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van Wee, Bert; van Cranenburgh, Sander

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Substitutability as a concept to understand travel behaviour and its implications

Bert van Wee[1]
Sander van Cranenburgh[2]

Abstract: *In this paper we propose the concept of Substitutability and define it as 'the extent to which one or multiple characteristics of the preferred travel behaviour alternative can be substituted by alternatives'. Characteristics include activity choice, mode choice, time choice, and route choice We argue it is a promising concept, which is relevant for travel behaviour research. In addition, it is relevant from an accessibility perspective, and from the perspective of 'freedom of choice'. We conceptualize the concept, present a mathematical expression, discuss its relationships with the concepts of the freedom of choice, accessibility, and robustness/reliability. We argue substitutability is a gradual concept, that can be measures pre trip, on trip, and while executing an activity pattern. It can be analysed at different levels: (1) components of trips for one person, (2) a full trip or activity for one person, (3) a cluster of activities/ trips for one person, (4) an aggregation of the three levels above, but now for a group of persons, and (5) the perspective of the origin of the trip or the perspective of the destination. In addition, we discuss modelling substitutability and its use for evaluation purposes, and we present a research agenda*.

Keywords*:* "substitutability", "accessibility", "research agenda".

1. Introduction

As in any field the transportation community makes use of concepts, examples being 'sustainability', 'fragmentation', 'multimodality', 'accessibility' and 'robustness'. A term sometimes used in the travel behavior community is 'substitutability' expressing that (parts of) trips can be substituted by alternatives (see below), but a search in SCOPUS , combing this term and 'travel behavio(u)r' revealed only six hits, and the combination with 'transport' only 41. Examples of the latter combination include You et al. (2013) who discuss the substitutability of travel demand and García-Olivares (2015) who discusses the substitutability of electricity and renewable materials for fossil fuels. To the best of our knowledge not any paper systematically explores the concept of substitutability and its relevance for travel behavior. Consequently, there is not a clear picture of definitions, a conceptualization of the concept is missing, and the relevance for research is unclear. Yet we argue the concept is potentially very useful and relevance for the

[1] Delft University of Technology, Transport and Logistics Group
[2] Delft University of Technology, Transport and Logistics Group

transport community, at least for those focusing on travel behavior, and for the design and evaluation of the transport and land use system. This paper aims to fill this gap.

Section 2 proposes a definition and explains why the concept is relevant. Section 3 explains the relevance of the concept, and links it to other related concepts. Section 4 conceptualizes the concept, followed by section 5 proposing a mathematical expression. Section 6 presents a research agenda, and section 7 finally summarize the main conclusions of this paper.

2. Definition and choice options

2.1 Definition

We define substitutability in the context of travel behavior as ‘the extent to which one or multiple characteristics of the preferred travel behavior alternative can be substituted by alternatives’. This is particularly of interest when the preferred alternative is no longer available (due to whatever circumstances, such as labor strikes, weather conditions, power black outs, etc.). We assume activities as given, although the characteristics of the transport system can influence activities.

2.2 Choice options

Choice options in case of travel behavior include:

- Activity choice: frequency and location. Only location based activities need travel, so the choice is limited to activities to which people travel. Note that substitution between location based activities and virtual activities does exist, examples being e-shopping, e-learning, e-working and skyping as alternatives for shopping, ‘normal’ learning and working, and meeting people.
- Mode choice, dominant examples being car-driving, car passengers, train, tram, metro, bus, bicycle, and walking.
- Route choice.
- Time choice. Note that time choice is often interpreted as ‘time of day’ only, but people can substitute activities and related travel also at other time scales. E.g. people can decide on the day of the week at which to do the weekly shopping, or the year in which to visit a certain touristic place of family abroad.

Within these choice options several possibilities for disaggregation are possible. This at least applies to mode choice: even if the choice for, for example travelling by train as the main mode is made, people can choose between a fast train and longer access or egress times, or a slower train with more stops, and a shorter access or egress time. And if a person has decided to travel by car and she has multiple cars available, the person can chose between these cars. The same may apply to cycling.

The different dimensions for choices as presented above can be made simultaneously: the choice options can be interrelated. Very obviously mode choice and route choice are interrelated because the networks for modes often differ (partly as in the case of cycling and driving, of fully, as in the case of travelling by rail and driving). Anther example: mode choice may depend on time of day choice, an example being a person travelling by car outside the rush hours, and by train during the rush hours. Or a person might chose a combination of routes and bikes, and the choices interact, e.g. a regular bike if a paved route is chosen, and a mountain bike in case of an unpaved route. A final example: a person might use a conventional bike to commute on Monday to Thursday, but a sports bike on casual Friday because she can wear other clothes on Friday. We think it is plausible that the heuristics people use while making travel behavior decisions can depend on characteristics of the person, the activity/activities to be carried out, the trip (pattern) to be made, and the travel party.

3. Relevance and related concepts

Why would the concept of substitutability be relevant? We think a high level of substitutability is to be evaluated positively. The higher this level, the more options to travel and participate in activities people have available, and they will prefer this over having fewer options available. In addition, a high level of substitutability increases the flexibility of travel, and reduces the vulnerability for disruptions. It can also reduce the probably of late arrivals, and reduce the margins people consider to avoid late arrivals.

The concept is related to several other concepts, a first one being the Freedom of choice. Wikipedia defines the freedom of choice as ‘an individual's opportunity and autonomy to perform an action selected from at least two available options, unconstrained by external parties’ (assessed 16-8-2016). The concept is often discussed in the literature in several areas, including economics and philosophy, and more specifically: ethics. A high level of the freedom of choice is evaluated positively (Van Wee, 2011; Martens, 2016).

Next, it is strongly related to the concept of accessibility, as explained above. Following Geurs and van Wee (2004: 128) and limiting ourselves to passenger transport we define accessibility as ‘as the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)’. A high level of substitutability is positively correlated to accessibility because such a high level increases the extent to which people can reach activity destinations. But the concepts are not synonyms. We give an example to explain the core of the difference. Let us assume a person living in an area with hardly any jobs, shops, schools, other people etc. nearby, but many options at a distance of surrounding cities and towns, all at 40 kms distance, each connected by many roads, railroads and bus connections because the person lives in the point of gravity of these cities and towns. Then her level of accessibility is low. But, the level of substitutability is very high, both because of the many activity/destination locations being available, as well as because of the many transport options. Let us now assume a person with a supermarket at 200 and one at 300 meters distance. Then the level of substitutability is way lower than in the first case, but the level of accessibility is much higher. Figure 1 visualizes this situation.

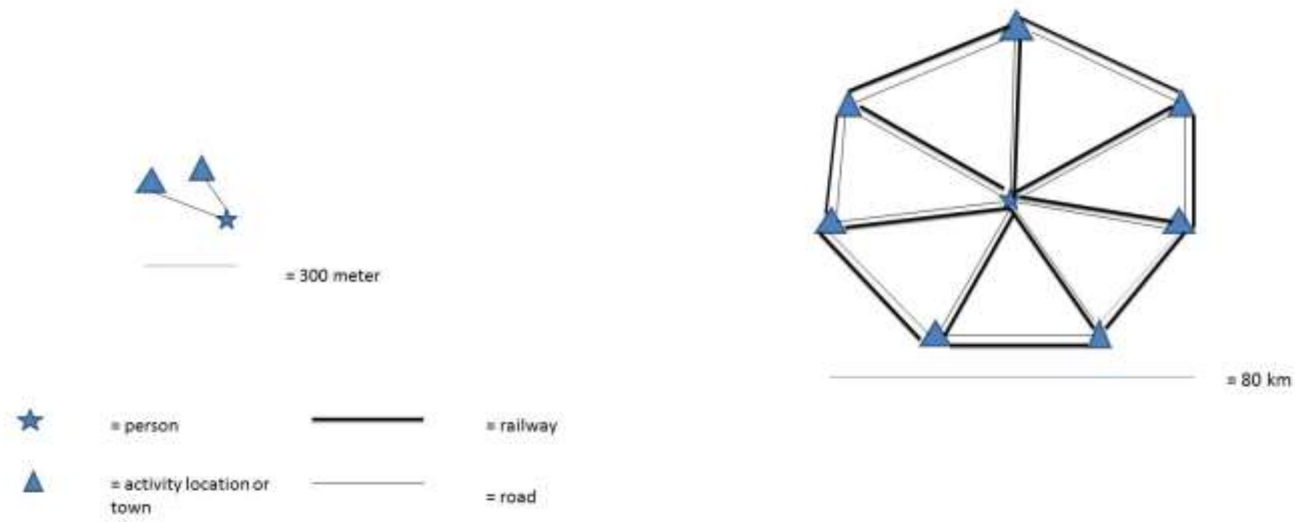


Figure 1 : Stylized example of (a) a high level of accessibility, and a low level of substitutability, and (b) a low level of accessibility and a high level of substitutability.

In addition it is related to the concepts of flexibility, robustness and vulnerability: a high level of substitutability is positively correlated to a high level of flexibility and robustness, and a low level of vulnerability. Note that substitutability is not the same as flexibility because flexibility is a broader concept and also includes characteristics of the traveler, whereas substitutability is a characteristic of the transport and land use system only, though experienced by a traveler. Its position relative to the robustness and vulnerability is that a high level of substitutability positively influences robustness and negatively influences vulnerability. There are multiple definitions of robustness, and the concept can be interpreted as a specific case of accessibility and can be expressed mathematically – see Liao and Van Wee (in press). A fundamental difference is that we normalize substitutability relative to the option with the lowest GTC (see equation 1).

To summarize, the concept of substitutability is strongly related to several other concepts, but it is not a synonym for any of those concepts. The concepts to which it is related most probably are accessibility or robustness interpreted as an accessibility indicator. We think that definitions and certainly operationalizations of accessibility are possible that explicitly include the level of substitutability (see also the research agenda below).

The concept can be of interest for researchers studying transport and land use systems, but also for planners designing such systems, and policy makers interested in the outcomes of alternative designs and decision making.

4. Conceptualizations

This section discusses several other aspects relevant for conceptualization.

A gradual concept
Substitutability is a gradual concept, it is not black or white. In other words, there is a gradual scale of substitutability. A person having two exactly equal bikes has a high level of substitutability in her choice for any of the two bikes. A person who needs to go to a hospital urgently and the only choice option to be there on time is to immediately take the only car available has zero substitutability. In practice a person often has different levels of substitutability. E.g. one route can for a small part be substituted by another. In that case the level of substitutability is low (same mode, time of day; minor change in route). Or a person can substitute a flight for a high speed rail trip which she values about equally (mode choice change, and probably also time change), resulting in a higher level of substitutability.

A normalized score or not?
It is an option to see substitutability as a concept that needs to have a value between zero and one, the value of zero meaning there is not any option to substitute, and one expressing plenty of perfect substitutes. Alternatively it is an option to not limit the value. In that case values >1 can be obtained in case of several good alternatives being available. A log specification is an elegant way to express the reduced additional value of an increasing number of options. A value of one could either mean that there is one perfect substitute (which has the same value for a person than the chosen option) or that there are multiple options with lower utility than the preferred option and the sum of the utility of these options (by coincidence) reaches the value of one.

The additional value of additional options
It is clear that if the probability that the preferred option is not available, people value alternatives. A major questions is: What is the additional value of having more than one alternative options available? We hypothesize the answer depends on several factors.

Heterogeneity amongst people: not all people will attach the same value to additional options in comparable circumstances and taste heterogeneity could be included in substitutability indicators. We do not further discuss heterogeneity in this paper.

Characteristics of the activity or activity program: in case of alternative activities, we expect the appreciation for more options to depend on characteristics of the activity. For example, let us consider a person scheduling a dinner in a restaurant, but it turns out that unexpectedly the preferred restaurant is closed. Even though the person will only visit one other restaurant, we think it is likely she will value having the choice between multiple alternatives. On the other hand, if a person wants to buy one kg or rice and the shop is closed, but there is a shop next door offering the same brand of rice for the same prices, having more options available probably is not of any value. Important characteristics of the activity relevant for the additional value of additional options include at least (a) the appreciation for heterogeneity for the specific activity (which also depend on characteristics of people – see above); in some cases people will not at all appreciate heterogeneity, such as in the case of a person preferring to visit the same supermarket, whereas in other cases she might prefer heterogeneity, such as in case of restaurants, (b) past activities (especially relevant in case of appreciation for heterogeneity, such as in the example of the restaurant above), and (b) flexibility in activity scheduling. This flexibility can be explained via an example. Let us assume a person wants to visit a relative at night, but due to a train strike and no other travel options being available this is not possible. Maybe she has several persons she wants to visit in, for example, one month, and she can easily reschedule which person to visit on which date. In that case the flexibility is high. But if the person she wants to visit will leave the country for a year next day, the flexibility is very low – if not: absent.

Overlap

In case of travel options, it is important to realize that options to some degree can overlap. Take the example of route choice: alternatives can partly overlap. The more the overlap, the more likely a problem on a route will also apply to alternatives, but on the other hand, the difference in (dis)utility will probably be very small. We refer to Liao and Van Wee (in press) how to correct for overlap. In case of substitutability we consider a partly overlapping travel option as a full alternative, as long as the reasons for the preferred option not being available relates to the non-overlapping part.

Individual versus social choices

Choices can be made on an individual basis, or can depend on other people. At the activity level substitution between persons is possible, examples being the question which person in a household does the shopping or brings children to school, but because we assume activities to be given, we do not further discuss such interdependencies. Assuming activities to be giving, a person often can decide on her own about travel choice options, but not always. Examples of interactions between people are that within a household there could be one car available, and therefore car availability depends on the behavior of other members. A person therefore might change modes if the car is not available, or might reschedule the time of an activity and wait until another household member returns home by car. Or people may decide to travel together, having implications on mode choice, time, and route.

Awareness

A fundamental notion is that the level of substitutability can be assessed by a researcher ‘objectively’ based on data, but also on the perceptions of the traveler. The level of substitutability is not only a matter of having options available, but also of being aware of the options available. E.g. a person without a drivers license travelling by train to work who hears about a train strike for the next day, and who is not aware of a bus connection, might think there is no option to substitute the train trip, although in reality there is.

Pre trip, on trip, during an activity pattern

The level of substitutability depends on the time at which is it measured relative to the trip. An obvious way to assess levels of substitutability is to assume the level before making a trip, at a time when all theoretically available options are still open.

But not all options are open at all times. The longer before a trip a person is aware of travel and activity options, the higher the level of substitutability. E.g. a person facing her car brakes down the moment she wants to leave home for a job interview, cannot decide to substitute the car trip by a train trip, if she would then be way too late. But if this happens three days in advance, she still can do this and take the train leaving home earlier.

Also during a trip substitution can take place, although during a trip the level generally is lower than before the trip. E.g. a person can switch routes because of an unexpected delay on the intended route. Maybe a person intended to buy a pair of shoes in a specific shop, but that shop turns out to be closed. Or a person can decide not to take the intended bus because it is heavily crowded, and wait for the next bus. Or she can change flights after booking the initial flight. If there are nearby shoe shops, she can substitute the activity location. The popularity of inner city areas for shopping might be partly related to the high level of substitutability of shops (activity locations).

The return trip: limitations

The choice for the trip from home to a destination often has implications for further travel on the same day (the return trip or other travel). For example, a person not travelling by car to work generally does not have a car available for the trip back home. Other limitations are cycling to a station – later on the same day the person probably needs to travel to the same station to pick up the bike.

Level of analysis

An important dimension is the aggregation level of the level of substitution. We distinguish:

1. Components of trips for one person
2. A full trip or activity for one person
3. A cluster of activities/ trips for one person
4. An aggregation of the three levels above, but now for a group of persons.
5. The perspective of the origin or destination of the trip

We now briefly discuss the these aggregation levels. First people can substitute components of trips. E.g. a person travelling by train and arriving at the destination can substitute her intended bus trip to the final destination by walking or renting a bicycle. Secondly that person can substitute the full trip or activity, i.e. change the mode for the full trip or the destination. Thirdly a person can change multiple activities and related trips, i.e. an activity program. Fourth these three levels can also be analyzed over a group of multiple people, examples for the successive levels being (1) options for multiple people to cycle from a neighborhood to the station as opposed to taking the bus, (2) options to either drive or travel by public transport from a neighborhood to the center of town, and (3) options for all people in a neighborhood to carry out a specific activity program by foot. Finally substitutability can be approached from the perspective of the origin (from which one or multiple persons chose the destination(s) and travel options) or the perspective of the destination (how easily can a group of persons substitute travel to a given destination, e.g. an office location of a recreational facility). Below we will not systematically discuss both perspective, but take the first perspective as the point of departure.

5. Mathematical expression for substitutability

To formalize substitutability, we employ the closely related concept of accessibility. According to Geurs and Van Wee (2004:128) accessibility is defined as ‘the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)’. The paper provides four categories of accessibility measures, utility based measures being one of these. We choose this category of measures, because it allows for elegantly incorporation both substitution options, as well as their relative attractiveness compared to the ‘best’ option, and next the value of those options. Within the utilitarian based approach there are several mathematical formalizations of accessibility. We built upon the most well-known measure of accessibility, namely the so-called LogSum (LS) (eq. 1), in which V_{jn} denotes the observed utility of alternative *j* for decision maker *n*.

In essence, – under certain utilitarian assumption regarding behavior – the LS_n is the expected maximum utility a decision-maker derives from making a choice among *J* available alternatives (e.g. De Jong et al., 2005). The LS is monotonous, in the sense that the LS increases (decreases) when more (less) alternatives are available (e.g. new routes are opened), or when alternatives become more (less) attractive (e.g. cheaper).

$$LS_n = \ln\left(\sum_j e^{V_{jn}}\right) + C \qquad (1)$$

We pose that substitutability can be conceived as the relatively loss in accessibility due to the omission of the preferred alternative e.g. because this alternative are no longer available due to strikes, maintenance works, or disruptions in the transport network. Specifically, we define substitutability as the ratio of the accessibility *without* the otherwise chosen alternative *i* available (denoted $LS_n^{Y=i}$ over the accessibility including the otherwise alternative *i* (eq. 2).

$$S_n = \frac{LS_n^{Y=i}}{LS_n}$$	(2)

In equation 2 substitutability is presented in a deterministic situation, in the sense that the analyst knows with certainty the chosen (i.e. most preferred) alternative. In practice however, this is seldom the case. Rather, the analyst holds probabilistic views on the likelihood of decision-makers choosing certain alternatives. Therefore, equation 3 generalizes equation 2 towards the probabilistic situation in which the chosen alternative is not known with certainty. In the numerator, the accessibility without the preferred alternative, $LS_n^{Y=i}$, is weighted by the probability $P(Y=i)$ that each alternative *i* is chosen. As a consequence, the effect of not being able to choose an alternative that had very little chance of being chosen in the first place has a relatively small effect on the substitutability.

$$S_n = \frac{\sum_i P(Y=i) LS_n^{Y=i}}{LS_n}$$	(3)

In order for the measure to provide meaningful results, two operational steps need to be taken. Firstly, the choice set, i.e. the set of alternatives that is considered by the decision-maker, needs to be defined. In the context of our measure for substitutability, we define the choice set to consist of those alternatives that yield a higher (observed) utility that the opt-out alternative, see equation 4, where V_O denotes the utility of the opt-out alternative. he opt-out alternative means that no travelling is undertaken. This alternative is always available to the decision-maker. In other words: only alternatives are considered for which the benefits of the alternative, minus the sum of its costs (of the activity if any plus the generalized transport costs) are positive. So, if an alternative would be the only alternative available, it still would not be chosen because of the negative utility. For example, a person who wants to go to a restaurant, but the nearest option is 50 km away, and the sum of the costs for dinner and generalize transport costs exceeds the benefits, will not visit a restaurant at all. So, t Secondly, the utility-space needs to be scaled, in order to avoid dividing by zero in equation 3. To do so, we set $V_O \equiv 0$. This normalization, in combination with positively constrained choice set, ensures a well-behaved measure for substitutability.

$$C_n = \{c_j \mid V_j \geq V_O\}$$	(4)

Finally, it is important to note that the measure for substitutability is a disaggregate measure, in the sense that it is defined at the level of the decision-maker. However, it is worthwhile to mention that the measure itself can easily be aggregated to reflect the substitutability at a more aggregate level. After all, policy analysts typically are not so much interested in the effect of a policy measure on one particular traveler, but rather like to assess the aggregated effects. Equation 3 can be aggregated to reflect the substitutability of a certain group of travelers that commute between a given Origen Destination (OD) pair.

Illustrations of the proposed measure of substitutability

To illustrate our measure of substitutability, Table 1 shows 4 stylized example situations. In each situation, we suppose that a traveler would like to go shopping. Furthermore, in all situations we assume that the traveler: experiences a positive utility from the shopping activity: ASC_{shop} = 5 utility points (independent of the location and characteristics of the shopping center); has a marginal utility of travel time of -0.2 and a marginal utility of travel cost of -0.5.

In **situation 1**, there are two shopping centers. One shopping center is located nearby and has 3 minutes of travel time, the other center is located at a bit further up and has 15 minutes travel time. The degree of substitutability can be derived by computing the probabilities and logsums. The degree of substitutability in this situation is S = 0.51. This is in line with intuition, in the sense that if either of the shopping centers is no longer available the traveler can still conduct his shopping activity.

In **situation 2** a new shopping center is opened close by. This new shopping center is a good substitute for shopping center 1. It has the same travel time and travel cost. In line with expectations, we see that the degree of substitutability increases substantially to a value of S = 0.87 due to the addition of an attractively located shopping center.

In **situation 3**, 6 more shopping centers are opened. All six are good substitutes for shopping centers 1 and 3. In this situation the substitutability is very high: whichever shopping center closes down or is no longer available, a good substitute is at hand. The computed degree of substitutability is in line with this intuition. It approaches is limiting value of 1.

Finally, **situation 4** illustrates the situation in which there are 10 shopping centers within reach. All shopping centers are good substitutes for one another. In line with expectations, we see that the degree of substitutability is high: S = 0.91. However, all shopping centers are reasonably far away. Therefore, to get there requires substantial efforts from the traveler (in terms of cost and time). Therefore, despite the fact that 10 shopping centers are available, the accessibility in this situation is low as compared to situation 1 to

3 (this is also indicated by the relatively low LogSum of 2.86). Hence, this situation clearly demonstrates the fundamental difference between the notion of accessibility and the notion of substitutability.

Table 1 : Four stylized situations and to illustrate substitutability

Situation 1: baseline

	Travel Time [min]	Travel Cost
Opt-out	0	€0
Centre 1	3	€0
Centre 2	15	€0

Observed utilities: $V_i = ASC + \beta_{time} TT_i + \beta_{\cos t} TC_i$

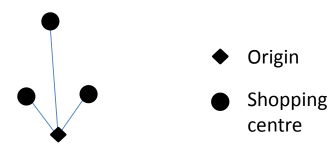
$V_O = 0$

$V_1 = 5 - 0.2 \cdot 3 = 4.4$

$V_2 = 5 - 0.2 \cdot 15 = 2$

Choice probabilities: $P_i = \dfrac{\exp(V_i)}{\sum_J \exp(V_j)}$

Situation 2: new shopping centre close by



	Travel Time [min]	Travel Cost
Opt-out	0	€0
Centre 1	3	€0
Centre 2	15	€0
Centre 3	3	€0

Observed utilities: $V_i = ASC + \beta_{time} TT_i + \beta_{\cos t} TC_i$

$V_O = 0$

$V_1 = 5 - 0.2 \cdot 3 = 4.4$

$V_2 = 5 - 0.2 \cdot 15 = 2$

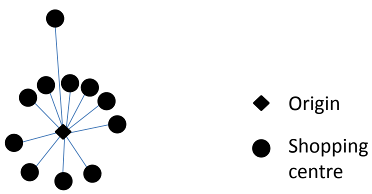
$V_3 = 5 - 0.2 \cdot 3 = 4.4$

Choice probabilities: $P_i = \dfrac{\exp(V_i)}{\sum_J \exp(V_j)}$

$P_O = 0.01$ $P_1 = 0.91$ $P_2 = 0.08$	$P_O = 0.01$ $P_1 = 0.48$ $P_2 = 0.04$ $P_3 = 0.48$
LogSum: $LS = \log \sum_J \exp(V_j)$ $LS = 4.5$	**LogSum:** $LS = \log \sum_J \exp(V_j)$ $LS = 5.14$
Foregone LogSums: $LS^{Y=i} = \log\left(\sum_{j \neq i} \exp(V_j)\right)$ $LS^{Y=1} = \log(\exp(V_O) + \exp(V_2)) = 2.13$ $LS^{Y=2} = \log(\exp(V_O) + \exp(V_1)) = 4.41$	**Foregone LogSums:** $LS^{Y=i} = \log\left(\sum_{j \neq i} \exp(V_j)\right)$ $LS^{Y=1} = \log(\exp(V_O) + \exp(V_2) + \exp(V_3)) = 4.50$ $LS^{Y=2} = \log(\exp(V_O) + \exp(V_1) + \exp(V_3)) = 5.10$ $LS^{Y=3} = \log(\exp(V_O) + \exp(V_1) + \exp(V_2)) = 4.50$
Substitutability: $S = \frac{\sum_i P(Y=i) LS^{Y=i}}{LS}$ $S = \frac{P(Y=1) LS^{Y=1} + P(Y=2) LS^{Y=2}}{LS}$ $= 0.51$	**Substitutability:** $S = \frac{\sum_i P(Y=i) LS^{Y=i}}{LS}$ $S = \frac{P(Y=1) LS^{Y=1} + P(Y=2) LS^{Y=2} + P(Y=3) LS^{Y=3}}{LS}$ $= 0.87$

Table 1 : Four stylized situations and to illustrate substitutability (continued)

Situation 3: many new shopping centres close by	Situation 4: Many shopping centres at distance



	Travel Time [min]	Travel Cost
Opt-out	0	€0
Centre 1	3	€0
Centre 2	15	€0
Centre 3	3	€0
…	…	…
Centre 10	3	€0

Observed utilities: $V_i = ASC + \beta_{time} TT_i + \beta_{\cos t} TC_i$

$V_O = 0$

$V_1 = 5 - 0.2 \cdot 3 = 4.4$

$V_2 = 5 - 0.2 \cdot 15 = 2$

$V_{3..10} = 5 - 0.2 \cdot 3 = 4.4$

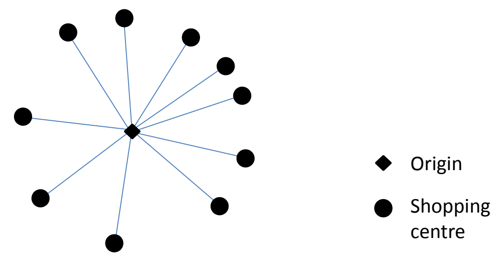
Choice probabilities: $P_i = \frac{\exp(V_i)}{\sum_J \exp(V_j)}$

$P_O = 0.00$

$P_1 = 0.11$

$P_2 = 0.01$

$P_{3..10} = 0.11$



	Travel Time [min]	Travel Cost
Opt-out	0	€0
Centre 1	15	€3
Centre 2	15	€3
Centre 3	15	€3
…	…	…
Centre 10	15	€3

Observed utilities: $V_i = ASC + \beta_{time} TT_i + \beta_{\cos t} TC_i$

$V_O = 0$

$V_1 = 5 - 0.2 \cdot 3 = 4.4$

$V_2 = 5 - 0.2 \cdot 15 = 2$

$V_3 = 5 - 0.2 \cdot 3 = 4.4$

Choice probabilities: $P_i = \frac{\exp(V_i)}{\sum_J \exp(V_j)}$

$P_O = 0.06$

$P_{1..10} = 0.09$

LogSum: $LS = \log \sum_J \exp\left(V_j\right)$ $LS = 6.61$	**LogSum:** $LS = \log \sum_J \exp\left(V_j\right)$ $LS = 2.86$
Foregone LogSums: $LS^{Y=i} = \log\left(\sum_{j \neq i} \exp\left(V_j\right)\right)$ $LS^{Y=1} = \log\left(\exp\left(V_O\right) + \exp\left(V_2\right) + \ldots + \exp\left(V_{10}\right)\right) = 6.49$ $LS^{Y=2} = \log\left(\exp\left(V_O\right) + \exp\left(V_1\right) + \exp\left(V_3\right) + \ldots + \exp\left(V_{10}\right)\right) = 6.60$ $LS^{Y=3..10} = 6.49$	**Foregone LogSums:** $LS^{Y=i} = \log\left(\sum_{j \neq i} \exp\left(V_j\right)\right)$ $LS^{Y=i} = 2.76 \forall i$
Substitutability: $S = \frac{\sum_i P\left(Y = i\right) LS^{Y=i}}{LS}$ $S = 0.98$	**Substitutability:** $S = \frac{\sum_i P\left(Y = i\right) LS^{Y=i}}{LS}$ $S = 0.91$

The mathematical approach we propose has the elegance that it is builds on established notions from the field of accessibility. Moreover, because the measure is normalized between zero and one, it is relatively easy to interpret. Specifically, if one would multiply S by 100 it can be seen as an index, where 100 expresses full substitutability: it is not any problem if the 'best' alternative would not be available, and 0 means there is no alternative available that the decision maker would use if the best alternative would not be available. However, it needs to be acknowledged that the proposed measure for substitutability does not explicitly deal with overlap, social choices, the awareness of the decision maker, and return trip implications.

Finally, it is important to realize this formulation is definitely not the only one possible. Perhaps other formulations can be conceived that are more appropriate e.g. incorporate more aspects that are of relevance for the broader notion of substitutability, or work better for certain purposes. The formulation that we propose is embedded in behavioral models of choice, but despite is clear outcome between zero and one, it is relatively complex as it builds on the LogSum. This, in turn, may hamper its use in the policy arena in the same way as the LogSum is still rarely used for transport policy appraisal; see e.g. De Jong et al, 2007. Perhaps, less complicated measure of substitutability may be proposed. We consider this an interesting avenue for further research.

6. Research agenda

We suggest next options for future research and development of methodologies in the area of substitutability.

- A methodology to disentangle the contribution of different components of the transport and land use system

Different components of the transport and land use system contribute to the level of substitutability. A methodology could be developed to disentangle the contribution of each component, comparable to the methodology as presented by Geurs and Ritsema van Eck (2003) to disentangle the concept of accessibility.

- Empirical research into perceptions

We recommend empirical research on the perception of substitutability for different groups of people, different trip purposes and different travel options. Groups of people can be distinguished based on car ownership and availability, maybe on the ownership and availability of other modes of transport (e.g. the bicycle), income groups, lifestyles, and types of residential areas. An important element in this research relates to the awareness set: of which options are which (groups) of people aware, under which conditions, and when? And how does the awareness set relate to the set of measured options, considering the characteristics of the land use and transport system? This research can also focus on perceptions of substitutability related to activities and activity programs. In case of both trips and activities / activity programs, research can provide th basis for parameter settings (see section 5), and maybe also for other mathematical formulations of the concept of substitutability.

- The role of constraints

Next we think including the role of constraints as included in time geography (Hägerstrand, 1970; Neutens et al., 2008, Farber et al., 2013) is a challenging topic for further research. How important are constraints for the selection of the consideration set? The constraint of not having a car available (as addressed above) is only one type of constraint. Other examples include the authority constraints (e.g. opening hours of shops, kindergarten) and coupling constraints (such as joint dinners, work related meetings). Some constraints probably are not 100% strict, such as he exact time of a dinner in a restaurant.

- The role of ICT

ICT can influence travel choices in several respects, including route choice (satellite navigation, Dynamic Route Information Panels), mode choice (providing travel information), or a preference for a longer train trip without having to switch trains so that the traveler can continue working on a laptop.

- Interactions between dimensions

Because the level of substitutability depends on different factors, these factors can potentially interact. E.g. a low level of substitutability due to the spatial distribution of opportunities can probably be partly compensated by changes in the transport system of ICT based accessibility.

- Implications for modelling

As already mentioned above we suggest the development of a full set of equations (compare Liao and van Wee, in press – robustness).

- Theoretical underpinnings

Above we assumed a utility based mathematical approach. Alternatives may be Random Regret Minimization and Prospect Theory based underpinnings. It is important do discuss the usefulness of different theoretical underpinnings for different contexts and substitutability studies.

- Implications for evaluation frameworks.

The major question is: how to evaluate the importance of different levels of substitutability in the eye of the decision maker? A first step can be answering the question how useful the utility and welfare based evaluation is, as suggested in the calculation of the levels of substitutability above? This can be done by discussing with decision makers which information they think is useful, and how it should be presented to them.

- Pros and cons of evaluation frameworks

In addition to the previous suggestion, Case studies exploring the pros and cons of different choices to be made methodologically, with respect to the choice of data, presenting the results, and using the concept in broader evaluation frameworks, such as Cost-Benefit Analyses (CBA) and Multi-Criteria Analyses (MCA).

- Policy implications.

Finally we recommend exploring the possible policy implications of explicitly including substitutability in policies, land-use planning, the transport system, ICT related policies, and policies related to opening hours being dominant policy areas.

7. Concluding remarks

Above we considered substitutability from the level of the origin of trips, the residential location of a decision maker being the most important origin. But as explained above, accessibility, and therefore also substitutability can also be considered from the perspective of the location to which people travel. E.g. a dentist needs a certain number of clients. Depending on the location higher or lower levels of substitutability of clients can occur.

So far we only discussed substitutability from a passenger activities and transport perspective. We argue the concept can also be applied to goods transport. E.g. a company producing wooden tables needs to buy wood, and multiple options companies selling wood can exist. The quality, prices and variety of the wood can vary, as well as the generalized transport cost of transporting the wood to the table producing company.

So far we only discussed substitutability in the context of travel behavior and activities, but it is probably also a useful concept in other areas, such as the substitution of products and services, software, contacts, …

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