Abstract

Telecommuting means that employees work completely or sometime at home or at remote telecommuting centres instead of daily travel to work at regular offices. Impacts of telecommuting on transport are becoming significant. This paper reviews the growth of telecommuting and analyzes the necessity to evaluate the influence of telecommuting in transport planning and control. The transport network equilibrium is applied to determine the flow pattern by maximizing the consumer surplus. The objective function is established from the demand and supply functions. The demand function is formed from the relationship between demand and the status of transport network. The supply function formulates the interaction between the travel time and the flow of links. When telecommuting is introduced, travel demand can decrease by different amounts in different areas and on different paths of the transport network. This redistributes trips in the network. In addition, the reduction of work trip demand by telecommuting leads to reduction of flows and travel time on roads at peak times. The users on roads with greater travel time will consider switching routes to roads with less travel time and that pushes the network to a new equilibrium state with a new flow pattern. Here combination of the demand function and the supply function enables us to solve above interactions and to simultaneously determine demand and the redistribution of flow pattern. The proposed model is referred to as an elastic-demand network equilibrium model.

Keywords: Telecommuting; flow pattern; equilibrium model.
1. INTRODUCTION

Although telecommuting is becoming a popular alternative arrangement of work due to its positive impacts in different aspects of society, determination of impacts of telecommuting on transport and how to bring these impacts in transport planning are still difficult problems. Determination of impacts of telecommuting on transport indicators such as travel time; vehicle-km traveled; traffic congestion and air pollution have been attempted for years. Those efforts were however based on aggregate models, not based on the change of traffic flow. Determination of impacts of telecommuting on the transport network could be more accurate by accounting for traffic flow pattern affected by telecommuting. In addition, transport planners want to know how the flow pattern changes as it directly affects the performance of the transport network. How the supply side fits to the future scenarios of transportation also depends on the determination for the change of the flow pattern. The resulting flow pattern improves the accuracy in determining of other impacts of telecommuting.

The concept of telecommuting was coined by Nilles in 1973 and many studies relevant to investigation of impacts of telecommuting have followed. Nilles (1988) studied the status and the trend of telecommuting and evaluated the portion of workers able to telecommute in the workforce. Some impacts of telecommuting on society and on transport were also analyzed in that study. More recently, ATAC (2006) further researched impacts of telecommuting on socio-economic aspects and encouraged the government to give priority to further develop telecommuting. That report also identified opportunities for actions to increase the uptake and spread of telecommuting. Definitions of telecommuting and guidelines for implementing and managing telecommuting were researched by Mokhtarian (1991). In that study, the supervision to ensure output and the reduction of commuting trips are necessary conditions for a work to be considered telecommuting. That definition is however found be limiting for our purpose as an important impact of telecommuting on transport is missing. For example, there are workers who can remote work for part of the day at home and they still commute to work for the rest of that day. They can work at home before going to work or after coming back from work. This type of remote work do not reduce commuting trips but reduce congestion in peak hours and reduce travel time as these workers can avoid commuting trips in peak hours. This remote work arrangement is covered by the transport-oriented definition of telecommuting proposed by Vu and Vandebona (2007), and referred to as part-day telecommuting. That study also developed a model to determine impacts of telecommuting on the transport network based on a framework that deals with full-day telecommuting and part-day telecommuting as separate types. A multiplicative model to evaluate impacts of telecommuting was earlier developed by Mokhtarian (1998) but it was based on a different framework which did not account for part-day telecommuting. Another study about impacts of telecommuting on transport evaluated changes in travel behavior of home-based telecommuters from the first experiment in Netherlands (Hamer et al., 1991). The center-based telecommuting and its impacts of on travel and emissions were reported in the Puget Sound demonstration project (Henderson and Mokhtarian, 1996). Most previous studies, however, are based on either pilot projects or approximations of aggregate data.

This paper reviews the growth of telecommuting and analyzes the necessity to evaluate the influence of telecommuting in transport planning and control. The transport network equilibrium is applied to determine the flow pattern of the transport network with telecommuting.
2. GROWTH OF TELECOMMUTING

2.1 State of the Practice of Telecommuting

Successes of projects encouraging telecommuting have concluded that telecommuting is rapidly increasing. Previous studies have shown that the number of telecommuters is significant and telecommuting will become a popular work pattern in the future. Vidal (2004) estimated that Australian mobile teleworkers will increase from 2.8 million (30%) in 2004 to 3.4 million (37%) by 2008. ITAC (2004) forecasted that an estimated 100 million US workers (approximately 70%) will telework by 2010. Most European surveys show that there is a far greater proportion of the workforce wanting to telework than are actually teleworking. Employees and employers will find it easier to implement telework due to the falling equipment and communications costs and the increased availability of off-the-shelf communications packages designed for teleworkers.

According to the European Union's Emergence Project, by 2010 27 million Europeans will work from home with the UK leading the field. By 2005, eight million are projected to work at home, compared to 2.2 million in 2001. Research suggests that France (43%) and the UK (48%) had the lowest levels of home working in the five European countries studied; Germany came top with 60% (The Herman Trend Alert, 2005).

According to The Statistical Indicators Benchmarking for the Information Society (SIBIS) study from 2002 to 2003 and Australian Telework Advisory Committee (ATAC) study 2005, Australian and international telecommuting has increased fast from low base over last decade and reached the level as in the Figure 1 in 2003.

![Figure 1: State of the practice of telecommuting](image)

Impacts of telecommuting depend on not only the proportion of telecommuting but also the frequency of telecommuting. In this paper, the fraction form of telecommuting frequency is used.
In this form, telecommuting frequency is the ratio between the number of telecommuting days and the number of working days. Five working days per week was used to convert the values of telecommuting frequency to fraction form. By this way, telecommuting once per fortnight corresponds to the telecommuting frequency of 0.1 and telecommuting once per four weeks corresponds to the telecommuting frequency of 0.05. Lake and Cherrett (2002) stated that predominant teleworking practice was part-time telecommuting, and the average telecommuting frequency was 0.3 away from the normal workplace. Telecommuting frequency was 0.2 in RTA (1995) and 0.24 in Mokhtarian (1998). In Sensis (2005), over 80% teleworkers teleworked up to frequency of 0.25. Telecommuting frequency of 0.3 was observed by Hamilton (2006) as well. ABS (2002) reported that nearly half of existing teleworkers would like to telework more. This can lead to an increase of telecommuting frequency in the future.

2.2 Forecasting Proportion of Telecommuting

To forecast proportion of telecommuting, we adopt the model proposed by Blackman (1974) to forecast the uptake of a new technology. The model has been later applied to telecommuting by Handy and Mokhtarian (1996) and Shafizadeh et al (2000). According to Handy and Mokhtarian (1996), the telecommuting growth can be approximated by considering telecommuting as a new technology and its adoption follows an S-shape curve, characterized by low growth rates at the initial and final stages, and high growth rates around the midway point. The general model of Blackman (1974) is given by Equation (1):

\[
\ln \left( \frac{f}{F - f} \right) = c_1(t - t_0) + c_2
\]

where \( f \) is the market share captured at time \( t \), \( F \) is the carrying capacity of the market and \( t_0 \) is the year when the innovation first captures a portion of the market. \( c_1 \) and \( c_2 \) are constants.

In telecommuting application \( f \) is the proportion of telecommuting in year \( t \) and \( F \) is the maximum proportion of telecommuting achievable by the workforce. The constants \( c_1 \) and \( c_2 \) need to be calibrated using historical data. Blackman suggested fitting a regression line to the historical data. To simplify this process, Equation (1) is rewritten in a linear form:

\[
\ln \left( \frac{f}{F - f} \right) = c_1 t' + c_2
\]

where

\[
t' = t - t_0
\]

\( t' \) is the period of time from the initial year to the year of interest.

Rearrangement of (2) forms the constrained logistic function that provides the proportion of telecommuting \( f \) as a function of time:
To estimate the initial year \( t_0 \) we compared the proportion of telecommuting in Australia and in US. The proportion of telecommuting in Australia in 1994 was 3.4\% (Brewer and Hensher, 1996), approximately equal to the level of telecommuting in US in 1990 (Shafizadeh et al, 2000). Thus, a four year time lag period was selected. Both Handy and Mokhtarian (1996) and Shafizadeh et al (2000) have selected 1980 as the initial year of telecommuting in US to forecast telecommuting. 1984 is our selection as the initial year that telecommuting captured a portion of workforce in Australia.

To estimate the maximum level of telecommuting we reviewed other studies. Studies from developed countries confirmed a positive trend with rapid increase of telecommuting proportion. The Canadian Telework Association estimated in 2004 that 65 per cent of jobs would be amenable to telework. ITAC also forecasted that 100 million US workers (approximately 70\%) will telework by 2010.

Nilles (1988) hypothesized that 80\% of information workers were potential telecommuters and 50\% of workforce was composed of information workers. Then Nilles proposed that 40\% of all workers were potential telecommuters. Later, other studies and surveys have shown that the telecommuters included workers other than just information workers (ECaTT 2000; ABS 2001). From these reasons the upper limit of telecommuting can be expected to be greater than 40\% of workforce.

However, to avoid overestimation of telecommuting adoption we selected 50\% as the maximum level of telecommuting in Australia. The proportion of telecommuting in 2000 was 11\% (ABS, 2001) and 2005 was 30\% (Vidal, 2004 and Sensis, 2005). Using these data to calibrate Equation (4) (Figure 2), an \( R^2 \) value of 0.99 was observed and the regression line is found to be:

\[
y = 0.2732x - 5.4397
\]

(5)

Thus, Equation (4) can be rewritten:
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\[ f = \frac{0.5 \times e^{(-5.44+0.27t)}}{1 + e^{(-5.44+0.27t)}} \] (6)

The proportion of telecommuting in Australia is forecasted as in Figure 3 using Equation (6).

![Figure 3. Simulation of growth of telecommuting in Australia.](image)

The proportion of telecommuting in Australia is forecasted as in Figure 3 using Equation (6).

With those amounts, effects of telecommuting are significant and need to be studied to enable policy makers and planners to work toward telecommuting scenarios of society. In this paper we focus on a method to determine impacts of telecommuting on transport networks.

3. NECESSITY TO EVALUATE THE INFLUENCE OF TELECOMMUTING IN TRAFFIC ASSIGNMENT

The traffic flow pattern of the transport network would change when more workers adopt telecommuting. This hypothesis is related to two issues. (1) Telecommuting reduces flows on roads and therefore reduces travel time on roads. The reduction of travel time by telecommuting can change flow distribution over transport networks if the travel time reduction is different in different paths of the network. The reason is that the users on roads with greater travel time would consider changing routes to roads with less travel time. (2) Previous studies (Mokhtarian et al., 1995) have shown that the number of relatively long distance commuting trips, which are eliminated by telecommuting, is more than the number of short distance commuting trips eliminated by telecommuting. In other words, the portion of workers with long commuting trips that adopt telecommuting is greater, and those telecommuters tend to telecommute more often. Because of this point, reduction of commuting trips can be different by areas and by roads. These two issues push the transport network to a new equilibrium point with a new flow pattern.

When the change of flow pattern is significant, it will be less accurate in transport planning and control if we ignore influence of telecommuting in determination of traffic flow pattern. The
change of the flow pattern now is significant in Australia and some other developed countries as the proportion of telecommuting in the workforce is large. The proportion of telecommuting has increased fast in recent years and become quite popular in some fields such as information technology and commerce. The proportion of telecommuting in some countries has reached 20 to 30% as shown in the former section. In this section, we want to state that the change of flow pattern is large in term of commuting trips and route choice. Commuting trips reduce due to eliminated trips and shifted trips by telecommuting. Route choice changes due to two reasons that we have just mentioned above. From this argument, it is necessary to evaluate the influence of telecommuting in transport planning and control.

4. METHODOLOGY

This paper applies transport network equilibrium to determine the traffic flow pattern with telecommuting. The reduction of travel demand by telecommuting is computed and embedded into the demand function. The elastic-demand network equilibrium model is solved to determine the flow pattern of links in the transport network with telecommuting.

The concept of transport network equilibrium was introduced by Wardrop (1952). The transport network equilibrium is well known as his first principle. This principle states that users minimize travel cost individually and a stable condition is reached when no traveler can unilaterally lower his or her travel time. Beckmann et al. (1956) formulated Wardrop’s first principle as a convex mathematical programming problem in order to solve the problem of transport network equilibrium for a transportation network. The formulation has been then applied and modified by researchers such as Dafermos (1971), Smith (1979) and Smith and Vuren (1989). In those articles, the trip rate between all Origin and Destination (O-D) pairs is fixed and known. This kind of model is called a fixed-demand model. On the other hand, in reality these trip rates may be influenced by path properties such as level of congestion and toll prices. To model the relationship between demand and performance, the travel demand is set to be a function of travel cost and this function is referred to as an elastic-demand model. An early example of the transport network equilibrium with elastic-demand was formulated by Gibert (1968), followed by Florian and Nguyen (1974) who presented a method to compute the elastic-demand equilibrium using iterative application of an algorithm developed for the fixed demand equilibrium. This topic area is now progressed to handle the multi-class, multi-criteria transport network equilibrium with elastic-demand (for example, Nagurney and Dong, 2002).

In the elastic-demand models, the flow pattern is obtained at the equilibrium point between the demand function and the supply function. The general formulation for demand between O-D (origin-destination) pair \( w \) depends on the potential demand \( q_w^0 \) and the travel cost \( u_w \):

\[
q_w = g(q_w^0, u_w, \alpha)
\]  
(7)

where \( \alpha \) is a vector of the parameters of the demand function.
In the network scenario with telecommuting, travel demand depends on the potential demand $q^0_w$, the travel cost $u_w$ of O-D pair $w$, and the fraction $x$ of eliminated trips (vehicular trips) by telecommuting:

$$q^{TC}_w = h(q^0_w, u_w, x, \alpha)$$  \hspace{1cm} (8)

The fraction $x$ of eliminated trips by telecommuting can be evaluated through:

$$x = \frac{\Delta TR}{TR}$$  \hspace{1cm} (9)

where $\Delta TR$ is the reduction of vehicular trips by telecommuting and $TR$ is the number of vehicular trips to work by car of all commuters. This equation is similar to that proposed by Vu and Vandebona (2007). Only the reduction of drive alone mode trips by telecommuting are considered here. The reason why we account only drive alone mode is (1) other private modes like car pool or drive share do not lead to vehicle trip reduction and (2) person trip reduction of public transport mode is insignificant to eliminate a bus or a train trip unless there is a extremely high telecommuting proportion.

$$\Delta TR = E \times TC \times (F_{FDTC} + F_{PDTC} \times \gamma) \times MS_{DA}$$  \hspace{1cm} (10)

where $E$ is the number of employed persons, $TC$ is the proportion of workers who telecommute (it is referred to here as the proportion of telecommuting). The proportion of telecommuting is computed using the model as in Equation (1). $F_{FDTC}$ and $F_{PDTC}$ are the frequency of full-day telecommuting and part-day telecommuting respectively, $\gamma$ is the proportion of commuting trips during peak hours that is shifted to non-peak hours on the days of part-day telecommuting and $MS_{DA}$ is the drive alone mode share.

The fraction form is used for variables in equation (10). In this form, the proportion of telecommuting is the ratio between the number of workers who telecommute and the number of workers in the workforce. The frequency of telecommuting is the ratio between the number of telecommuting days and the number of working days. Five working days per week was used to convert the values of telecommuting frequency to fraction form. According this method, telecommuting once per fortnight corresponds to the telecommuting frequency of 0.1 and telecommuting once per four weeks corresponds to the telecommuting frequency of 0.05.

The number of vehicular trips to work by car of all commuters (telecommuters and non-telecommuters) in equation (9) can be computed as

$$TR = E \times MS_{PR} \times O_v$$  \hspace{1cm} (11)

where $MS_{PR}$ is the share of private mode of work trips of all commuters and $O_v$ is the average vehicle occupancy of work trips.

The relationship between traffic flow and travel time on links of the transport network can be expressed by the travel time function. Travel time $t_l$ of link $l$ depends on physical characteristics
of link (free flow travel time \( t_i^0 \)) and the level of congestion (traffic volume \( f_i \) on link \( l \) and capacity \( s_l \) of link \( l \))

\[
t_i = z_i^0, f_i, s_i, \beta_i
\]

(12)

where \( \beta \) is a vector of the parameters of the supply function.

Consider a general transport network \( G = (N, L) \), defined by a set \( N \) of nodes and a set \( L \) of links. The travel time function \( t_{il} \), \( l \in L \), is assumed to be differentiable, convex, and monotonically increasing with the amount of flow, \( f_i \). Let \( c_l \) denote the toll charged on link \( l \in L \), \( W \) denotes the set of Origin and Destination pairs (O–D pairs), \( P_w \) is the set of paths between the O–D pair \( w \in W \) and \( P \) is the set of all paths in the network.

Minimise \( \sum_{l \in L} \int t_{il}(f) df - \sum_{w \in W} \int u_w(q) dq \)

(13)

subject to

\[
f_i = \sum_{p \in P_w} f_p \delta_{wp}
\]

(14)

\[
\sum_{p \in P_w} f_p = q_w
\]

(15)

\[
f_i \leq s_i, l \in L
\]

(16)

\[
f_i \geq 0
\]

(17)

\[
f_p \geq 0
\]

(18)

The objective function (13) is the sum of integrals of link supply functions (12) and integrals of inverse O-D pair demand functions (8). The objective function should be viewed strictly as a mathematical construct that is used to solve equilibrium problems, instead of as any intuitive economic or behavioral interpretation. Equation (14) is the flow conservation constraint; equation (15) is the O-D demand constraint; equation (16) is capacity constraint and equation (17) and (18) are non-negativity constraint.

5. NUMERICAL EXAMPLE

In this section we apply the network equilibrium to determine the traffic flow pattern and vehicle travel time for the network in two scenarios: (i) with telecommuting and (ii) without telecommuting.
Experimental network includes three zones and six links. There are two ways between each two zones and each way is considered as a separate link. Each zone is both an origin and a destination. Between each O-D pair exists two routes, a directed link and a path through the remaining node (Figure 5). The supply function will be

\[ t_i(f) = t_i^0 \left[ 1 + 0.15 \left( \frac{f_i}{s_i} \right)^4 \right] \]  

(19)

The input data for supply functions are given in Table 1 including link free-flow travel time and constrained and non-constrained link capacity. Non-constrained capacity of links presented is much higher than possible volumes so that the results will not be affected by capacity. Those values are selected after trial runs of the program.

![Example network](image)

**Figure 4. Example network**

<table>
<thead>
<tr>
<th>Link ( l )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_i^0 )</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>( s_i )</td>
<td>Non-constrained</td>
<td>900</td>
<td>800</td>
<td>700</td>
<td>700</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>Constrained</td>
<td>300</td>
<td>200</td>
<td>300</td>
<td>300</td>
<td>200</td>
</tr>
</tbody>
</table>

The demand functions are selected as follows

\[ \begin{align*}
q_{12} &= 700 \exp(-0.02u_{12}) \\
q_{23} &= 500 \exp(-0.04u_{23}) \\
q_{31} &= 600 \exp(-0.05u_{31}) \\
q_{21} &= 700 \exp(-0.02u_{21}) \\
q_{32} &= 500 \exp(-0.04u_{32}) \\
q_{13} &= 600 \exp(-0.05u_{13}) \\
\end{align*} \]  

(20)
The model is a nonlinear optimization satisfying conditions for existence of the unique solution. The Lagrangian multiplier method is used to solve the problem and the model is coded in GAMS21.3. The model has 49 variables and 13 constraints with 97 Jacobian elements, 12 of which are nonlinear. The Hessian of the Lagrangian has 12 elements on the diagonal, 0 elements below the diagonal, and 12 nonlinear variables. Table 2 presents traffic flows on links, travel demand between O-D pairs of the experimental network, values of the objective function $F$ and total vehicle travel time $T$ with and without telecommuting. The flow of each link is the sum of flows on all paths via that link.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Non-constrained capacity</th>
<th>Constrained capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Telecommuting 0.2</td>
<td>Non-telecommuting</td>
</tr>
<tr>
<td>$f_1$</td>
<td>Veh/h</td>
<td>452.01</td>
</tr>
<tr>
<td>$f_2$</td>
<td>Veh/h</td>
<td>401.79</td>
</tr>
<tr>
<td>$f_3$</td>
<td>Veh/h</td>
<td>351.56</td>
</tr>
<tr>
<td>$f_4$</td>
<td>Veh/h</td>
<td>351.56</td>
</tr>
<tr>
<td>$f_5$</td>
<td>Veh/h</td>
<td>401.79</td>
</tr>
<tr>
<td>$f_6$</td>
<td>Veh/h</td>
<td>452.01</td>
</tr>
<tr>
<td>$q_{12}$</td>
<td>Veh/h</td>
<td>505.95</td>
</tr>
<tr>
<td>$q_{13}$</td>
<td>Veh/h</td>
<td>372.73</td>
</tr>
<tr>
<td>$q_{21}$</td>
<td>Veh/h</td>
<td>505.95</td>
</tr>
<tr>
<td>$q_{23}$</td>
<td>Veh/h</td>
<td>326.69</td>
</tr>
<tr>
<td>$q_{31}$</td>
<td>Veh/h</td>
<td>372.73</td>
</tr>
<tr>
<td>$q_{32}$</td>
<td>Veh/h</td>
<td>326.69</td>
</tr>
</tbody>
</table>

In this paper, a predetermined fraction of eliminated commuting trips by telecommuting is applied. Determination of this factor using the transport network equilibrium method would be our next target. In this problem, the reduction of the number of commuting trips by telecommuting will be expressed as a function of input variables such as travel distances and traffic status. This relationship is then embedded into the objective function and solved by optimization technique to determine the reduction of the number of commuting trips by telecommuting and the flow pattern simultaneously. We expect such an improved model would increase the accuracy of results in reality and increase ability in forecasting of the model as the proportion of telecommuting depends on travel cost which in turn is the function of traffic flow.

6. CONCLUSIONS

The paper has reviewed and forecasted the growth of telecommuting, analyzed the necessary to account for influence of telecommuting in traffic assignment and proposed the method to determine traffic flow pattern under influence of telecommuting. The objective function is
established from the demand and supply functions. The demand function is formed from the relationship between demand and the status of transport network. The supply function formulates the interaction between the travel time and the flow of links. When telecommuting is introduced, travel demand would decrease by different amounts in different areas and on different paths of the transport network. This redistributes trips in the network. In addition, the reduction of demand by telecommuting leads to reduction of flows and travel time on roads. The reduction of travel time by telecommuting can change traffic flow distribution over the transport network when the travel time reduction is different on different paths of the network. The users on roads with greater travel time will consider switching routes to roads with less travel time and that pushes the network to a new equilibrium state with a new flow pattern. Here combination of the demand function and the supply function enables us to solve above interactions and to simultaneously determine demand and the redistribution of flow pattern. The model is referred to as an elastic-demand network equilibrium model. The new flow pattern is then utilized to compute impacts of telecommuting.

The key part of this method is a user equilibrium model with elastic demand under the influence of telecommuting. The fraction of eliminated commuting trips by telecommuting is computed in advance from properties of employment and telecommuting. This factor is then embedded into the demand function. The model of elastic-demand network equilibrium includes an objective function and five boundary value expressions. Travel demands between Origin and Destination pairs and traffic flow pattern on links are determined by maximizing the consumer surplus. The model can be applied for traffic assignment of the four-stage transport planning model. Other transport impacts of telecommuting such as saving of travel time; reduction of vehicle-km traveled; impact on air pollution and noise pollution can be also determined with this form of model. A numerical example is carried out to illustrate the method. In the numerical example, the flow pattern of a transport network with three Origin and Destination pairs and six links is determined.

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