EVOLUTION OF TRIP CHAINING COMPLEXITY IN LONDON FROM 1991 TO 2010

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ABSTRACT

As people's socio-economic activities become more complex and connected, it is conjectured that as one of the behavioral indicators, trip chaining--the propensity to link a series of activities into a multi-stop tour, is likely to become more prevalent and complex over time. Using three waves of large-scale household travel surveys, this paper characterized the trip chaining patterns in London, examined their evolution over the past two decades and identified the socioeconomic variables that contributed to the trend. Overall trip chaining complexity in London increased over time. Work-based tours were most complex and school-based tours simplest, while other tours had the most significant increase of complexity. Interestingly, transit-based tours become more complex in a faster pace than car-based tours. Based on a series of discrete choice modeling, it was found that having larger households, full-time employment, being male, and having access to car decrease the propensity for trip chaining, while having children, higher income, traveling in the AM peak, and having driver licenses increase trip chaining. Comparison across years reveals decreasing access to car, diminishing household size, more people with driver license, increasing household income and senior's more active participation in trip chaining are among the factors contributed to the increasing complexity. The study results provides useful insights into improving transit service to accommodate the increasing need of trip chaining as well as constraining car use through controlling parking.

Key words: Trip chaining; Travel behavior; Mode choice; Discrete choice modeling; London

1. INTRODUCTION

Trip chaining involves the linking of series of activities at multiple destinations into a multi-stop tour or journey. Given the limited time and income constraints faced by an individual, trip chaining potentially saves time and reduces travel costs. In most cases, the overall utility of an individual's trip chain increases with the number of trip links (Adler & Ben-Akiva 1979). At the household level, trip chaining arises when household members gain from arranging activities such that overall travel distances and times are shortened and disutility minimized across all travel activities (Hensher & Reyes 2000).

In most academic research, a trip chain (also known as tour or journey) is conventionally defined as a sequence of trips that starts at home, involves one or more intermediate stops, and ends back at home (Ye, Pendyala & Gottardi 2007). No intermediate home stop is present within the trip chain, which means a chain is formed whenever the home location is reached. The aforementioned definition of a trip chain is adopted in this paper, as almost all journeys commence and end at home. This definition is also consistent with research on activity chains and the underlying assumption that travel is a derived demand (Primerano, Taylor, Pitaksringkarn & Tisato 2008). It should be noted that trip chain and tour are used as interchangeable terms in this paper. Strathman and Dueker further distinguished the complexity of trip chains by classifying them as "simple" or "complex" (Strathman & Dueker 1995). Simple trip chains are home-to-home tours with one intermediate stop while complex trip chains are home-to-home tours with two or more intermediate stops. Hence, a trip chain of the form home-work-home is considered simple whereas a trip chain of the form home-work-shop-home is complex.

Over the past few decades, people's socio-economic activities become more complex and connected thanks to transportation and communication technology among other factors. One interesting question is how is the activity complexity reflected in people's travel patterns? It may be conjectured that trip chaining is likely to become increasingly prevalent and complex over time because the ability to chain multiple activities together in a single chain may provide greater efficiency and convenience than a series of single-stop simple chains. However, the change of trip chaining complexity and its socio-economic drivers are rarely studied, possibly due to the rarity of time-series data on comparable factors.

Using three waves of large-scale household travel surveys, this paper characterizes the trip chaining patterns in London, examines their evolution over the past two decades and identifies the socioeconomic variables that contribute to the trend.

2. LITERATURE REVIEW

A review of previous research has identified numerous influences that impact trip chaining patterns. The majority of these studies have focused on socio-economic factors contributing to the propensity to make stops within a trip chain, such as gender (Strathman & Dueker

1995; Strathman, Dueker & Davis 1994; Schmöcker, Su & Noland 2009; Bhat 1997; Mcguckin & Murakami 1999), age (Schmöcker, Su & Noland 2009; Bhat 1997; Noland & Thomas 2007), personal income (Hensher & Reyes 2000; Adler & Ben-Akiva 1979), household structure and life cycle (Golob 1986; Golob & McNally 1997; Oster 1979; Strathman, Dueker & Davis 1994), presence of children (Hensher & Reyes 2000; Noland & Thomas 2007), household size (Oster 1979; Hensher & Reyes 2000; Strathman & Dueker 1995) and household income (Strathman, Dueker & Davis 1994; Bhat 1997; Noland & Thomas 2007). Other researchers have focused on the effects of technology advancements (Schmöcker, Su & Noland 2009) and trip-specific attributes such as commute distance (Susilo & Kitamura 2008), travel times and costs (Bhat 1997) and day of the trip (Primerano, Taylor, Pitaksringkarn & Tisato 2008).

The impacts of trip chaining have also been discussed in prior literature. Trip chaining was found to significantly affect a commuter's in-vehicle travel time and route choice (Mcguckin, Zmud & Nakamoto 2005). However, its impact extends beyond these individual-specific aspects and can lead to traffic and policy implications at the macro level.

If complex trip chains arose from embedding non-work activities in the work commute, the relative shift of non-work trips to peak commuting periods would cause an increase in peak period travel demand and exacerbate congestion (Ye, Pendyala & Gottardi 2007; Oster 1979). In addition, as cars provided the flexibility to pursue multiple activities within a single journey, complex trip chaining could result in a higher reliance on car usage and hence greater traffic congestion. Complex trip chaining might thus serve as a barrier to public transportation usage as travelers would be constrained by routes, schedules and issues of access and egress (Ye, Pendyala & Gottardi 2007; Hensher & Reyes 2000).

The earlier arguments implied that trip chaining complexity could be a driver of mode choice. However, one could also argue that mode choice has an impact on the number of stops within trip chains. This conjecture was affirmed by Strathman et al. who found that mode choice was a significant factor influencing a household's trip chaining behavior (Strathman, Dueker & Davis 1994). Bhat also described that the lower travel time usually associated with using the car could help to ease time constraints and result in more stop-making (Bhat 1997). Furthermore, the carpooling option, which forms part of the total car mode share, tended to produce more complex trip chains due to the varying trip purposes and destinations of the driver and passengers (Ye, Pendyala & Gottardi 2007).

Ye et al. investigated the interdependency between trip chaining complexity and mode choice and their findings gave credence to the assumption of a significant and positive bidirectional causal relationship between trip chaining complexity and auto mode choice (Ye, Pendyala & Gottardi 2007). In this spirit, our study incorporates trip chaining and mode choice within a combined decision framework and adopts a nested logit approach for model development.

Another goal of this research is to investigate the trends in trip chaining patterns over time within the same metropolitan area. Prior empirical research of such nature mostly adopted descriptive methods in their analyses. McGuckin et al. described trends related to work-related trip chains in the United States and found a 9% increase in chained trips among weekday workers between 1995 and 2001 (Mcguckin, Zmud & Nakamoto 2005). Likewise, Levinson and Kumar discovered a rise in trip chaining activity when household travel survey data from the 1968 and 1987-88 metropolitan Washington, DC, were analyzed (Levinson & Kumar 1995). Using data from Osaka household travel surveys conducted in years 1980, 1990 and 2000, Susilo and Kitamura found the average number of stops per trip chain to have increased between 1980 and 2000 for both auto and transit commuters (Susilo & Kitamura 2008).

3. CHANGE IN TRIP CHAINING COMPLEXITY

One of the key tasks of this study is to examine the change of trip chaining complexity over time. This can be achieved by comparing travel survey data collected from different periods of time. Three waves of large-scale household travel surveys in London: 1991, 2001, and 2006-2010 are used to investigate the changes in trip chaining complexity. In this paper, trip chaining complexity is measured using proportion of complex tours.

3.1 Data Description

This study uses data from the 1991 and 2001 London Area Travel Survey (LATS), and the 2006-2010 London Travel Demand Survey (LTDS), made available by Transport for London. In addition to gathering household and individual socio-economic information, both LATS and LTDS collect trip-diary surveys, in which respondents are invited to fill in a self-completion trip diary for one day during the following week. While LATS was done within a single year, LTDS is implemented throughout years. Since this study aims to investigate the travel behavior changes in a longer period of time (two decades to be specific), the LTDS data collected from 2006 to 2010 is treated as a whole without digging further into the changes within the five-year period. It is also worth noting that the 2001 LATS is only for Monday to Friday, but the 1991 LATS and LTDS cover weekends. To make the data from the three different surveys consistent and comparable, this paper only focuses on the data for weekdays. Because of the large sample sizes for these surveys, all the results presented in the Section 3 are statistically significant.

Table 1 provides a descriptive summary of the socio-economic characteristics for each of the periods. Percentages of households in inner London and households with children younger than five years old exhibit a steady downward trend between 1991 and 2006-2010. The former indicates that London, like many other big cities, is experiencing decentralization, and the latter suggests that less London households choose to have children. Also, as expected, Londoners' household income has increased significantly over the past two decades. Interestingly, the share of households with access to cars also decreases while the share of people with a car driver license increase. It seems more people would like to enjoy the freedom of driving but would not own a car possibly due to economic reasons. Having a car in London is costly, especially after the congestion charging policy was implemented. Also, the opposite changing trajectories of car access and driver license suggest car sharing (or car pooling) is gaining popularity in London. Besides, gender and age group compositions also show a relatively high degree of similarity across the periods.

Table 1 - Socio-economic Characteristics

	London 1991	London 2001	London 2006-2010
Household info			
Total households	49953	29973	27179
Household with size >= 3	39.3%	32.1%	34.1%
Household in inner London	35.0%	34.8%	34.4%
Household with children younger than 5 yr old	13.4%	12.3%	11.7%
Household with access to cars	62.9%	61.6%	61.4%
Household income <£10,000	40.1%	29.8%	24.0%
Household income >£50,000	12.7%	13.9%	20.9%
Individual info			
Total respondents	124843	67252	62252
Male	48.1%	48.1%	48.1%
Youth(5~16 yr old)	21.8%	21.3%	21.6%
Senior(>=60 yr old)	18.8%	18.0%	19.3%
Licensed	49.3%	51.9%	54.5%
Work status(excluding youth)			
Full-time employment	45.9%	46.4%	46.5%
Part-time employment	8.6%	9.8%	9.5%
Student	5.9%	7.6%	8.4%
Retired	20.0%	19.5%	19.5%

The trip characteristics for each period are summarized in Table 2. Trip rate (the average number of unlinked trips undertaken per person per day) rises from 2.41 in 1991 to 2.62 in 2001, and later drops to 2.54 in 2006-2010. Further investigation reveals that a substantial drop of trip rate in around 2008-2009. It is likely that the latest economic recession plays a very important role in the decrease of trip rate in the past decade. Average trip distance constantly decreased for the whole study period. But it is worth notice this does not necessarily mean people's travel range decreased because no significant change is found on average distance between activity location and home. One possible explanation could be that trip chaining enables people to reach a series of locations in a single tour, which if arranged properly could save much travel distance compared to going to each location from home separately. Despite the shrinking trip distance, the average trip duration is in an increasing trend, which indicates the average travel speed in London has dropped significantly, presumably due to increasing traffic congestion. Traffic congestion may impose a higher constraint on travel time and thus people may be more likely to link a series of trips together to save time. On the other hand, since time is finite, people generally have a budget for time spent on traveling per day. Worsening traffic congestion may cause more people to reach their budgets and thus they have to cut down their travel demand, which could help explain the decreasing trip rate.

An analysis of the distribution of trip purpose suggests that the activities of London residents have become increasingly diverse. From 1991 to 2010, an increasing proportion of trips are carried out for purposes unrelated to work, particularly in shopping and services. Among reasons are economic development that brings in more shopping and service opportunities and rising income level that makes these activities more affordable. In terms of mode share, it is found that car share decreased significantly from 48.9% in 1991 to 40.3% in 2006-2010, while bus and rail (including London Underground and National Rail services) gained more popularity. Probably, this is attributed to expanded transit infrastructure and improved transit services, as well as severe traffic congestion in London. There is a large jump for walking between 1991 and 2001. This may be caused by inconsistent definition of a trip by walk. To avoid such ambiguity, most the analysis presented later in the paper only focuses on car, bus and rail.

Table 2 - Trip Characteristics

	London 1991	London 2001	London 2006-2010
Trip Information			
Total trips	301378	176447	158326
Trip rate	2.41	2.62	2.54
Average trip distance	6.43km	6.33km	6.10km
Average trip duration	26.65min	26.93min	27.77min
Average trip speed	14.48km/h	14.10km/h	13.18km/h
Distribution by purpose			
Work	18.9%	17.0%	16.4%
Education	6.4%	5.9%	5.9%
Shopping/service	12.2%	16.8%	16.9%
Leisure	11.9%	12.1%	12.1%
Home	42.0%	40.6%	40.8%
Distribution by mode			
Car	48.9%	44.6%	40.3%
Bus	10.8%	10.9%	13.4%
Rail	9.8%	10.9%	12.0%
Walk	23.9%	29.0%	29.3%

3.2 Trip Chaining Complexity

The travel survey data was originally collected at the trip level. It is then aggregated to the tour level based on the definition of trip chain. Table 3 presents a summary of the tour characteristics across the periods. The average number of tours per day by London travelers rises from 0.99 in 1991 to 1.05 in 2001, and then drops to 1.02 in 2006-2010. The change of tour rate agrees with the change of trip rate. Unlike the trend of trip distance, average tour distance peaked at around 2001. As for the travel distance saved by trip chaining per day, it reached the highest point in the second half of the last decade. Probably, it is because higher time constraint push people to chain trips together more efficiently. Time spent on traveling within a tour increased across time while the total tour duration underwent slight reduction. This means a larger proportion of time is spent on traveling while less time on activities. Again, traffic congestion is likely to be one of the reasons.

Possibly for the same reason, a modal shift is also undergoing. In this study, only a single primary mode is assigned for each tour. In instances where multiple modes were used within the same tour, the primary mode was assigned based on the one with the longest travel time. The car mode share includes tours made both as a car driver and a car passenger. It is found that car usage steadily decreases and shares of bus and rail rises over the past two decades, which is similar with the modal shift at the trip level.

Table 3 - Trip Chain Characteristics

	London 1991	London 2001	London 2006-2010
Total number of tours	123853	70425	63373
Tour rate	0.99	1.05	1.02
Average tour distance	13.76km	15.13km	14.45km
Average distance saved per day	1.82km	1.55km	2.06km
Average tour duration (travel)	60.34min	64.18min	65.75min
Average tour duration (total)	327.85min	327.48min	326.58min
Distribution by mode			
Share of auto-based tours	45.9%	43.3%	39.4%
Share of bus-based tours	12.6%	12.6%	15.2%
Share of rail-based tours	10.9%	12.5%	13.4%
Distribution by primary purpose			
Share of work-based tours	34.5%	32.9%	31.8%
Share of school-based tours	14.8%	14.1%	13.9%
Distribution by number of trips			
2	78.7%	74.1%	73.6%
3	12.4%	14.0%	14.6%
4	5.6%	7.8%	7.9%
5 and above	3.3%	4.1%	3.9%
Distribution by complexity			
Share of complex chains	**21.3%**	**25.9%**	**26.4%**

In terms of travel purpose, intuitively, tours are categorized as work-based, school-based and other. A trip chain is classified as work-based if it includes at least one trip with a work-related purpose, and school-based if it involves at least one trip with a school purpose. When a tour includes both a work purpose and a school purpose, the one with longer activity duration (not trip duration) is assigned as the primary purpose. If a tour is neither a work-based tour nor a school-based tour, it belongs to other tours. As is shown in Table 3, both the shares of work-based tours and school-based tours are in a decreasing trend, which agrees with the finding in Section 3.1 that London residents' activities are becoming more diverse.

In this paper, the share of complex chains is used as the indicator of trip chaining complexity. The overall share of complex chains increased over the years, particularly between 1991 and 2001. This is broadly consistent with our conjecture of complex trip chains becoming increasingly prevalent over time, brought about by greater efficiency and convenience arising from linking multiple activities together in a single chain.

Change in trip chaining complexity is then analyzed by purpose and by mode. Overall, work-based tours are most complex, but other tours are catching up quickly. While work-based tours reached its higher share of complex chains in 2001, the complexity of other tours is still increasing. School-based tours are similar with work-based tours in that they are more fixed and routine than other tours. However, it is found that the complexity of school-based tours is significantly lower than that of work-based tours. Although it is in a slightly upward trend, the pace is much slower than that of other tours. Thus it appears the three types of tours display different changing patterns.

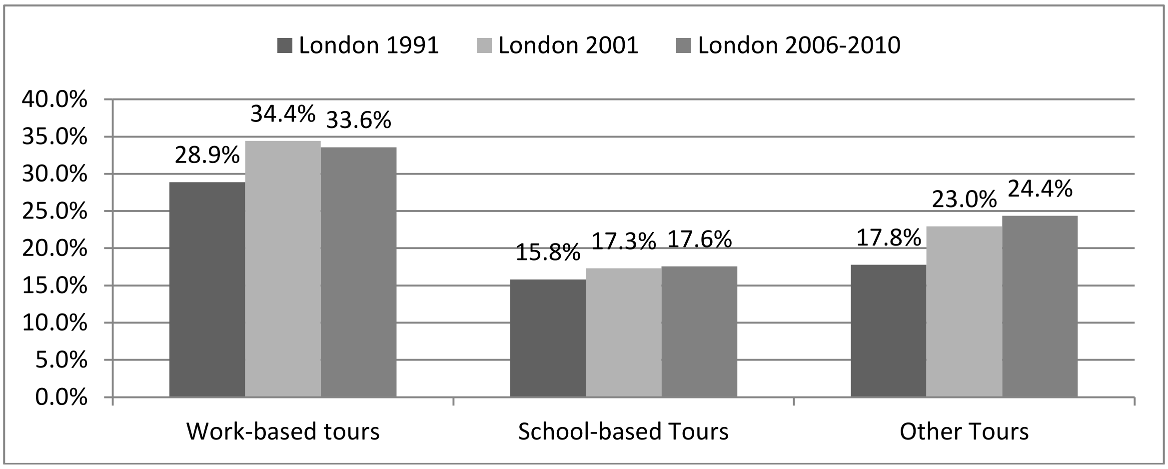

Figure 1 - Share of complex chain by purpose

Similarly, change in trip chaining complexity is broken down by mode and the results are shown in Figure 2. The increases in trip chaining complexity for bus and rail are much more significant than the increase for car. In 1991, car-based tours and rail-based tours have similar trip chaining complexity, with bus-based tours being simpler, while in 2006-2010, the complexity of bus-based tours has caught up with the complexity of car-based tours, and rail-based tours are most complex. It is commonly thought that car-based tours are more complex, but this is not the case in London, possibly due to the high level of service of London transit system and high cost for car use. Bus and rail share a similar trend in terms of trip chaining complexity, but in different level.

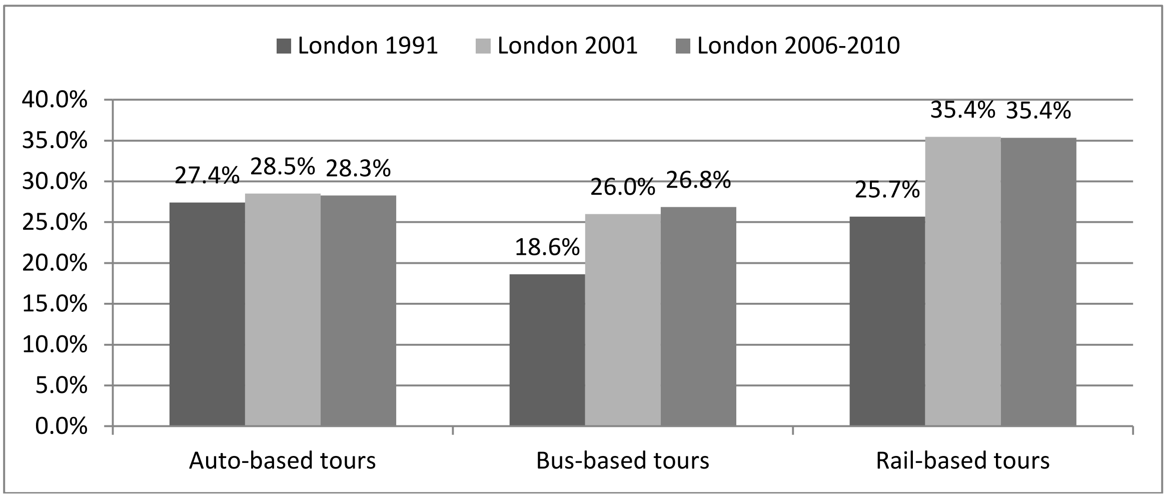

Figure 2 - Share of complex chain by mode

4. DRIVERS OF INCREASING TRIP CHAINING COMPLEXITY

Knowing that trip chaining has become increasingly complex in London, a further question to ask is what the causal factors are. This could be answered through discrete choice modeling.

4.1 Choice of Models

Data is sampled to model trip chaining. As mentioned before, weekend data is removed to make the three sets of survey data more comparable. Only car, bus and rail are studied in this paper, and tours based on other modes are excluded. To avoid excessive sampling, only one tour was randomly selected for a person from each surveyed household in all three periods. The final sample was subsequently obtained by randomly selecting 12,000 cases for each time period (1991, 2001 and 2006-2010).

Given the focus of the paper on comparison across time, only variables available in all three surveys can be selected as independent variables, most of which are socio-economic variables. In addition, no alternative-specific variables are included in the model specification, which is a limitation of this study. This is due to the inherent difficulty in obtaining data that vary across both individuals and alternatives. In this study, all independent variables are designed as dummy variables. A list of them is as follows:

- ***Household size*** is reflected using one dummy variable. It is 1 if household size is no less than 3, 0 otherwise.
- ***Presence of children*** is reflected with one dummy variable. It is 1 if household has at least a child under 5 years old, 0 otherwise.
- ***Household income*** is represented with two dummy variables. Annual household income above £50,000 is categorized as high income while income lower than £10,000 as low income. Since the data was collected across years, income is adjusted to 2001 value based on consumer price index.

- ***Access to car*** is also represented with one dummy variable. It is 1 if household has access to car, 0 otherwise.
- ***Gender***, another dummy variable, is 1 if person is male, 0 otherwise.
- ***Age*** is represented with two dummy variables. Youth, is 1 if person is under 16 years old (but above 5 years old), 0 otherwise. Senior, is 1 if person is older than 60 years old, 0 otherwise.
- ***Working status***, is represented with three dummy variables – full-time employment, part-time employment, and student.
- ***Possession of a driver license***, is 1 if person has a car driver license, 0 otherwise.
- ***Starting time of tour***, is 1 if tour starts at am peak, 0 otherwise.
- ***Household location*** is reflected in the model using 33 dummy variables (representing the 32 boroughs and City of London). These variables are treated as fixed-effect variables. They are used to reflect land use (and maybe policy) differences spatially, but will not be examined deeply in this paper.

As for the dependent variable, this paper treats trip chaining as a binary choice – complex or simple. This categorization of trip chaining complexity is the most basic approach. Again, since the focus of the paper lies in understanding the temporal changes of trip chaining and its causal factors, such simplification could make it easier for comparisons of model estimations across years.

The paper first present an overall model including all independent variables listed above, showing the general impacts of different socio-economic variables on trip chaining complexity. Then trip chaining complexity is modeled separately for three purposes – work, school and other. This is to explore whether the impacts of socio-economic factors are different among different primary purposes. The relationship between trip chaining and mode choice has not been fully understood. Instead of assuming a causal relationship between these two decisions, the paper assumes a joint choice process, in which people make decisions on trip chaining and mode simultaneously. The results of the joint choice model are also presented. In other words, the three models to be presented in this paper are summarized as below:

- The simple trip chaining model is estimated using binary logit. This is to examine the overall impacts of the independent variables on trip chaining.
- The trip chaining model by primary purpose is to repeat the simple trip chaining model for each of the three primary purposes. This is to examine possible differences of the impacts of the independent variables among primary travel purposes.
- The joint choice model is estimated using multinomial logit (trip chaining + mode choice) separately for each of the three primary purposes. This is to examine the impacts of the independent variables on the joint choice of trip chaining and mode choice and their variation among primary travel purposes.

Since the paper is interested in the change of trip chaining complexity over time, the models are specified to reflect significant changes in coefficients. It is worth notice that the models are not estimated separately for each period. Instead, the independent variables are modified to get different coefficients of the same factor for different periods. This is done through the following process:

1) Assume the coefficients of all the explanatory factors stay constant across the three periods (1991, 2001, and 2006-2010). Use one coefficient for each explanatory factor to represent their impacts for all periods.
2) For an explanatory factor X_i, consider the possibility that, β_i, the coefficient of X_i may change between over time. Assume the coefficient changed between Period 1 (1991) and Period 2 (2001), change the model specification from base utility function (a) to new utility function (b) to allow two different coefficients for X_i, one representing the impact of X_i in 1991 and the other representing the impact of X_i in 2001 – 2010.
$$U = \cdots + \beta_i \cdot X_i + \cdots \quad \text{(a)}$$
$$U = \cdots + \beta_{i,Period1} \cdot X_{i,Period1} + \beta_{i,Period2\&3} \cdot X_{i,Period2\&3} \cdots \quad \text{(b)}$$
Where
$X_{i,Period1} = (X_i | group = period1)$, which means $X_{i,Period1}$ is a subset of X_i when the observation is collected in Period 1;
$X_{i,Period2\&3} = (X_i | group <> period1)$, which means $X_{i,Period2\&3}$ is a subset of X_i when the observation is collected in Period 2 or 3.
3) Use likelihood ratio test to compare the test whether the new model specification in utility function (b) (with more coefficients for X_i) provides significantly better model goodness of fit than the base model specification (a). If yes, it proves the impact of factor X_i indeed changed significantly between 1991 and 2001, and the new model specification in utility function (b) should be preserved for further analysis. If not, the new model specification does not work well, and the previous model specification in utility function (a) should be preserved for further analysis.
4) Repeat steps 2) to 3) to test the possible change of β_i between Period 2 and Period 3. It is worth notice that the exact forms of utility functions depends on the result of the comparison between Period 1 and Period 2. If β_i significantly changed between Period 1 and Period 2, the base utility function (c) and the new utility function (d) should be
$$U = \cdots + \beta_{i,Period1} \cdot X_{i,Period1} + \beta_{i,Period2\&3} \cdot X_{i,Period2\&3} \cdots \quad \text{(c)}$$
$$U = \cdots + \beta_{i,Period1} \cdot X_{i,Period1} + \beta_{i,Period2} \cdot X_{i,Period2} + \beta_{i,Period3} \cdot X_{i,Period3} \cdots \quad \text{(d)}$$
If the change β_i between Period 1 and Period 2 is insignificant, the base utility function (e) and the new utility function (f) should be
$$U = \cdots + \beta_i \cdot X_i + \cdots \quad \text{(e)}$$
$$U = \cdots + \beta_{i,Period1\&2} \cdot X_{i,Period1\&2} + \beta_{i,Period3} \cdot X_{i,Period3} \cdots \quad \text{(f)}$$
Similarly, likelihood ratio test is carried out to determine whether the new model specification in utility function (d) or (f) provides significantly better model goodness of fit than the base model specification in utility function (c) or (e).
5) Repeat steps 2) to 4) for all explanatory factors.

Hundreds of likelihood ratio tests are carried out to identify the best model combination and structure. The modeling process is carried out using Biogeme, a discrete choice modeling software (Bierlaire 2009).

4.2 Trip Chaining Model Results

Table 4 - Overall Trip Chaining Model Results

Variable	1991	2001	2006-2010
Constant	**-1.22**	**-0.654**	**-0.442**
Household size >=3	**-0.265**	~	~
Presence of children (age<5)	**0.309**	~	~
Household with income > £50,000	**0.247**	~	~
Household with income < £10,000	0.0159	~	~
Person being male	**-0.161**	~	~
Person being senior (age>=60)	**-0.322**	-0.0111	~
Person being youth (5<=age<=16)	-0.0354	~	~
Person being full-time employed	**-0.205**	~	~
Person being part-time employed	-0.0671	~	~
Person being student (age>16)	-0.0995	~	~
Possession of a driver license	**0.161**	~	~
Tour starting in AM peak	**0.302**	~	~
Access to car	**0.162**	**-0.100**	~
Primary purpose being work	**0.328**	~	**0.113**
Primary purpose being school	**-0.198**	~	~
Rho-square		0.139	
Adjusted Rho-square		0.137	
Initial log likelihood		-11362.069	
Final log likelihood		-10379.503	
No. of parameters		56	

The coefficients in bold is significant with p value < 0.05.
"~ " means the coefficient is not significantly different from the coefficient in previous period.
33 household location variables are omitted

The trip chaining model uses trip chaining complexity as the dependent variable (which is binary with simple chain being the base). The estimation results of the model are summarized in Table 4. The coefficients in bold is significant with p value < 0.05. "~" means the coefficient is not significantly different from the coefficient in previous period. A positive coefficient means the variable affect trip chaining complexity positively, and vice versa. For example, a coefficient of 0.162 for "access to car" in 1991 means that the probability of chaining multiple trips together for a person with access to car is EXP(0.162) times the probability for a person with lower than median household income. And this odds ratio changed to EXP(-0.1) in 2001. It should be noted that the coefficients of the 33 household location variables are not shown in the table.

The negative constant implies that complex tours generate a lower level of utility as compared to simple tours, holding all else constant. Individuals in larger households tend to make less complex tours as opposed to individuals in smaller households. One possible conjecture is that the greater scope of task sharing within a multi-person household reduces the need to chain different types of activities. The presence of children is a stimulus for complex trip chaining, presumably due to the need for parents to escort their children. Having an annual household greater than £50,000 contributes to the propensity of making complex trip chains, because people with higher income usually have more obligations and thus higher constraints on time. Consequently, they tend to have higher trip chaining complexity to multi-task and save time. It is also found that women's propensity to form complex chains is significantly greater than men, because women typically bear more household responsibilities. Being youth does not seem to have a significant influence on trip chaining except for other tours. Senior used to have lower trip chaining complexity, but this changed in around 2001. Full-time employment shows a negative influence on trip chaining complexity, but part-time employment and student status show no impact. Tours beginning in the morning rush hours are more prone to being multi-stop trip chains. For work-related tours, it is probably due to the linking of a non-work activity with the work commute in the overall trip chain. For other tours, it may be the case that those who escort others to work or school would usually arrange some other activities to do along the way (e.g. breakfast). The possession of a driver license contributes positively to complex trip chaining patterns. One possible explanation may be that people with driver licenses are usually those with higher travel demand. Also, licensed drivers usually need to pick up and drop off others, and thus are likely to chain trips in a more complex form. Interestingly, the coefficient of access to car dropped from a positive value in 1991 to a negative one after 2001. This means that access to car has changed from stimulating trip chaining to deterring it. Among the possible reasons is increasing congestion level, lacking of parking space, increasing parking fees, implementation of congestion charging, improvement of public transportation. Tours with a primary purpose of work tend to be more complex while tours with a primary purpose of school usually have lower complexity.

4.3 Trip Chaining, Purpose, and Mode

As is shown in Section 3.2, trip chaining complexity is strongly correlated with tour purpose and mode. This section models trip chaining complexity separately for different purposes, assuming the impacts of tour purpose can be better reflected via other independent variables. Traditionally, travel purpose is usually classified into work and non-work, or commute and non-commute. The former classification groups school-based and other tours together, while the latter groups school-based and work based tours. This paper tests these two grouping possibilities, as well as all three separately. Likelihood ratio tests are performed to select the best grouping structure. And in the end it is decided that modeling for work, school and other all separately provide the best goodness-of-fit. The results are shown in Table 5.

Table 5 - Trip Chaining Model Results by Primary Purpose

Tour type	Work-based tours			School-based tours			Other tours		
Variable	1991	2001	2006-2010	1991	2001	2006-2010	1991	2001	2006-2010
Constant	**-0.789**	**-0.412**	~	**-1.38**	-0.0432	~	**-1.21**	**-0.662**	~
Household size >=3	**-0.190**	~	~	-0.115	~	~	**-0.174**	~	~
Presence of children (age<5)	**0.225**	~	~	0.0695	~	~	**0.147**	~	~
Household with income >£50,000	**0.323**	~	~	0.199	~	~	-0.0348	~	~
Household with income <£10,000	-0.0458	~	~	-0.0092	~	~	0.0136	~	~
Person being male	**-0.187**	~	~	-0.125	~	~	**-0.151**	~	~
Person being senior (age>=60)	-0.0710	~	~	0.048	~	~	**-0.372**	0.00637	~
Person being youth (5<=age<=16)	-0.379	~	~	-0.17	~	~	**0.2826**	~	~
Person being full-time employed	**-0.160**	~	~	NA	NA	NA	**-0.118**	~	~
Person being part-time employed	NA	NA	NA	NA	NA	NA	-0.0478	~	~
Person being student (age>16)	NA	NA	NA	-0.201	~	~	0.0840	~	~
Possession of a driver license	**0.216**	~	~	0.166	~	~	**0.138**	~	~
Tour starting in AM peak	**0.270**	~	~	-0.0183	~	~	**0.404**	~	~
Access to car	-0.0613	~	~	**0.575**	-0.0114	~	0.114	**-0.165**	
Rho-square		0.101			0.233			0.170	
Adjusted Rho-square		0.097			0.210			0.165	
Initial log likelihood		-11362.069			-2087.066			-11504.164	
Final log likelihood		-10209.325			--1600.024			-9551.248	
No. of parameters		48			49			52	

The coefficients in bold is significant with p value < 0.05.
"~" means the coefficient is not significantly different from the coefficient in previous period.
33 household location variables are omitted
"NA" stands for "not applicable".

For work-based and other tours, the presence of children increase complex trip chaining and household size decrease it, presumably due to the need for parents to escort their children. But for those who take school-based tours, neither presence of children nor household size is a factor, because students are usually younger people who do not need to hold the responsibility of childcare. The impact of high household income on tour complexity is significantly positive for work-based, but not significant for school-based and other tours. Age does not seem to have a significant influence on trip chaining except for other tours. Youths are significantly more likely to take complex other tours than adults. While seniors' tendency to carry out complex trips was lower in 1991, such tendency increased to similar level (compared to adults) in around 2001. The effect of access to car is found to change in the same direction for school-based and other tours. It changed from positive to none for the former, and from none to negative for the latter.

The relationship between trip chaining and mode choice has not been fully understood. Instead of assuming a causal relationship between these two decisions, this paper assumes people make choice of trip chaining and mode simultaneously, which is arguably closer to reality, and can reveal differences among different modes. In this case, the dependent variable has six alternatives (simple car, simple bus, simple rail, complex car, complex bus, and complex rail). Three model structures are tried, including a (multinomial logit) MNL model and two nested logit (NL) models, one with two nests categorized by trip chaining complexity (called NL-A) and the other with three nests categorized by mode (called NL-B). Again, using likelihood ratio test, it is decided that MNL is the most efficient model.

The joint choice model uses the combination of trip chaining complexity and mode choice as the dependent variable (which has six alternatives with simple car being the base). The MNL model estimation results for the joint choice model are presented in Table 6. It should be that in order to simplify the model, one dummy variable indicating living in inner London or not is used to substitute the 33 fixed effect variables. Besides, some other variables are omitted for brevity.

By comparing the coefficients within each mode, impacts of the explanatory variables on trip chaining complexity is found. Most of the findings in terms of trip chaining are generally consistent with those from trip chaining model. Similarly, larger household sizes, household locations in the inner city, male individuals and individuals with access to car are found to exhibit negative impacts on complex trip chaining. While the presence of young children in a household, owning a driving license and starting the trip chain in the morning peak have a significant positive influence on trip chaining complexity. These findings are generally true, but may not be true for each mode, tour purpose and period. For example, access to car appears to stimulate the propensity for complex trip chaining for auto-based tours with a purpose other than school and work, while generally car access is a negative factor for trip chaining complexity.

For work-based trip chaining patterns, the household size coefficient for the rail alternative is significantly more negative than that of the car and bus alternatives, indicating people from larger families are less likely to choose rail, and more likely to choose car and bus. But this pattern is not shown in school-based tours. High income travelers have a significantly stronger preference for rail as opposed to choosing bus and car. Male is less likely to use bus for both simple chains and complex chains. Senior is also less likely to choose transit, and the coefficients for transit have decreased throughout the years. As expected, those with a driver license or access to car are more prone to using the car mode. But the impacts of driver license, car access have become weaker in the latest period. Trip chains made by people living in inner city area are significantly more likely to use transit as opposed to car especially for complex chains, presumably due to better access to bus and rail services. Tours that start in the morning peak also significantly tend to be more transit-oriented, with the coefficient for rail higher than that for bus. This arises from commuters wanting to avoid the traffic congestion during the peak hours, so commuters are more likely to use modes which are less impacted by road congestion, such as rail.

Table 6 - Joint Choice Model Results

Tour type	Work-based tours			School-based tours			Other tours		
	1991	2001	2006-2010	1991	2001	2006-2010	1991	2001	2006-2010
Simple Bus									
Constant	**2.55**	**2.43**	**2.56**	**3.11**	~	~	**1.06**	~	~
Household size >=3	**0.141**	~	~	**0.384**	~	~	0.116	~	~
Presence of children	-0.106	~	~	**-0.743**	~	~	**-0.287**	~	~
Household with high income	-0.125	~	~	**-0.555**	~	~	**-0.501**	~	~
Household in inner city	**0.959**	~	~	**0.619**	~	~	**1.00**	~	~
Person being male	**-0.565**	~	~	0.0707	~	~	**0.154**	~	~
Person being senior	-0.0273	~	~	-0.552	~	~	**0.640**	**0.302**	~
Person being youth	0.414	~	~	**-1.59**	~	~	**-0.820**	~	~
Holding a driver license	**-2.44**	**-2.11**	~	**-2.68**	~	~	**-1.43**	~	~
Tour starting in AM peak	0.0457	~	~	**0.939**	~	~	**0.662**	**0.355**	~
Access to car	**-2.43**	~	~	**-2.85**	~	~	**-2.75**	**-2.57**	~
Simple Rail									
Constant	**2.03**	~	~	**2.43**	~	~	**-0.583**	~	~
Household size >=3	**-0.372**	~	~	-0.0828	~	~	-0.207	~	**-0.589**
Presence of children	**0.277**	~	~	**-1.11**	~	~	-0.245	~	~
Household with high income	**0.681**	~	~	0.201	~	~	**0.406**	~	~
Household in inner city	**0.603**	~	~	**0.936**	~	~	**1.11**	~	~
Person being male	-0.00446	~	~	**0.354**	~	~	**0.499**	~	~
Person being senior	**-0.524**	~	~	**-1.30**	~	~	**-0.370**	~	~
Person being youth	-0.389	~	~	**-2.69**	~	**-3.70**	**-1.52**	~	~
Holding a driver license	**-1.55**	**-1.38**	~	**-1.38**	~	~	**-0.885**	~	~
Tour starting in AM peak	**0.566**	**0.376**	~	**0.749**	~	~	**0.931**	**0.275**	~
Access to car	**-2.16**	~	~	**-2.73**	~	~	**-2.33**	~	~
Complex Car									
Constant	**-1.10**	**-0.799**	**-1.03**	**-1.41**	~	~	**-1.62**	**-1.44**	~
Household size >=3	**-0.221**	~	~	0.0433	~	~	**-0.187**	~	~
Presence of children	**0.321**	~	~	0.0713	~	~	**0.244**	~	~
Household with high income	**0.395**	~	~	**0.341**	~	~	0.00310	~	~
Household in inner city	**-0.169**	~	~	0.0498	~	~	-0.0421	~	~
Person being male	**-0.297**	~	~	-0.268	~	~	**-0.184**	~	~
Person being senior	-0.0223	~	~	0.0490	~	~	-0.0099	~	~
Person being youth	0.864	~	~	0.285	~	~	**0.330**	~	~
Holding a driver license	0.198	~	~	0.622	~	~	0.140	~	~
Tour starting in AM peak	**0.504**	**0.256**	~	0.254	~	~	**0.439**	~	~
Access to car	0.0206	~	~	-0.142	~	~	**0.310**	~	~

The coefficients in bold is significant with p value < 0.05.
"-" means the coefficient is not significantly different from the coefficient in previous period.

Table 6 - Joint Choice Model Results (Continued)

Tour type	Work-based tours			School-based tours			Other tours		
	1991	2001	2006-2010	1991	2001	2006-2010	1991	2001	2006-2010
Complex Bus									
Constant	**0.920**	**1.40**	~	**1.81**	~	~	**-0.394**	0.143	**0.569**
Household size >=3	-0.0468	~	~	-0.171	~	~	0.0120	~	~
Presence of children	0.0463	~	~	**-0.579**	~	~	-0.122	~	~
Household with high income	**0.228**	~	~	-0.0147	~	~	**-0.331**	~	~
Household in inner city	**1.03**	~	~	**0.785**	~	~	**1.06**	**0.724**	~
Person being male	**-0.879**	~	~	-0.209	~	~	-0.106	~	~
Person being senior	0.209	~	~	0.265	~	~	**0.357**	~	~
Person being youth	1.68	~	~	**-1.81**	~	~	**-0.659**	~	~
Holding a driver license	**-1.96**	~	~	**-2.10**	~	~	**-1.20**	~	~
Tour starting in AM peak	**0.482**	~	~	**0.750**	~	~	**1.02**	**0.487**	~
Access to car	**-2.51**	~	~	**-2.79**	~	~	**-2.91**	~	~
Complex Rail									
Constant	**1.05**	~	~	**1.76**	~	~	**-1.47**	~	~
Household size >=3	**-0.644**	~	~	-0.125	~	~	**-0.569**	~	~
Presence of children	**0.556**	~	~	**-1.14**	~	~	**-0.497**	~	~
Household with high income	**1.23**	~	~	-0.0232	~	~	**0.860**	~	~
Household in inner city	**0.540**	~	~	**0.916**	~	0.159	**1.27**	~	**0.713**
Person being male	**-0.211**	~	~	0.204	~	~	**0.302**	~	~
Person being senior	**-0.499**	~	~	-1.04	~	~	**-0.857**	-0.208	~
Person being youth	-5.38	~	~	**-3.59**	~	~	**-0.610**	~	~
Holding a driver license	**-1.58**	**-1.03**	~	**-1.14**	~	~	**-0.857**	~	**-0.208**
Tour starting in AM peak	**0.718**	~	~	0.472	~	~	**1.25**	**0.779**	~
Access to car	**-2.34**	~	~	**-2.77**	~	~	**-2.42**	~	~
Rho-square	0.207			0.252			0.353		
Adjusted Rho-square	0.204			0.241			0.351		
Initial log likelihood	-29370.521			-5394.988			-29737.832		
Final log likelihood	-23305.365			-4033.512			-19232.617		
No. of parameters	67			59			71		

The coefficients in bold is significant with p value < 0.05.
"~" means the coefficient is not significantly different from the coefficient in previous period.

4.4 Drivers for the change in trip chaining complexity

The change in trip chaining complexity could be caused in the change of explanatory variables, or the change of the coefficients of these variables. The former can be shown via descriptive analysis (see Table 1) and the latter is revealed through discrete choice modeling (see Tables 5 and 6). A few socio-economic drivers of the increasingly complex trip chaining pattern are listed below:

One important contributor of the increasing trip chaining complexity is shrinking household size, especially between 1991 and 2001. It is found that people from smaller families are more likely to chain multiple trips together. Thus the shrinking household size could lead to the increase in trip chaining complexity. It is to be noted that the household size, although overall declining, has a small increasing trend after 2001, and this may partly explain why the change of trip chaining complexity from 2001 to 2006-2010 is relatively moderate.

Increase in people with driver licenses is found to be another factor. Possession of a driver license is positively related to complex trip chaining. And during the study period, proportion of licensed people went up continuously. This again contributes to the increasing trip chaining complexity.

Another possible factor is the increasing income. Steady economic development leads to rise of Londoners' wealth. This study has shown that having a higher household income has a positive influence on trip chaining complexity. Thus rising household income is one of the major factors that cause trip chaining complexity to continuously grow.

Seniors have become more active in terms of trip chaining. This study reveals a decrease of the coefficient of being a senior between 1991 and 2001. This means seniors in London was less likely to chain trips together in 1991, but 10 years later they had a similar trip chaining complexity with adults. The increasing involvement of seniors in trip chaining is another factor that can explain why the complexity has gone up.

5. CONCLUSION AND DISCUSSION

Using three waves of large-scale household travel surveys, this paper characterizes the trip chaining patterns in London, examines their evolution over the past two decades and identifies the socioeconomic variables that contribute to the trend. Descriptive analysis shows that the overall trend for trip chaining patterns in London is increasing, possibly due to the greater efficiency and convenience arising from linking multiple activities together in a single chain. In terms of tour purpose, work-based tours are most complex and school-based tours are simplest, while the increase of other tour complexity is more pronounced, which indicates a probable difference in trip chaining patterns between different purposes. On the contrary to previous findings, transit-based tours are becoming complex in a faster pace than car-based tours. Rail has surpassed car as the most complex mode in London. Having larger household, living in inner London, being male, and having access to car decrease the propensity for trip chaining, while having children, traveling in the AM peak, and having driver license increase trip chaining. Comparison across years reveals decreasing access to car, diminishing household size, and more people with a driver license are among the factors contributed to the increasing complexity. Increasing positive impacts of income and less households living in inner city are also found to increase trip chaining complexity, but only for work-based tours.

A better understanding of trip chaining trends helps to predict people's future travel behavior, and facilitate development or impact analysis of relevant transportation policies, land use planning and the assessment of infrastructure investments.

One of the primary goals of transportation policymakers is to induce a modal shift from car to public transportation since car is a major source of air pollution and traffic congestion. Findings in this paper can provide insights into ways to make public transportation a more attractive option and cars a less appealing choice. In contrast to previous studies which found that complex trip chains tend to be more auto-oriented and public transit is regarded as less fitting for trip chaining, London's case suggests that transit service, if well integrated, can support increasingly complex trip chaining behavior. Because of the efficiency and convenience gained from linking multiple activities together in a single chain, it is likely that the increasing trend of trip chaining complexity found in this paper will continue in the future. This could be an opportunity for public transportation if it can be tailored to better accommodate this trend. On one hand, public transportation network needs to be expanded and system connectivity needs to be improved, to make it efficient and convenient for transit passengers to reach multiple destinations in a single journey. On the other hand, land use planning, especially transit oriented development (TOD), can bring more activities close to public transportation, such that access/egress time can be reduced (since a complex chain involves multiple times of transit access/egress). In addition, transit agencies should focus on the development of a more accessible and reliable passenger information system to facilitate people in making their trip chaining decisions. This is especially pertinent in the age of mobile phone and internet when many trip-related decisions are made during the course of travel. Furthermore, the fare system may be adjusted to limit the commuter's marginal cost of transit service. For instance, by increasing the maximum journey time limits for bus and rail trips, this would allow passengers using these modes to satisfy multiple needs and carry out a wider array of activities within a trip chain without incurring monetary penalties. In terms of car use, as trip chaining patterns become more complex, the number of stops made by car users correspondingly increases. Hence, measures that make parking more burdensome and expensive, such as reductions in parking space and increases in parking costs, will become even more effective solutions at curbing car usage in the future. If car is used throughout the trip chain, parking restrictions in one stop within the chain constrains car use throughout the chain.

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