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Social networks, social influence and activity-travel behaviour: a review of models and empirical evidence

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ABSTRACT
The study of social networks in activity-travel research has recently gained momentum because social activities and social influence were relatively poorly explained in activity-based models of travel demand. Over the last decade, many scholars have shown interest in identifying personal social networks that constitute an important source of explanation of activity-travel behaviour. This paper seeks to review two research streams: social networks and activity-travel behaviour, and social influence and travel decisions. We classify models, summarise empirical findings and discuss important issues that require further research.

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1. Introduction

People are members of social networks and therefore interact with other members of their network. To the extent interaction involves the need for face-to-face contact, it induces travel (Axhausen, 2008; Schlich, Schőnfelder, Hanson, & Axhausen, 2004). Consequently, social network characteristics, such as the number of social network members and the composition and spatial distribution of the network are "a source of explanation of social activity-travel generation" (Carrasco & Miller, 2009). Social networks are not only a source of explanation of the frequency and nature of social activities and corresponding travel behaviour, but also a source of explanation of other activity-travel decisions, including information exchange, social influence and attitude formation.

Transportation research was relatively late acknowledging the potential relevance of social networks. It was not after Axhausen's (2004a, 2004b, 2005a, 2005b, 2007) seminal publications that the topic started to receive some attention. Originally, much of this work was confined to the groups in Zurich, Toronto and Eindhoven due to the availability of social network data. The Zurich Group first administered a small study asking about current and past social networks (Ohnmacht & Axhausen, 2005), then organised a larger survey for Frei's work, and more recently administered a smaller survey with Larsen and Urry in NW England (Larsen, Urry & Axhausen, 2006) and a survey in Singapore (Tan,

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Chua, & Axhausen, 2015). The Toronto Group (Carrasco, Miller) based their work on social network data collected by Wellman. Carrasco later collected multi-wave data in Concepcion, Chile. As for the Eindhoven Group, first van den Berg, Arentze & Timmermans collected ego-social network data in the Eindhoven region (a second wave was collected last year). Next, as part of the U4IA project, Sharmeen, Arentze & Timmermans collected data on dynamics in social networks. Most recently, Rasouli & Timmermans collected data on clique-based networks, intended for dynamic simulation of social acceptance and the new version of Albatross. Other groups joined these efforts, turning social network analysis and travel into a mature area of research.

Because the number of studies on this topic has become substantial, it may be timely to review this literature. The aim of this article therefore is to review studies in transportation addressing the relationship between social networks and social activity-travel behaviour, and between social influence and activity-travel decisions. The following two sections present the state-of-the art in these two streams of research, focusing on modelling approaches and empirical evidence. The last section discusses future research directions and concludes the paper.

2. Social networks and social activity-travel: ego-centric analysis

Most analytical work on social networks and social interaction focused on the various facets of social activity-travel patterns. That is, many studies have analysed social activity generation (participation and frequency), destination, timing and duration, the transport mode (mode of communication) involved and the travel party. Properties of personal networks are employed as factors affecting social activity-travel behaviour. These studies therefore required the identification of personal networks and their characteristics. Ego-centric networks have generally been employed. Such networks consist of the focal actor (ego) and a set of alters. We start with an overview of the ego-centric approach and discuss the relevant studies.

2.1. Ego-centric approach

2.1.1. Identifying ego-centric networks

From the respondent's perspective, an ego-centric network can be viewed as "my network". The task of identifying the set of alters generally involves a protocol to elicit manageable lists of alters from all social network members of a respondent. Usually the list is generated by asking respondents to list names of their social network members based on name generators that consist of one or a series of questions. Four approaches can be identified in designing the name generators: the interaction, the role relation, the affective and the exchange approaches (Van der Poel, 1993). The interaction approach asks respondents to list all contacts they had during a certain period of time. The role relation approach elicits alters by different types of relationship such as friend and neighbour. The affective approach asks respondents to name the persons with whom they feel "close". The exchange approach assumes that "people who are sources of rewarding interactions will be particularly important in shaping respondents' attitudes and behavior" (McCallister & Fischer, 1978). An example of a name generator for this approach is "people with whom you discuss important matters" (Burt, 1984). When identifying a

network, in addition to deciding which approach to use, researchers need to decide whether the number of alters is limited and if so on the maximum number that is elicited. Usually, this number is limited to reduce respondent burden.

In the study of social activity-travel behaviour, these approaches are often combined in designing the name generators. Examples of those name generators are "very-close people: people with whom you discuss important matters, or who you regularly keep in touch with, or who are there for you if you need help". and "somewhat-close people: people who are more than just casual acquaintances, but not very close" (Carrasco, Hogan, Wellman, & Miller, 2008b). In addition, the questions can be developed to elicit specific alters associated with social activities, such as "people with whom the respondents spend leisure time" (Frei & Axhausen, 2007), and "people with whom you make plans to spend free time" (Kowald & Axhausen, 2012).

While these approaches may be generally acceptable for social network analysis, they should be carefully applied in the study of social activity-travel behaviour. First, there is an inherent selection bias in that the name generators are inclined to identify specific parts of personal networks. Because the name generators tend to identify non-random samples of social networks, the average characteristics of travel with the elicited alters may result in biased estimates for the entire network. Second, it is problematic to arbitrarily fix the maximum size of the social network because it will not only introduce bias in the estimate of the network size, but it also ignores differences in network size across individuals and the known impact of network size on the amount and nature of travel.

2.1.2. Attributes of ego-centric data

In order to identify the nature of the ties, respondents are asked to give information about the characteristics of each alter and each ego–alter relationship. The attributes collected via an ego-centric approach can be classified into ego level, ego-network level and ego–alter level.

Ego-level attributes include the ego's socio-demographics and residential characteristics. Mobility characteristics such as car ownership, seasonal ticket for public transport and commuting time, are also included.

Ego-network-level attributes represent aggregate features of personal networks such as the number of alters (i.e. network size), proportions of alters by type of relationship (i.e. network composition) and the total number of social interactions for a particular period. Homophily can be considered as an aggregate feature, indicating the proportion of alters with the same socio-demographic characteristics as the ego.

Ego–alter-level attributes indicate the interpersonal characteristics between ego and each of the alters, such as tie strength, geographical distance, duration of relationship and contract frequencies. The differences in socio-demographic characteristics between ego and alter are often employed as explanatory variables to describe their interpersonal characteristics. In addition, the information about specific activity-travel episodes with alters are considered as ego–alter-level attributes.

2.2. Properties of social networks

In this section, we discuss models and empirical evidence of the relationship between attributes of ego-centric social networks and particular facets of social travel. We start

Table 1. Models of social network properties based on ego-centric approaches in travel behaviour research.

Research domain	Reference	Identified network (applied in model)[a]	Type of model	Attributes and model specification[b]		
				Ego-level attributes	Ego-network-level attributes	Ego–alter-level attributes
Network size	Frei and Axhausen (2007)	1. Very close 2. Spend leisure time	Negative binominal regression	[E] Socio-economics [E] Mobility characteristics	[D] Network size	(Nothing)
	Van den Berg et al. (2009)	1. Very close 2. Somewhat close	Linear regression	[E] Socio-economics [E] Mobility characteristics [E] Residential characteristics	[E] Number of clubs/unions [D] Network size	(Nothing)
Geographical distribution of residential location	Frei and Axhausen (2007)	1. Very close 2. Spend leisure time	Tobit; Probit	[E] Socio-economics [E] Mobility characteristics	[E] Network size [D] Size of geographical distribution of alters	(Nothing)
	Carrasco et al. (2008)	1. Very close 2. Somewhat close	Multilevel	[E] Socio-economics	[E] Network composition (proportion) [E] Network subgrouping	[E] Types of relationship [E] Alter's socio-economics [E] Alter's degree centrality [E] Tie strength [D] Geographical distance
	Van den Berg et al. (2009)	1. Very close 2. Somewhat close	Linear regression	[E] Socio-economics [E] Mobility characteristics [E] Residential characteristics	[E] Network size [E] Number of clubs/unions	[E] Types of relationship [D] Geographical distance
	Kowald et al. (2013)	Various (different data sets from five cities)	Multilevel	[E] Socio-economics [E] Mobility characteristics	[E] Network composition (proportion)	[E] Types of relationship [E] Similarity of socio-economics [E] Tie strength [E] Duration of relationship [D] Geographical distance

Note: [a]"Very close" indicates "people who you discuss important matters with, or who you regularly keep in touch with, or who are there for you if you need help."; "Somewhat close" indicates "people who are more than just casual acquaintances, but not very close."
[b][E]: Explanatory variable; [D]: Dependent variable.

with a discussion of studies investigating properties of ego-centric networks in terms of network size, and geographical distribution. Table 1 presents an overview of models of social network properties and the attributes selected in each study.

2.2.1. Network size

Frei and Axhausen (2007) and Van den Berg, Arentze, and Timmermans (2009) investigated the relationships between personal characteristics and social network size by estimating a regression model. The results reveal that elderly tend to have a smaller number of contacts and that the presence of young children seems to create opportunities to establish new social contacts for their parents, such as their peers' parents. On the other hand, people living with a partner seem to feel less need to maintain social contacts. Regarding mobility characteristics, people who have an annual or monthly public transport ticket and/or own a car tend to have a larger network. The result may suggest a positive influence of mobility options on maintaining a larger network. However, the causal relationship may also be reverse in the sense that people with a larger social network may also have more face-to-face social interaction, which in turn might require these mobility options.

2.2.2. Geographical distribution of residential location

Frei and Axhausen (2007) measured the spatial dispersion of a personal network. Rather than using an aggregate measure, Van den Berg et al. (2009) measured the geographical distance between ego and each of the alters, and explored the effects of personal characteristics and type of ego–alter relationship on the distance. The results suggest that the network of higher income egos tends to have larger distances. Regarding the type of ego–alter relationship, relatives are associated with longer distances, while club members are associated with shorter distances.

Carrasco, Miller, and Wellman (2008) provided a little more insight because they were able to consider several ego–alter-level attributes. They employed a multilevel modelling approach in order to consider the unobserved correlation due to the hierarchical structure (or panel structure) of ego-centric data. Because the data contain multiple ego–alter relationships per ego, the ego–alter relationships from the same ego are likely to be dependent on each other. In their approach, it is assumed that the correlation can be captured by ego's socio-demographic characteristics and ego-network-level attributes. Using the multilevel modelling approach, Kowald et al. (2013) compared the geographical distribution of personal networks among five cities in different countries. They concluded that people tend to maintain relationships with their family members regardless of the geographical distance, but the distance patterns associated with strong ties differ across the countries.

2.3. Social activity participation

Studies about social activity participation based on the ego-centric approach assume that the propensity to perform a social activity is a function of personal network characteristics. Table 2 gives an overview of the relevant studies and their model specifications. We classify the existing models according to the nature of the dependent variable.

Table 2. Models of social activity participation based on ego-centric approaches.

				Attributes and model specification[b]		
Research domain	Reference	Identified network (Applied in model)[a]	Type of model	Ego-level attributes	Ego-network-level attributes	Ego–alter-level attributes
Ego frequency of social activity participation	Van den Berg et al. (2010)	1. Interact face to face during 2 days 2. Very close (*Number only*) 3. Somewhat close (*Number only*)	Poisson	[E] Socio-economics [E] Residential characteristics	[E] Network size [E] Number of clubs/unions [E] Day of the week [D] Face-to-face contact frequency per day	(Nothing)
	Van den Berg et al. (2012c)	1. Very close 2. Somewhat close	Structural equation –path analysis	[E] Socio-economics [E] Residential characteristics [E] Mobility characteristics	[ED] Network size [ED] Network composition (proportion) [ED] Number of clubs [ED] Frequency of going to club per month	(Nothing)
	Lin and Wang (2014)	1. Interact face to face and through ICTs in the past week (*Number only*)	Structural equation –path analysis	[E] Socio-economics [ED] Major source of: (1) emotional support, (2) instrumental support, (3) social companionship	[ED] Number of alters contacted in the past week [ED] Proportion of contacts with family in the past week [ED] Number of out-of-home non-work activities with: (1) Family/relatives, (2) Friends/acquaintances, (3) Alone (solo activity), in the past week [ED] Number of travel with: (1) Family/relatives (2) Friends/acquaintances, (3) Alone (solo travel), in the past week	(Nothing)

Ego–alter frequency of social activity participation	Carrasco and Miller (2009)	1. Very close 2. Somewhat close	Multilevel	[E] Socio-economics	[E] Network composition (proportion) [E] Density [E] Network subgrouping [E] Group degree centralisation	[E] Types of relationship [E] Alter's socio-economics [E] Alter's degree centrality [E] Tie strength [E] Geographical distance [E] Contact frequencies per year: (1) phone, (2) instant message [D] Face-to-face contact frequency per year
	Frei and Axhausen (2008)	1. Very close 2. Spend leisure time	Structural equation – Multilevel path analysis	[E] Socio-economics [E] Mobility characteristics	(Nothing)	[E] Types of relationship [E] Geographical distance [E] Duration of relationship [ED] Face-to-face contact frequency per year [ED] Contact frequency by phone per year [ED] Contact frequency by e-mail per year [ED] Contact frequency by SMS per year
	Van den Berg et al. (2009)	1. Very close 2. Somewhat close	Ordinal regression	[E] Socio-economics [E] Mobility characteristics [E] Residential characteristics	[E] Network size [E] Number of clubs/unions	[E] Types of relationship [E] Geographical distance [D1] [E4] Contact frequency by phone per month [D2] [E4] Contact frequency by SMS per month [D3] [E4] Contact frequency by e-mail per month [D4] Face-to-face contact frequency per month

(*Continued*)

Table 2. Continued.

Research domain	Reference	Identified network (Applied in model)[a]	Type of model	Attributes and model specification[b]		
				Ego-level attributes	Ego-network-level attributes	Ego–alter-level attributes
	Van den Berg et al. (2012b)	1. Very close 2. Somewhat close	Structural equation – multilevel path analysis	[E] Socio-economics	(Nothing)	[E] Types of relationship [E] Geographical distance [E] Tie strength [E] Duration of relationship [ED] Face-to-face contact frequency per month [ED] Contact frequency by phone per month [ED] Contact frequency by e-mail per month [ED] Contact frequency by SMS per month
	Sharmeen et al. (2014)	1. Gained or changed due to a life event within the past 2 years 2. Very close 3. Somewhat close	Ordered logit	[E] Socio-economics [E] Residential characteristics [E] Life cycle events	[E] Network size [E] Number of club memberships	[E] Types of relationship [E] Similarity of socio-economics [E] Geographical distance [E] Tie strength [E] Face-to-face contact frequency in the previous time frame [D] Face-to-face contact frequency
	Van den Berg et al. (2015)	1. Interact face to face during 2 days 2. Very close (*Number only*) 3. Somewhat close (*Number only*)	Multilevel	[E] Socio-economics [E] Perceived neighbourhood characteristics [E] Mobility characteristics	[E] Network size	[E] Day of week of the interaction [D] Local social interaction

Propensity of socialising	Carrasco and Miller (2006)	1. Very close and somewhat close (*Number only*) 2. Very close and somewhat close who interact with (i) at least once a week (ii) between once a week and once a month (*Number only*)	Structural equation	[E] Socio-economics	[E] Network size [ED] Propensity to perform: (1) hosting/visiting with strong ties, (2) hosting/visiting with weak ties, (3) bar/restaurants with strong ties, (4) bar/restaurants with weak ties	(Nothing)
	Carrasco et al. (2008a)	1. Very close 2. Somewhat close	Multilevel	[E] Socio-economics	[E] Network size [E] Network composition (proportion) [E] Network subgrouping [E] Group degree centralisation [E] Group betweenness centralisation	[E] Types of relationship [E] Alter's betweenness [E] Similarity of socio-economics [E] Tie strength [E] Geographical distance [D] Degree of socialising

Note: [a]"Very close" indicates "people who you discuss important matters with, or who you regularly keep in touch with, or who are there for you if you need help."; "Somewhat close" indicates "people who are more than just casual acquaintances, but not very close."
[b][E]: Explanatory variable; [D]: Dependent variable; [D#]: Dependent variable of model #; [ED]: Endogenous variable.

2.3.1. Ego frequency of social activity participation

Models of the *frequency of social activity participation* estimate the aggregate number of face-to-face social interactions of an individual within a particular period. Van den Berg, Arentze, and Timmermans (2010) estimated a Poisson regression model and found that people with a large social network tend to generate more face-to-face social interactions. Furthermore, joining clubs or unions tend to induce people to perform more face-to-face social interactions. Van den Berg, Arentze, and Timmermans (2012c) investigated endogenous effects among network size, network composition and the aggregate frequency using a structural equation model. Their results suggest an endogenous effect between network size and social interaction frequency: the larger the number of social network members, the more frequently social activities are conducted and vice versa. In addition, people who are involved in a smaller number of clubs tend to have a larger portion of relatives in their network, and thus they tend to socialise less often with club members. Lin and Wang (2014) investigated endogenous effects between social activity participation and the contact frequencies using a structural equation model. They found that people tend to perform more social activities with those they contact more often those from whom they receive emotional and instrumental support.

2.3.2. Ego–alter frequency of social activity participation

Models of *ego–alter frequency of social activity participation* consider heterogeneity in social interaction frequency according to specific alters. The studies investigate to what extent the characteristics of the alter and the ego–alter relationship influence interaction frequency. In addition, these studies address the role of ICTs in generating face-to-face social interaction; whether it is a substitution or complementary role.

Carrasco and Miller (2009) showed that people tend to have more frequent social activities with friends, males and very close alters. However, longer geographical distance between ego and alter tends to reduce the frequency. In addition, they investigated the effects of contact frequencies by different ICT modes. The contact frequency by phone tends to increase the social activity frequency, but contact by instant messaging has a substitution role with respect to the social activities. E-mail also tends to play a substitution role for distant alters, but it has a complementary role for closer alters. Van den Berg et al. (2009) estimated ordinal regression models and concluded that ICT has a complementary effect to face-to-face interaction, implying a larger contact frequency by ICT induces more frequent face-to-face contact.

Frei and Axhausen (2008) and Van den Berg, Arentze, and Timmermans (2012b) investigated the endogeneity among contact frequencies by different communication modes. Both studies suggest that ICT has a complementary effect on face-to-face interaction. Furthermore, the geographical distance between individuals is significantly and negatively associated with the frequencies of face-to-face, phone, and SMS, but it tends to have a positive or insignificant effect on the frequency of e-mail. In addition, Van den Berg et al. (2012b) found an effect of tie strength, indicating that people tend to more frequently contact alters with whom they hold strong ties through the modes of contact.

Sharmeen, Arentze, and Timmermans (2014) considered the dynamic nature of face-to-face interaction. They found that the face-to-face interaction frequencies are path

dependent, which means that a more frequent contact would continue to be more frequent. Van den Berg, Arentze, and Timmermans (2015) focused on local interaction frequency (within 1 km), and found that more mobile people are less likely to interact with fellow residents compared to social network members at a larger distance.

2.3.3. Propensity of socialising

Models of *the propensity of socialising* concern the potential tendency to perform a social activity rather than explicitly using frequency. Carrasco and Miller (2006) investigated people's propensity to perform specific types of social activity such as hosting or visiting social network members, and gathering at bars or restaurants. They found that network size tends to be positively associated with the propensity of socialising. Carrasco, Hogan, Wellman, and Miller (2008a) measured the degree of socialising between ego and each of alters, representing activeness in initiating contact. The results suggest that people with larger networks are more likely to initiate contact, and that this tendency varies according to with whom they socialise.

2.4. Nature of social activity-travel behaviour

Social travel demand is derived from a need for social activity participation. As personal network is a major source of social activity participation, the characteristics of personal network may be associated with social travel patterns such as destination (activity location), distance travelled, time components (departure time and activity duration) and travel mode. Table 3 provides an overview of some of these studies and their model specifications.

2.4.1. Location type

Van den Berg et al. (2010) analysed the location types where face-to-face interactions are undertaken. There is the tendency that the activity place for face-to-face interaction varies according to not only the purpose of the interaction but also personal network size. For instance, people who have a larger number of very close friends tend to conduct the social activities more at the home of other persons and sport/club locations than other places. Furthermore, Van den Berg, Kemperman, and Timmermans (2014) observed heterogeneity stemming from differences in socio-demographics and neighbourhood characteristics using latent class analysis. For instance, people living in urban areas tend to have social interactions in public outdoor spaces and on the road, while people living in rural areas tend to meet their social network members at restaurants, cafes and sports facilities.

2.4.2. Travel distance

The distance travelled for face-to-face social interaction tends to be associated with personal characteristics, the interaction purpose and the number of alters involved in the interaction. According to Van den Berg et al. (2010), males and younger people tend to be more willing to travel further for the interaction, and that people living with children tend to travel shorter distances. In addition, people tend to travel further for visiting to alters' homes than for other purposes. Moore, Carrasco, and Tudela (2013) found that the distance tends to be longer when the social activity involves a larger number of

Table 3. Models of social activity-travel characteristics based on ego-centric approaches.

Research domain	Reference	Identified network[a]	Type of model	Attributes and model specification[b]		
				Ego-level attributes	Ego-network-level attributes	Ego–alter-level attributes
Location type	Van den Berg et al. (2010)	1. Interact face to face during 2 days 2. Very close (*Number only*) 3. Somewhat close (*Number only*)	Multinomial logistic	[E] Socio-economics [E] Residential characteristics	[E] Network size [E] Number of clubs/unions [E] Face-to- face contact frequency per day	[E] Day of the week [D1] [E2] Interaction purpose [D2] Location type
	Van den Berg et al. (2014)	1. Interact face to face during 2 days	Latent class choice (Ego–Alter)	(Nothing)	(Nothing)	[D] Location type
Travel distance	Van den Berg et al. (2010)	1. Interact face to face during 2 days 2. Very close (*Number only*) 3. Somewhat close (*Number only*)	Tobit	[E] Socio-economics [E] Residential characteristics	[E] Network size [E] Number of clubs/unions [E] Face-to- face contact frequency per day	[E] Day of the week [E] Interaction purpose [E] Location type [D] Distance travelled
	Moore et al. (2013)	1. Very close 2. Somewhat close	Structural equation – Path analysis	[E] Socio-economics [E] Residential characteristics [E] Time pressure	[E] Network size [E] Density of network [E] Homophily of socio-economics [E] Network composition (proportion)	[E] Mean geographical distance between: (1) ego home and alters' homes involved in the activity, (2) the activity place and alters' homes involved in the activity [ED] Geographical distance between ego home and the activity place [ED] Activity duration [ED] Number of alters involved in the activity
	Van den Berg et al. (2013)	1. Interact face to face or through ICTs during 2 days 2. Very close (*Number only*) 3. Somewhat close (*Number only*)	Structural equation – Path analysis	[E] Socio-economics [E] Residential characteristics	[E] Number of active clubs [ED] Network size [ED] Contact frequency by phone for 2 days [ED] Internet interactions frequency for 2 days [ED] Number of trips for social interactions for 2 days [ED] Total social travel distance for 2 days	(Nothing)
Activity duration	Habib et al. (2008)	1. Interact face to face during a week	Integration of logit and accelerated hazard	[E] Socio-economics	[E] Network size [E] Network composition (proportion)[E] Variability of with whom	[E] Number of alters involved in the activity [E] Number of potential locations of the activity [E] Activity duration flexibility [E] Travel time for the activity

						[D1&D2] With whom [D1] Activity duration [D2] Start time of the activity
	Habib and Carrasco (2011)	1. Interact face to face during a week	Integration of logit and accelerated hazard	[E] Socio-economics	[E] Network composition (proportion) [E] Variability of with whom	[E] Number of alters involved in the activity [E] Activity duration flexibility [E] Travel time [D] With whom [D] Activity duration [D] Start time of the activity
	Van den Berg et al. (2012a)	1. Interact face to face during 2 days	Latent class accelerated hazard	(Nothing)	(Nothing)	[E] Types of relationship [E] Geographical distance [E] Tie strength [E] Number of alters involved in the activity [E] Social activity characteristics [D] Social activity duration
	Moore et al. (2013)	(see above "Travel distance")	(see above "Travel distance")	(see above "Travel distance")	(see above "Travel distance")	(see above "Travel distance")
Travel mode	Sharmeen and Timmermans (2014)	1. Gained or changed due to a life event within the past 2 years 2. Very close 3. Somewhat close	Logit	[E] Socio-economics [E] Life cycle events [E] Mobility characteristics (before the event) [D] Travel mode (most often used) for social activity	[E] Network size	(Nothing)
	Rezende et al. (2016)	1. Discuss important matters for the last 3 months	Logit	[E] Socio-economics [E] Residential characteristics [D1] Mode choice of car owner for social event [D2] Mode choice of non-car owner for social event	[E] Density of network [E] Contact frequency [E] Duration of relationships [E] Homophily of socio-economics [E] Heterogeneity of socio-economics	(Nothing)

Note: [a]"Very close" indicates "people who you discuss important matters with, or who you regularly keep in touch with, or who are there for you if you need help."; "Somewhat close" indicates "people who are more than just casual acquaintances, but not very close."
[b][E]: Explanatory variable; [E#]: Explanatory variable of [D#]; [D]: Dependent variable; [D#]: Dependent variable of model #; [ED]: Endogenous variable.

people participating. Van den Berg et al. (2013) investigated the endogenous relationship between the number of trips for social interactions, and the total social travel distance for two consecutive days by an individual. Their results revealed that social travel distance is not only a consequence of the number of trips, but also a consequence of the particular propensity of people to make extra trips for social activities when they are travelling longer distances. Other interesting studies on the influence of distance include Ohnmacht (2009) and Mok, Wellman, and Carrasco (2010).

2.4.3. Activity duration

Social activity duration tends to depend on with whom the activity is conducted, how many alters participate and the distance travelled to the activity location. Habib, Carrasco, and Miller (2008) and Habib and Carrasco (2011) developed integrated discrete choice and continuous models to simultaneously consider the effects of travel party on start time and duration of the activity. Their empirical results suggest that people tend to spend more time on a social activity that involves a larger number of their networks. In addition, when people participate in social activities with household members, they tend to spend less time and start later. Furthermore, longer travel time tends to involve longer activity duration, and earlier start times. Van den Berg, Arentze, and Timmermans (2012a) investigated heterogeneity in social activity duration according to different alters involved in the activity using a latent class accelerated hazard model. The results reveal the heterogeneous effects of gender similarity. Singles with lower socio-economic status tend to spend less time on social activities with a person of the same gender, while couples without children tend to spend longer time with a person of the same gender. Moore et al. (2013) conducted a path analysis to investigate the relationships between distance travelled for social activities, and activity duration. The results indicate that the distance travelled has a positive effect on activity duration.

2.4.4. Travel mode

Sharmeen and Timmermans (2014) investigated which travel mode people use for social travel. They found that male, old or highly educated persons prefer using a private car for social trips, while students are less likely to choose a car for social trips. In addition, they found habitual and inherent preferences of people for a particular mode choice. Even for social trips, people are more likely to use the same mode used for the work commute. Rezende, Sadri, and Ukkusuri (2016) investigated university students' behaviour to carpool for a special event. According to their results, students who have dense networks tend to have more carpool travel. In addition, homophily indexes had significant effects on choosing carpooling. For instance, students who have higher homophily networks in terms of age and income tend to be more likely to travel with their social network members using a car for participating in the special event.

3. Social influence and activity-travel decisions: discrete choice analysis

Another emerging stream of transportation research has focused on social influence as an additional explanatory source in understanding people's activity-travel decisions. Social influence is defined in terms of changes in one's thoughts, emotions, attitudes or

behaviour caused by recommendations, attitudes or behaviour of social network members or peer groups.

Conformity behaviour, as a type of social influence, refers to the phenomenon that individuals tend to mimic the behaviour of others. People may act upon or change their decisions to match attitudes, beliefs and behaviours according to the norms of their social network in order to achieve their goals efficiently, to be accepted by the members of the group, and/or to maintain positive self-concept (Cialdini & Goldstein, 2004). This phenomenon is also known as *endogenous effect* implying that the propensity of an individual to behave in a certain way varies with the behaviour of the reference group (Manski, 1993). The literature has used a myriad of terms such as spill-over effect, peer effect, social multiplier, bandwagon effect, imitation, contagion, herd behaviour and so forth to label this phenomenon.

In this section, we review the studies that have investigated social influence in activity-travel decisions using discrete choice models.

3.1. Discrete choice models of social influence

Brock and Durlauf (2001, 2002, 2007) developed a discrete choice model of social interaction. The model captures *the aggregate effect* of the behaviour of a social group on individual decision-making. The model assumes that an individual receives some additional utility by conforming to his/her group members' behaviour. In this context, the social group can be referred as the *reference group* of an individual making a decision. The additional utility is assumed measured by a *social influence variable* that represents the aggregate behaviour of the reference group.

Brock and Durlauf assumed that social influence is mediated by the subjective beliefs about the behaviours of the group members. By imposing the self-consistency assumption, the subjective beliefs are equalised to rational expectations that can be measured by the objective expectations of each member. According to this assumption, the social influence variable of a particular alternative can be simply defined by the proportion of members in the reference group, who choose the alternative.

Several scholars in transportation research suggested variations of the Brock-Durlauf model. First, because an individual may receive a different amount of influence from different group members depending on their social relationship, there were attempts to reflect interpersonal heterogeneity in social influence. The strength of the relationship between individuals can be referred as *social distance* (Akerlof, 1997). Note that this concept is very similar to the concept of tie strength. Heterogeneous interpersonal relationships were modelled by embedding a weight factor using an autocorrelation linear model (e.g. Leenders, 2002). Páez and Scott (2007) and Páez, Scott, and Volz (2008) suggested considering the weight factor in a discrete choice model of social interactions. However, the weight factor was used only for distinguishing the reference group members of each individual. In contrast, Kim, Rasouli, and Timmermans (2016) dealt with social distance as a random latent variable. They suggested and integrated model framework to simultaneously estimate latent social distance and its impact on social influence.

Maness and Cirillo (2016) were concerned with the indirect effects of social influence that cause taste variation. They hypothesised that a change in taste may occur when people have been informed of preferable features of that behaviour, or observed

their reference group. They employed a latent class approach to differentiate individuals between a "more-informed" class and a "less-informed" class. Instead of including the social influence variable in the utility function, they included the social influence variable in the class membership function. Therefore, the model assumes that the marginal effect of a certain attribute varies according to the behaviours of the reference group.

3.2. Measuring social influence

The results of these studies on social influence highly depend on how the reference group is identified and (aggregate) behaviour is measured. Various approaches have been suggested in the transportation literature.

3.2.1. Proxy variable approach

The estimation of the social influence parameter generally requires data that include identifiable social relationships of each observed individual. However, the typical activity-travel behaviour data does not include explicit social network information. Dugundji and Walker (2005) suggested using a field effect variable that captures aggregate-level interdependence. The social reference group was assumed to have similar socio-demographics with the ego, while the spatial reference group was assumed to be identifiable based on spatial proximity of residential location. Because of the lack of explicit reference group data, they assumed that the aggregate behaviour of one's *true* reference group can be represented by the average behaviour of a particular sub-set of observations whose socio-demographic characteristics and residential location match those of the reference group. The average behaviour of the sub-set was employed as a proxy of the social influence variable. This approach has been widely applied in the transportation literature (see Table 4). However, this approach is based on very strong assumptions about the similarity of the behaviour of the social network and the selected sub-set of observations.

3.2.2. Experimental approach

Several studies tried to investigate social influence using stated choice methods, which have the potential advantage that researchers can control what is manipulated and how to create the necessary and sufficient conditions to estimate particular choice models. For instance, Kuwano, Tsukai, and Matsubara (2012) investigating social conformity in terms of purchasing electric vehicles included market share as an experimental social influence variable that was varied across hypothetical choice situations. Rasouli and Timmermans (2013) independently suggested a similar approach but rather than varying market share, they systematically varied the percentage of different types of social network members (family, friends, colleagues and peers) who have bought an electric car.

3.2.3. Ego-centric network approach

An alternate approach assumes that the personal network of an ego represents the reference group that influences the ego's behaviour. Pike (2014) conducted an ego-centric network survey to investigate travel mode choice behaviour of university students. The

Table 4. Discrete choice models of social influences on activity-travel decisions.

Application domain	Reference	Choice alternatives	Type of choice model	Social influence variable specification: Definition of reference groups	Approach to measure the group behaviour	Measurement of the group behaviour
Travel mode choice	Dugundji and Walker (2005)	(1) Public transit (2) Bicycle/ motorcycle (3) Car driver/ passenger	Mixed-cross nested logit	1. People living in the same residential district 2. People living in the same postcode 3. People having similar socio-economics 4. People in the overlap between groups 1 and 3 5. People in the overlap between groups 2 and 3	Proxy variable	Mode share of each travel mode
	Dugundji and Gulyás (2008)	(1) Public transit (2) Bicycle/ motorcycle (3) Car driver/ passenger	Logit/Nested logit	People living in the same residential district and having similar socio-economics	Proxy variable	Mode share of each travel mode
	Goetzke (2008)	(1) Drive alone (2) Transit	Logit	Neighbours: - including the 40 geographically closest observations of each individual - excluding observations living further away than 1.2 km from each individual	Proxy variable	Percentage of transit-use
	Goetzke and Rave (2011)	(1) Bicycle (2) Other mode	Logit	People living in the same municipality	Proxy variable	Percentage of bicycle use (*corrected for endogeneity*)
	Walker et al. (2011)	(1) Public transit (2) Bicycle/ motorcycle (3) Car driver/ passenger	Logit	1. People living in the same post code 2. People having similar income level	Proxy variable	Mode share of each travel mode (*corrected for endogeneity*)
	Dugundji and Gulyás (2013)	(1) Public transit (2) Bicycle/ motorcycle (3) Car driver/ passenger	Nested logit	1. People living in the same residential district 2. People having similar socio-economics 3. People in the overlap between groups 1 and 2	Proxy variable	Mode share of each travel mode

(*Continued*)

Table 4. Continued.

Application domain	Reference	Choice alternatives	Type of choice model	Social influence variable specification: Definition of reference groups	Approach to measure the group behaviour	Measurement of the group behaviour
				4. People living in the same post code and having similar socio-economics		
	Pike (2014)	(1) Bike (2) Drive (3) Bus	Logit	1. Social network members (max. five persons selected by ego) 2. People living within 1.25 miles	1. Ego-centric 2. Proxy variable	1. Proportion of alters using each travel mode 2. Mode share of each travel mode
	Pike (2015)	(1) Bicycle (2) Other mode	Probit	Social network members (max. five persons selected by ego)	Ego-centric	Proportion of alters using bicycle (*corrected for endogeneity*)
	Pike and Lubell (2016)	(1) Drive (2) Bus (3) Bike	Logit	Social network members (max. five persons selected by ego)	Ego-centric	Proportion of alters using bicycle
Car/bicycle ownership	Goetzke and Weinberger (2012)	(1) Forgoing auto ownership (2) Owning least one automobile	Probit	Households in the same census tract	Proxy variable	Percentage of households with automobile (*corrected for endogeneity*)
	Maness and Cirillo (2016)	(1) Owning a bicycle (2) Not owning a bicycle	Latent class choice	Households in the same metropolitan area	Proxy variable	Percentage of households with bicycle (*Endogeneity was checked, but it was not found to be present.*)
Electric vehicle purchase	Kuwano et al. (2012)	(1) Gasoline (2) Hybrid (3) Electric	Latent class choice	Overall market	Experimental	Market share of electric vehicle sales
	Rasouli and Timmermans (2013); Rasouli and Timmermans (2016); Kim et al. (2014)	(1) Purchase electric vehicles (2) Do-nothing	Logit; mixed logit; hybrid choice	1. Friends 2. Family 3. Colleagues 4. Peers 5. Reviewers	Experimental	1–4. Percentage of members who purchase electric vehicle; 5. Opinion (positive or negative, etc.)
Joining car-sharing	Kim et al. (2016)	(1) Do-nothing (2) Buy a car (3) Join car-sharing	Regret-based hybrid choice	1. Family (three persons selected by ego) 2. Friends (three persons selected by ego) 3. Others (three persons selected by ego)	Combined ego-centric and experimental	Interpersonally weighted average number of alters who join car-sharing

percentage of alters using each mode was used as the measurement of the social influence variable.

3.2.4. Combined ego-centric network and experimental approach

Kim et al. (2016) developed a combined ego-centric and experimental approach in a study on designed social influence in car-sharing decisions. First, they collected information of the personal network of each respondent. Next, a sequential stated adaptation experiment was conducted, which consists of two stated choice experiments. In the first experiment, respondents were asked to choose an alternative from various choice situations. In the second experiment, respondents were asked again to choose an alternative in the same choice situations, but this time showing them their previous choice and hypothetical choices of their actual social network members. The hypothetical choices of alters were experimentally designed and varied across different choice situations. The sequential design thus allows one to experimentally investigate the changes in respondents' decision due to their actual social network members. On the other hand, we can imagine this approach may create choice situations that the ego may find unlikely if the constructed choice of an alter dramatically differs from the egos expectations of the choices of the alter.

3.3. Applications

In this section, we discuss empirical evidence about the impact of social influence on activity-travel decisions. Table 4 shows the relevant studies, listing application domain, choice alternatives, type of choice model and social influence variable specification.

3.3.1. Travel mode choice

Several studies examined social influence on commute mode choice decisions based on the proxy variable approach. Dugundji and Walker (2005) defined five reference groups based on proximity of residential location and similarity of socio-demographic characteristics. Social influences were estimated to be positive and significant, suggesting that one's decision of commute mode tends to be influenced by that behaviour of others who live in the same residential area and/or have similar socio-economic status. Goetzke (2008) also found significant social influence from the spatial reference group on commute mode choice behaviour using the data collected through a household travel diary survey in New York City, U.S. Walker, Ehlers, Banerjee, and Dugundji (2011), re-visiting Dugundji and Walker (2005), corrected for endogeneity in the social influence variables using the BLP (Berry, Levinsohn & Pakes) method, but their results still support the contention that an individual's commute mode choice behaviour is influenced by his/her spatial and socio reference groups.

Goetzke and Rave (2011) investigated social influence in bicycle use for different trip purposes. They found that social influences are heterogeneous across trip purpose. While social influence was not statistically significant in work/school and errands trips, it was in shopping and recreation trips. Pike (2014, 2015) found that university students who have relatively many social contacts who bike tend to be more likely to use bicycle for commuting. Pike and Lubell (2016) found that this positive social influence tends to decrease by increasing commute distance.

3.3.2. Car/bicycle ownership

As for long-term decisions, decision to purchase private mobility options tend to be influenced by reference groups. Goetzke and Weinberger (2012) investigated social influence in household decisions about car ownership. They focused on the spatial reference group influence using the proxy variable approach. Their results reveal a significant tendency that a household decision to own a car is likely to be influenced by other households' car ownership in the same census tract. Maness and Cirillo (2016) studied bicycle ownership of household in U.S. using the National Household Travel Survey data. Their findings suggest the indirect conformity behaviour associated with spatial field effect implying that those who have frequently observed others owning bicycle tend to be more positively inclined to have a bicycle than those who have less frequently observed. Belgiawan, Schmöcker, Abou-Zeid, Walker, and Fujii (2017) quantified the influence of social norms on car ownership intention by estimating ordered hybrid choice models using 1229 university students from three developed and four developing countries. They found significant influence of parents and university peers.

3.3.3. Electric vehicle purchase

Kuwano et al. (2012) applied a stated choice method to investigate social influence in purchasing electric vehicles. The results reveal that the general market share is positively associated with people's intention to purchase electric vehicles. Similarly, Rasouli and Timmermans (2013, 2016) and Kim, Rasouli, and Timmermans (2014) considered heterogeneity in the social conformity effect by different types of relationship such as family, friend, colleague and peers, using a stated choice experiment. The results revealed that the strength of social influence varies across types of relationship: the influence from friend tends to be stronger than from the other categories. Furthermore, the results show nonlinearity in social influence. This may suggest that certain levels of market shares in social networks may stimulate people to conform purchasing electric vehicles or conversely reduce their desire to act as the members of their social network do.

3.3.4. Joining car-sharing organisation

Kim et al. (2016) investigated social influence in the decision to join a car-sharing organisation. Heterogeneity in social influence was captured in terms of social distance. Their estimation results indicated that people tend to be more willing to join a car-sharing organisation when more family members and friends joined a car-sharing organisation, and that social influence increases with deceasing social distance. Furthermore, people tend to be more influenced by those members whom they contact more frequently through ICT and face-to-face. In addition, people tend to pay more attention to behaviours of the young generation of their family and peer groups when deciding to join a car-sharing organisation.

4. Discussion and research directions

Research on the effects of social networks on activity-travel patterns emerged to better understand social travel in its own right and to improve the performance of comprehensive activity-based models of travel demand forecasting in which the prediction of social travel was a weak link. As shown in this review paper, over the last decade numerous empirical

studies have confirmed the contention that the intensity and nature of social activity-travel behaviour is significantly influenced by properties of personal social networks.

In qualifying the rapidly increasing number of empirical studies on various influences on particular facets of social travel behaviour, many of the early studies using relatively simple statistical models may be criticised on their lack of theoretical underpinnings and caveats in their research. We have identified some instances of possibly spurious results. In addition, the use of specific name generators and selection of alters seems to have often resulted in biased results. Thus, as long as we view this early work as descriptive, trying to isolate the correlations in the data set, it has led to accumulated knowledge of key factors correlated with facets of social travel behaviour. However, this work is not sufficient to be included in large scale models of travel demand. Methodologically, it often has not been sufficient to test for spurious results, specification, moderating effects, etc.

Although this stream of research has provided accumulated evidence of the relationship between social networks and travel behaviour, the vast majority of studies has only focused on specific facets, considered ego-centric social networks, addressed social interaction more than social influence and has been cross-sectional in nature. Future research should explore the identification of clique-based and snowball approaches (cf. Silvis, Niemeier, & D'Souza, 2006).

Second, in order to investigate social influence and activity-travel decisions, not only networks but also the behaviour of network members should be identified. Based on an ego-centric approach, we can collect alters' behaviours by asking egos to report it (e.g. Pike, 2014; Pike & Lubell, 2016). However, it may cause measurement errors due to memory bias or lack of enough knowledge. Another limitation of such "ego-reported" approach is that this approach cannot be applied in stated choice studies in that alters' stated preference in a hypothetical choice situation is not known to egos. Instead of the "ego-reported" approach, an experimental approach can be employed in stated choice studies, which hypothetically creates alters' behaviour that is experimentally varied across hypothetical situations (e.g. Kim et al., 2016; Kuwano et al., 2012; Rasouli & Timmermans, 2013). On the other hand, there is the argument of the validity of the hypothetical alters' behaviour in measuring true social influence in activity-travel decisions.

Third, this review paper has also shown that most studies have been concerned with social interaction. Social influence has been studied considerably less, except for some studies that looked at the conformity effect, focusing on behaviour. Thus, a viable line of future research would be how social influence mediates the dynamics in choice set composition and spatial awareness. Information exchange and attitude formation may also influence the acceptance and adaptation of new technology and mobility concepts, such as electric cars, car and ride-sharing services and mobility-as-a-service concerns (e.g. Xiao & Lo, 2016).

Lastly, the integration of the results of studies on social activity travel into comprehensive activity-based travel demand models is still a major challenge that needs to be completed. A few studies have tried to develop relatively comprehensive models by integrating the formation of social networks, their maintenance, dynamics and activity-travel behaviours into a micro-simulation framework (e.g. Arentze & Timmermans, 2008; Ettema, Arentze, & Timmermans, 2011; Hackney & Marchal, 2011; Han, Arentze, Timmermans, Janssens, & Wets, 2011; Okushima, 2015). However, they tend to be conceptual in

nature. When the frontier in activity-based modelling has shifted from cross-sectional to multiple horizon dynamic models (Rasouli & Timmermans, 2014), the recent interest in changes in social networks deserves further investigation.

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