route of 720 kilometers in the right situation. With both definitions a difference arises between the two situations due to the state of the infrastructure and the planning software. In case a shipper uses the CO_2-intensity from the left situation to calculate its emissions, while the transport is actually using the route of the right situation, the real world CO_2-emissions are underestimated by the shipper. These examples show that the SFD is an ambiguous distance measure, which is mutable and inconsistent. Due to inconsistency of data in a CF method the requirement of verifiability (for example by accountants or other organizations in the transport chain) is not met, while this is an important requirement of a proper CF method.

---

[15] The use of SFD in unimodal carbon footprinting may provide reasonable results in some cases, however, due to availability of a better distance metric, we deem it unsuitable on the basis of comparison with the better option of GCD-based carbon footprinting.

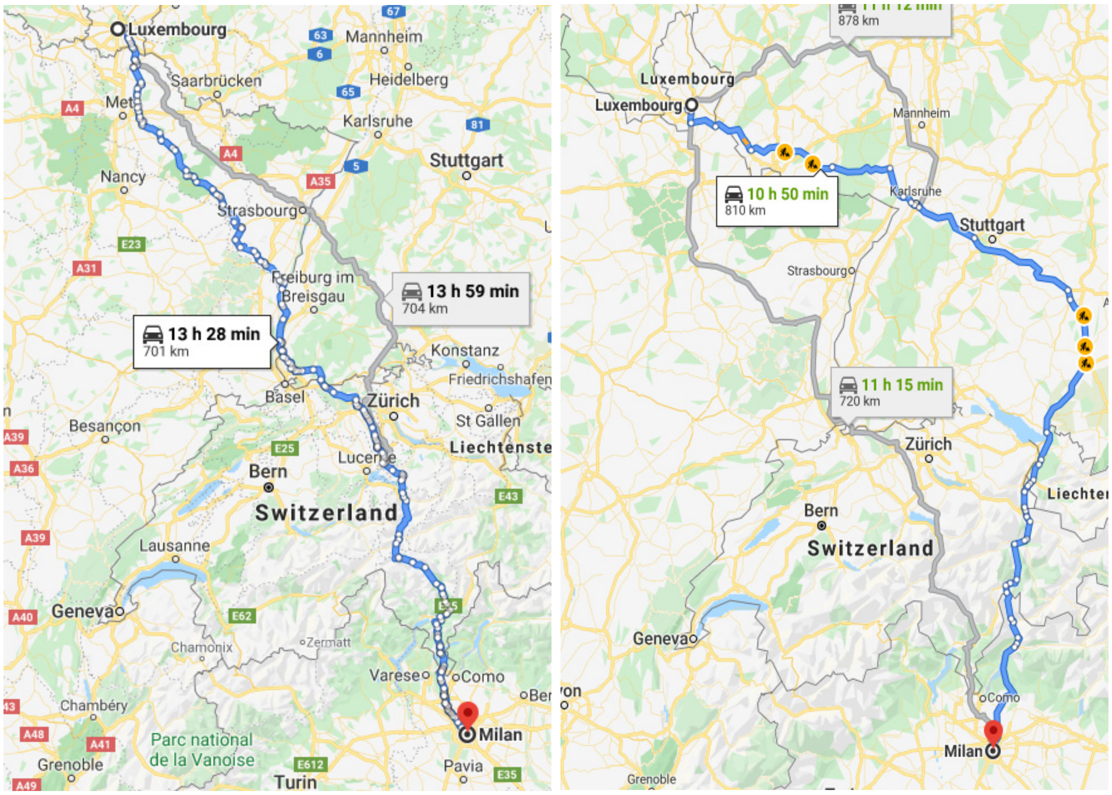

Figure 4: The SFD depends on the definition, on the state of the infrastructure and on planning software.

5 Conclusions and recommendations

Carbon footprinting is an important instrument for the decarbonization of transport and logistics. As a consequence of this importance, a proper implementation and standardization of a carbon footprinting methodology is the only way to realize its potential. Moreover, a bad methodology for carbon footprinting can do more harm than good. Therefore, in this paper we analyzed one of the critical components of any carbon footprinting method for transport and logistics – the distance metric.

In carbon footprinting the distance is mostly applicable for computation of transport activity measured as tonne-kilometres shipped. Although it can also be used for estimation of fuel use and the volume of GHG emissions, this is a niche application and should only be used in case if fuel data is not available. The main use of distance is thus in the denominator of the carbon intensity factor, kg CO_2 / tkm. The use of GCD ensures directional correctness of the method and fairness in allocation through practical factors such as adequacy of emission allocation; minimum data requirements and ease of data collection; traceability, verifiability and ease of auditing; suitability for carbon optimization; reliability of emission intensity factor as a decision variable and a means of communication of the emission data. Other considered distance metrics perform worse than GCD on these criteria.

On the basis of the conducted analysis, we strongly recommend the use of GCD in determining transport activity, defined as quantity of goods transported times distance over which the goods are transported. We strongly recommend to make GCD the norm for determining transport activity and for emission allocation in the standards, such as the ISO 14083 which is now under development. A standardized carbon footprinting method based on GCD transport activity data will ensure directional correctness, fairness of allocation, comparability and reproducibility of the results, and ease of implementation. These factors will help in its applications to reduce the CO_2 intensity of transport and logistics in the short to medium term, and to decarbonize it fully in the longer term.

6 References

Bewustbezorgd, Hoe werkt de rekentool? Een geavanceerd rekenmodel op basis van vervoerdersdata. https://bewustbezorgd.org/voor-webshops/hoe-werkt-de-rekentool/ retrieved 31-05-2021

Davydenko I., Smokers R. (2017), Carbon footprinting as evidence based facilitator of environmentally friendly transport and logistics solutions, Fourth International Workshop on Sustainable Road Freight Transport, 30/11/2017, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge

Davydenko, I., Hopman, M., van Gijlswijk, R. N., Rondaij, A., & Spreen, J. S. (2019). Towards harmonization of Carbon Footprinting methodologies: a recipe for reporting in compliance with the GLEC Framework, Objectif CO_2 and SmartWay for the accounting tool BigMile, TNO 2019 R11486

Davydenko, I., Nesterova, N. N., Ehrler, V., Illie, R., Lewis, A., Swahn, M., & Smith, C. (2018). *Testing Results. Deliverable 4.4*. TNO.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. Numerische Mathematik. 1: 269–271.

Verena Ch. Ehrler, Saskia Seidel, Andreas Lischke, David Rüdiger, Kerstin Dobers, Davide Luzzini, Susana Val (2017), Approach for closure of identified gaps for eco-labeling of transport chain emissions, LEARN project deliverable D3.2.

McKinnon, A. (2018). *Decarbonizing logistics: distributing goods in a low carbon world*. Kogan Page Publishers.

Swahn M., Peterson A. (2013), Företagens logistikanalyser – åtgärder för bättre resurseffektivitet och mindre miljöpåverkan, Trafikverket 2013, http://trafikverket.diva-portal.org/smash/get/diva2:1364598/FULLTEXT01

Robusto, C. C. (1957). The cosine-haversine formula. The American Mathematical Monthly, 64(1), 38-40.

7 Signature

The Hague,14 June 2021

TNO

J. Spreen
Projectleader

Dr. I.Y. Davydenko
Author