TELECOMMUTING AS A STRATEGY FOR REDUCING ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSIONS IN MULTI-NUCLEATED URBAN REGIONS

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ABSTRACT

This paper describes the potential of telecommuting in reducing the consumption of petroleum-based fuels and greenhouse gas emissions in the transportation system of a multi-nucleated urban region. The formation of multi-nucleated urban regions and commuting needs are described. In support of the sustainability objective, telecommuting as a supplemental measure to providing a balance of jobs and housing in satellite community centres is noted. Telecommuting is described in conceptual and operational terms and its potential influence on residential location choice decision is noted. As a part of a case study of telecommuting in the National Capital Area (Canada), a Bayesian decision model is advanced that can explain the acceptance of telecommuting by an employee. Fuel saving and greenhouse gas emissions reduction potential of telecommuting is described and finally conclusions and policy implications are presented. .

Keywords: Multi-nucleated urban region, land use, information technology, telecommuting, urban transportation, fuel consumption, green house gas emissions

1. INTRODUCTION

Traffic congestion keeps on rising in many urban areas around the world and as a result commuting trip time, fuel consumption and emissions are outstanding issues. Multi-nucleated urban regions that have achieved a certain degree of a balance between jobs and housing in satellite communities have experienced a reduction in commuting trips to the central city. However, in most such regions, the balance of jobs and housing is much below the level that could offer work opportunities to a majority of residents of outlying satellite communities. Consequently, there is still a high degree of commuting during peak periods.

A number of travel demand management measures could be considered for reducing automobile traffic in major corridors of multi-nucleated urban regions which are already well served by public transit. Electronic road pricing, vehicle restrictions or other demand management measures are normally considered in order to avoid severe traffic congestion

in the travel corridors and central business district street network. Telecommuting is an attractive concept that has been noted by researchers and policy experts as a potentially very effective strategy for making a favourable impact on traffic congestion, fuel consumption, air quality, and greenhouse gas (GHG) emissions. However, in order to succeed, active support of a number of stakeholders is necessary. These include employees, employers, and civic leaders with policy responsibility. This paper advances ideas on the study of the role of telecommuting in saving fuel and emissions.

2. MULTI-NUCLEATED URBAN REGIONS

A multi-nucleated urban region is an urban form that is drawing planning and policy attention around the world. There has been the emergence of such planned urban areas whose development is guided in-part by growth pressures to go out of a central city even one with a greenbelt (e.g., Ottawa, Canada). Also, the "smart growth" idea has played a role (Smart Growth Network 2010, Laquian 2004). As opposed to accommodating growth in an unstructured sprawled form, planners and policy makers considered it desirable to direct urban growth in a number of well defined development nodes that offer the opportunity to some residents to live and work in the same satellite community. These satellite communities can be linked to the central city with high quality rapid transit. If there is sufficient demand, these can also be linked with each other by rapid transit.

If people can live, work and find their leisure and entertainment in these satellite communities; they can cut down on commuting, avoid traffic jams and reduce emissions. Since these outlying community centres can offer cheaper good quality housing opportunities, some residents are likely to locate or relocate in such centres, provided that they can commute efficiently to the central city, if they have to do so. As a side benefit, they can also conserve green space and agricultural land between these intense nodes of development (Laquian 2004).

The National Capital Area (NCA) of Canada serves as an example of a multi-nucleated region. Figure 1 shows the central cities of Ottawa (in the province of Ontario) and Gatineau/Hull (in the province of Quebec). Outside the main cities, a number of first tier community centres are located. The map also shows a second tier of outlying communities that are a part of the multi-nucleated urban region. All satellite communities are served with highways. The first tier satellite communities are either already served with bus rapid transit or will be served as a part of the strategic plan. Some second tier communities are served with bus services.

The household size is low in the central city as compared to satellite communities and this trend will continue into future years. (Table 1). The residence location choices made by households are in part influenced by need for space at relatively low prices. The satellite communities do offer employment opportunities, but these are much lower than in the central city (Table 2). Unless future employment opportunities in satellite communities improve, it is inevitable that a majority of residents of satellite cities have to commute to employment locations in the central business district of the main city or to other job sites. In spite of the

presence of public transit, freeways and other roads in the travel corridors experience traffic jams.
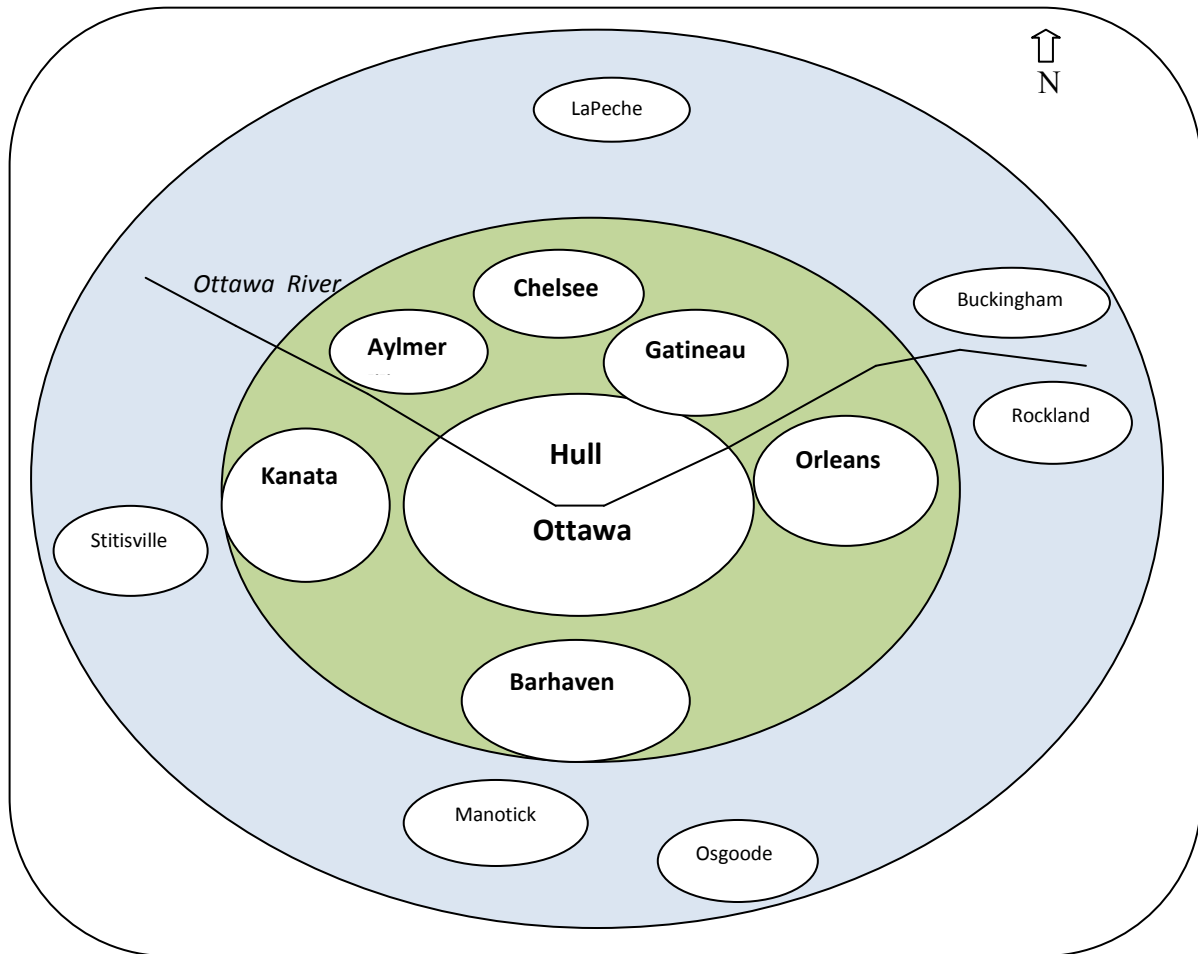

Figure 1. Multi-nucleated National Capital Region (Canada)
(Note: Sample tier 1 and tier 2 communities shown)

Table 1. Population/household ratio, Ottawa (Canada)

	1991	2001	2011	2021
Inside the greenbelt	2.46	2.32	2.19	2.08
First tier satellite communities	3.31	3.08	2.94	2.75
Second tier satellite/rural communities	3.18	3.00	2.94	2.80

Note: The above data apply to Ottawa (Ontario) region (shown south of Ottawa River in Figure 1). Source: City of Ottawa (2008).

Table 2. Employment/population ratio, Ottawa (Canada)

	1991	2001	2011	2021
Inside the greenbelt	0.70	0.78	0.85	0.87
First tier satellite communities	0.19	0.29	0.60	0.42
Second tier satellite/rural communities	0.19	0.23	0.26	0.25

Note: The above data apply to Ottawa (Ontario) region (shown south of Ottawa River in Figure 1). Source: City of Ottawa (2008).

3. SUSTAINABILITY FACTORS FOR MULTI-NUCLEATED URBAN REGIONS

A multi-nucleated urban region has well defined interconnected and interacting components. This research is closely interested in three major parts, namely land use, transportation and communications. Such an urban region should offer its present and future inhabitants the opportunity to attain economic, social, recreational and other goals. Given the imbalance of jobs and housing in satellite communities, it is necessary to implement policies and programs so as to avoid future problems of traffic congestion, inefficient use of fuels and emissions. That is, transportation between the central city and satellite communities should be made sustainable and the supplemental measure of telecommuting should be given careful consideration.

For multi-nucleated urban regions, the sustainability solutions include: (1) efficient use of scarce urban land, (2) a balanced transportation system that offers the users the opportunity to use modes that are alternatives to the automobile (i.e. public transportation, non-motorized modes for local travel, telecommuting), (3) Efficient use of non-renewable petroleum fuels and substitution of renewable energy sources for petroleum fuels, (4) controlling air quality pollutants, (5) reduction of greenhouse gas (GHG) emissions, (6) reduction of other ecological effects of transportation, and (7) controlling noise from transportation.

The City of Ottawa's strategic directions regarding transportation that were defined as apart of the official plan include the following: use of alternative fuels, increased use of public low or zero emission transit, and transportation demand management. It is interesting to note that telecommuting is included in the list of demand management measures (City of Ottawa 2008).

4. TELECOMMUTING

Telecommuting refers to the use of information technology to partially or completely replace daily trips to and from workplace. Telecommuting could involve work-at-home or at a location other than the central work place (e.g., a telecentre close to home) during normal work hours (Dearborn 2002). Although the objective of substituting telecommunications for physical transport has been of interest since the early 1940s, telecommuting was never pursued seriously due to technology limitations and the prevailing attitudes at the time. The interest in the substitution objective was renewed in the 1970s. However, one of the main reasons that telecommuting was not accepted widely in the 1970s and even in later years was the technological constraint. Computer hardware and software, as well as telecommunication systems were deficient (Tayyaran 2000).

Since 1990s, concerns about adverse effects of severe traffic congestion and developments in computer and telecommunication technology resulted in considerable interest in telecommuting. The convergence of technological and institutional developments induced the widespread use of information technology. In turn, this has enhanced worker ability to effectively communicate with customers as well as the office. Although availability and use of computer is not a pre-requisite for telecommuting, most tasks that require the exchange of information between the telecommuter and the main office can be carried out effectively by the use of computer and communication systems.

In recent years, access to new generation information technology has improved and this trend is likely to continue in the future (Ahmadi, et al 2000). For example, the City of Ottawa is planning to become a world leader in the provision of affordable, high quality, equitable broadband access to all its citizens. According to this vision, Ottawa's new broadband network will form an integral part of the infrastructure of the region. It will be rapidly deployed and is expected to be competitive, cost effective, and scalable for future growth. Further, for efficient and barrier free communications, it will be compatible with existing and emerging provincial and national high-speed networks (City of Ottawa 2009).

Advances in communications technology, including broadband and high speed internet access are making new types of working arrangements and enterprises possible for the first time (Hughes and Nelson 2002). The availability of broadband infrastructure is reducing the monopoly of the central city on highest-paying jobs. According to recent studies, knowledge-based industries and their employees in Canada and the U.S.A. are becoming less dependent on the services of a central city. As a result, interest is telecommuting is likely to increase (Innovisions Canada 2002, Hughes and Nelson 2002).

 Also, new opportunities in the form of employer-initiated programs have become available that make it possible to telecommute and therefore modify commuting behaviour. Key benefits of telecommuting have been identified in the literature (Dearborn 2002, Mitomo et al 1996, Hughes and Nelson 2002, Steen et al. 999, ITE 1996). See Table 3.

Table 3. Key benefits of telecommuting

Benefits for employees	Benefits for employers	Societal benefits
• Eliminating wasted time commuting • Flexibility in balancing their professional and personal lives • Saving on commuting cost • Reducing job and commuting stress	• Less employee turnover as result of happier workers • Less need for office space • Possibly greater productivity • Improved position in the labour market	• Less traffic congestion • Less pressure to expand infrastructure capacity • Less traffic accidents • Conservation of energy and reduction of greenhouse gas emissions • Reduced air pollution from vehicles

5. CONCERNS REGARDING TELECOMMUTING

In spite of many benefits, telecommuting is not without concerns. The main ones are:

- Increased travel distance for telecommuters in case of the location/relocation to outlying areas
- Potential increased non-work related travel.
- Less physical presence in the office

Research at Carleton University and elsewhere studied the role of telecommuting as a factor in employee decision to locate/relocate in outlying areas. There are of course other reasons as well (e.g., cost of housing, desire to have extra space, etc.). The Carleton University research showed that telecommuting is a significant factor in the residential location choice decision (Tayyaran and Khan 2007; Tayyaran, Khan and Anderson 2003; Tayyaran 2000).

A study by Mokhtarian (1999) found similar results. That is, it was found that a connection exists between telecommuting and relocations to distant communities. However, it should be noted that although telecommuting is not the only reason, it enhances the option of moving to a more distant location.

Therefore, in estimating benefits of telecommuting, the additional distance covered by telecommuters vis-à-vis non-telecommuters should be taken into account. Surveys show the acceptance of longer but infrequent commuting trips by actual and potential commuters (Tayyaran 2000). A related subject that should be discussed here is the concept of travel time budget. Past research found that commuters residing in various parts of the urbanized region may have a travel time budget and if they spend less time on their commuting trips during a week, they are likely to increase their non-work related travel.

However, there is much uncertainty surrounding the issue of the potential increase in non-

work related travel as a part of the concept of travel time budget. There is little evidence in the context of telecommuting that the reduction of vehicle-kms of travel achievable through telecommuting is completely offset by increase in off-peak non-work related travel. However, it would be prudent to discount benefits of telecommuting due to a possible increase in non-work related travel on telecommuting days.

6. LEVEL OF TELECOMMUTING

The information technology-assisted telecommuting has been noted in the literature as a transportation demand management strategy. It is seen by many policy experts as one of the most cost-effective measures to achieve sustainability in urban transportation. It has much potential in this regard, given that it can potentially reduce traffic congestion, conserve fuel, reduce greenhouse gases and improve air quality in urban areas (Transportation Climate Change Table 1999, ITE 1996).

The benefits of telecommuting, described in Section 4 have induced its acceptance by employees, employers and urban governments. On the policy and institutional front, significant developments have taken place in the U.S.A. For example, in November 1999, the U.S. Congress adopted and the president signed the National Telecommuting and Air Quality Act (Ritter and Beatty 2000).

A 2007 study of the National Science Foundation (USA) employees showed about one-third participation level (Telework Exchange 2007). In the USA, in 2007, about 3% of the total workforce telecommuted at least once a month (Rodrigue, et al 2009) and 4.2% of the overall US Federal government work force telecommuted.

 Some cities across Canada and the USA have included telecommuting as a demand management measure in their long term planning and expect that it would reduce peak period work trips. Transportation planners and policy analysts have been making an adjustment to transportation demand by recognizing a certain amount of substitution of telecommuting for travel. They expect that telecommuting will result in a reduction in the number of peak-hour trips due to fewer commutes. For instance, in the late 1990s, the Regional Municipality of Ottawa-Carleton in Ontario, Canada, included telecommuting as a transportation demand management measure in its transportation master plan. They expected that this measure alone would reduce peak hour work trips by 7% (ITE 1996).

As for future, there has been considerable optimism in developing forecasts. For example, according to Mitomo, Jitsuzumi and Ota (1996), in 2020, in Japan, 15% to 28% of total workforce will telecommute either from home or from satellite offices. In the case of Washington, D.C., a Brookings Institution study pointed out that there is evidence that telecommuting is likely to become larger and a more important aspect of the workplace (Dearborn 2002). According to an article published in the Urban Transportation Monitor (2000), Washington, D.C. area had set the goal of 20% telecommuting by 2005. In 2009, the General Services Administration (GSA) (USA) stated its goal to increase future participation

level to 50% (GSA 2007). Although telecommuting is seen as one of the most cost-effective measures to solve the urban area sustainability problem, policy and planning studies on telecommuting are scarce.

7. CASE STUDY OF NATIONAL CAPITAL AREA (CANADA)

A research study was carried out at Carleton University under the supervision of the author for the investigation of the impacts of telecommuting and related intelligent transportation systems (ITS) on land use patterns (Tayyaran 2000). The focus of the study was on households' residential location choice decisions so as to verify if telecommuting and ITS play a role in decentralization of land use.

To study these effects, discrete choice methodology within the well-developed random utility theory framework was adopted for model development. As a part of the research framework, combined revealed preference (RP) and stated preference (SP) logit analysis was performed to estimate the parameters of the utility function.

A part of the survey data collected and conclusions derived from the residential location choice decision models are used in the case study described here.

7.1 Attitude Survey

The required data were collected through an attitudinal survey of employees of selected private and public organizations within the multi-nucleated Ottawa region (Canada). Literature sources indicate that job type and human factors play a role in considering telecommuting (Belanger 1999). In addition to high technology industry employees, telecommuting is adopted by industries such as finance, consulting services, education and research, insurance, and retail (Mokhtarian 1992). Research also shows that both private and public sectors use telecommuting successfully. Therefore, it was decided to survey both sectors. The sampling process for each sector is explained next.

For the private sector, the simple random sampling method was applied, which is based on the use of random numbers. The private sector organizations that participated in the survey were within the following industries: high technology such as web design, software development, telecommunications, consulting services, finance, and research and education.

In the case of the public sector, it was found that there were a few organizations (six in total) in the Region who permitted telecommuting by some of their employees. All six organizations were requested to participate in the survey. Out of these, three agreed. Within these agencies, only those divisions where a telecommuting program was in effect participated in the survey. Although this approach did not provide us with a true random sample of all public agencies in the region, the method could be considered as quasi-

random sampling, since the employees within these organizations were surveyed randomly (Tayyaran 2000).

The final survey was carried out between August 1998 and February 1999. Although the survey was carried out some years ago, the information on attitudes is believed to be current for the purpose of this research. The survey consisted of three parts. Part one contained an introduction letter that outlined the purpose of the survey plus explanations about telecommuting. Part two contained questions about the respondent's housing choice, travel behaviour, employment, and demographic information. Part three contained the stated preference task.

7.2 Analysis of Survey Data

A total of 1252 surveys were sent out to private and public sector organizations. Of these, a total of 390 usable questionnaires were returned yielding an overall response rate of 31% (384 surveys were usable for RP analysis and 385 surveys were usable for SP analysis) (Tayyaran 2000). A part of the information collected is used here to model the decision to telecommute and to show the effects of telecommuting.

Most respondents were professional/technical persons. In general, they were engineers, analysts, computer programmers, etc. The sample consists of 25% telecommuters and 75% non-telecommuters. Males accounted for 54% of the sample and 75% were home owners.

Location of residence of respondents is shown in Table 4. Fifty-eight percent of respondents lived in the central area of the region, 25% resided in suburban first tier satellite communities and 17% lived in outlying second tier satellite communities. As compared to non-telecommuters, a higher percentage of telecommuters lived in outlying areas.

Table 4. Residence location of non-telecommuters and telecommuters

Location	Non-telecommuters	Telecommuters	Total
Central	172(60%)	51(53%)	223(58%)
Suburban (Tier 1 satellite)	72(25%)	24(24%)	96(25%)
Outlying (Tier 2 satellite)	43(15%)	22(23%)	65(17%)
	287(100%)	97(100%)	384(100%)

Table 5 presents selected transportation characteristics of the sample in aggregate terms. Mode of travel and average commute time data for telecommuters and non-telecommuters can be observed in Table 6.

It can be seen that automobile mode choice for telecommuters and non-telecommuters is roughly the same. But, telecommuters use public transit more than their counterparts whereas the reverse is true with respect to walk/cycle mode. Although not shown in the

table, the sample as a whole uses public transit more than the transit market share for the region.

Statistical analysis reported by Tayyaran (2000) indicates that:

- gender did not have an impact on the adoption of telecommuting by workers
- there is no significant difference between telecommuters and non-telecommuters with respect to their job category
- there is a significant difference between the two groups with respect to age -- the average age of telecommuters is higher than that of non-telecommuters.

Table 5. Sample characteristics

Item	Average for the sample
Vehicles/household	1.48
Vehicles/licenced driver	0.74
Average distance from residence to work (kms)	19.00
Average one-way commute time (minutes)	29.00
Average speed (km/h)	39.30

Table 6. Transportation characteristics of respondents

Travel to work Information	Non-telecommuters	Telecommuters	Total
Mode of travel:			
• Automobile	64%	62%	63%
• Public transit	24%	32%	26%
• Walk/cycle	12%	6%	11%
Average one-way commute time	28 min	32 min	29 min
Average one-way commute distance	18.6 km	21.0 km	19.0 km

Table 7 presents characteristics of respondents in terms of selected telecommuting variables. The average duration of telecommuting per week is 11 hours (equivalent to 1.57 days/week). This amounts to 30% of the work week. The average of years of participation in a telecommuting program is 2.9 years.

In response to a question on whether the survey participant ever contemplated moving or actually moved because of telecommuting, 13% of telecommuters said yes.

Forty-six percent of non-telecommuters indicated that their jobs are suitable for telecommuting. A very high percentage (69%) of this group stated that they would either definitely or probably telecommute if they were given the opportunity to do so. This shows an

interest among respondents in adopting telecommuting. However, the reader is cautioned that it does not necessarily imply that they would telecommute if they had the opportunity.

7.3 Saving Of Travel Time and Vehicle-Kms

The survey data and selected results of the Carleton University research in telecommuting and related ITS provide an opportunity to estimate travel distance and time savings. In turn, these are used to estimate fuel and GHG emission reduction attributable to telecommuting (please see Section 9 of this paper). The steps and assumptions are noted next.

Table 7. Telecommuting information

Item	Non-telecommuters	Telecommuters
Number in the sample	287 (75%)	97(25%)
Average number of hrs/week of Telecommuting	N/A	11 hours
Average duration of participation	N/A	2.9 years
Ever contemplated moving or actually moved because of telecommuting	N/A	13%
Suitability of job for telecommuting?		
Yes	46%	N/A
Not sure	17%	N/A
Whether or not telecommute if given the opportunity:		
Definitely or probability YES	69%	N/A
Not sure	15%	N/A
Definitely or probably NOT	16%	N/A

(1) Average telecommuting time/week is 11 hours. This amounts to 30% of a working week of 37 hours. Therefore, for a telecommuter, a 30 percent reduction in work trips can be achieved. If 25% of workers in the region telecommute, reduction in peak period work trips = 7.5%. If 10% of workers telecommute, peak period work trip reduction = 3%.

(2) On the assumption of automobile dependence and single occupancy, savings of vehicle-kms = (reduction due to less travel) - (additional vehicle kms due to extra distance covered by telecommuters). This is a realistic adjustment to vehicle-kms saved, given the decentralization effect of telecommuting. Telecommuters on the average travel an extra 2.4 kms/one way trip.

Prior to telecommuting vehicle-kms = (18.6 kms/one-way trip for non-telecommuters)(2)x(225 commuting days/year) = 8,370 veh-kms/year

Vehicle-kms after switching to telecommuting for 30% of work week
= (21 kms/one way commute)(2)(225)(1-0.3) = 6,615 veh-kms/year

Percent saving of vehicle-kms = [(8,370 - 6,615)/(8,370)]x100 = 21.0%

Please note that the acceptance of an additional 2.4 kms (or 4 minutes/trip) (average) by telecommuters as shown in Table 6 reflects a partial effect of the concept of travel time budget.

(3) It is realistic to make a further adjustment for the effect of travel time budget. Assume that 30% of the above computed saving for a telecommuter is offset by increased non-work type of travel. Therefore, percent saving becomes (21.0%)(0.7) = 14.7%

8. BAYESIAN MODEL OF TELECOMMUTING DECISION

The principles of statistical decision theory are used here to model the potential telecommuter's decision to identify the optimal choice in situations when the outcomes are not known with certainty. Bayesian decision making under risk and uncertainty involves probabilistic states-of-nature (e.g., states of traffic congestion) and gains/payoffs that have to be defined for the applicable actions (i.e., to telecommute or not) and states-of-nature combinations. It is a fundamental statistical approach that enables one to assess the probability of an event, given prior information. A very useful feature is that it adds much flexibility to decision analysis owing to the ability to update probabilities as a result of new information (Congdon 2006, Korb and Nicholson 2004).

8.1 Structuring the Decision-Making Problem

Modelling travel vs. telecommunication decision has been a subject of much challenge since the 1970s (Khan 1976). This is the first time that a Bayesian approach is being used to model the decision of a potential telecommuter whether to telecommute or not.

The potential telecommuter has three mutually exclusive decision alternatives under consideration (*A1, A2, and A3*), called terminal actions.
A1: Do-not telecommute
A2: Telecommute for 30% of the work hours per week
A3: Telecommute for 50% of the work hours per week.

These are characterized under three traffic condition scenarios ($\theta 1$, $\theta 2$, $\theta 3$), with the middle scenario $\theta 2$ to be considered the most likely one to occur.

$\theta 1$: Moderate traffic congestion during peak period

$\theta 2$: Congested traffic condition during peak period

$\theta 3$: Highly congested traffic condition during peak period

In the language of the statistical decision theory, these are called uncertain "states-of-nature". The states-of-nature listed above have the possibility of occurrence; but, after one of the mutually exclusive alternatives has been selected by the decision-maker, only one will be experienced. Due to the stochastic nature of the states-of-nature, probabilities have to be assigned to each state in the set of states-of-nature.

In this decision analysis problem, an experiment (i.e., a trial period of telecommuting) is under consideration. This information acquisition activity, called an experiment (e_1) is designed to obtain more information about the state of nature (i.e., traffic conditions) prior to the selection of an alternative *A*. The option of no experiment is designated as e_0. The set of outcomes/results of the experiment (i.e., experimental outcomes) are *z1, z2,* and *z3*. These correspond to *θ1, θ2, and θ3*, respectively. The option of not undertaking the experiment e_0 results in no new information z_0.

8.2 Evaluation of Telecommuting Alternatives

In concept, a number of factors can be defined for evaluating telecommuting alternatives from the perspective of an employee who has to decide whether to participate in a telecommuting program, if offered the opportunity by the employer. In such a situation, it is customary that the cost of the telecommunication services and the computer is borne by the employer. Therefore, from the perspective of a potential telecommuter, telecommuting can be credited with the following positive effects: travel time saving, travel cost saving, flexibility in balancing professional and personal lives, reducing job and commuting stress, increased productivity, etc.

On the negative side, employees who participate in telecommuting programs feel that lack of physical presence in the office even for a part of the working hours puts them at a disadvantage in terms of face-to-face interaction with colleagues and supervisors. According to Galt (2009), even for the most productive telecommuters, some "face time" is often necessary if they want to stay on the corporate radar.

A major challenge in the assessment of telecommuting alternatives is the task of quantifying their "gain", expressed by variable *g*. For a given *A&θ* combination, a number of "gain" factors (i.e., $g_1, g_2, \ldots g_m$) could be quantified in their original units or in qualitative terms. In this research, three "gain" variables were quantified. These are travel time saving, travel cost saving and "lack of physical presence in the office". It should be noted that the potential telecommuter wishes to maximize the gain variables of saving of travel time and travel cost. On the other hand, it is in the best interest of the employee to minimize the "lack of physical presence in the office" or in other words to maximize "face time".

For the alternative of no telecommuting (i.e., *A1*), under *θ1*, the average travel time is 28 minutes/one-way work trip (Table 6). On a weekly basis, the travel time amounts to 28 minutes/direction x 2 x 5 days/week = 280 minutes. Under *θ2,* the average speed of travel is 85% of average speed under *θ1* and this results in 33 minutes for one way travel time and 330 minutes for one week. Commuting in the *θ3* scenario is slower to that extent that the average speed becomes 75% of speed under *θ1*. The one way travel time is 37 minutes and 370 minutes for a week. Since Alternative *A1* does not involve telecommuting, the travel time saving is zero. For the same reason, travel cost saving is zero for *A1* under all traffic states.

Alternative *A2* calls for 30% reduction for a telecommuter's travel time and cost. Under *θ1,* a telecommuter on the average travels an additional 4 minutes due to residence location. So, one way travel time becomes 32 minutes and on a weekly basis, the travel time is (32x2x5)(1-0.3) = 224 minutes. The travel time reduction under *θ1* due to telecommuting is 320-224=96 minutes. It is assumed that 30% of this saving is lost to additional non-work travel that a telecommuter is likely to engage in. So, the travel time saving becomes 96(0.7) or 67 minutes.

For Alternative *A2*, under *θ2*, the additional travel time for a commuter is 4x(1/0.85) minutes and travel time saving due to 30% reduction in travel time amounts to 80 minutes per week. Under *θ3*, the additional travel time for a telecommuter is 4x(1/0.75) minutes and the weekly travel time saving is 88 minutes.

Alternative *A3* is based on 50% reduction in commuting travel time. The travel time saving per week due to telecommuting is 112 minutes, 133 minutes and 147 minutes under traffic states *θ1*, *θ2*, and *θ3,* respectively.

Saving of travel cost for each Alternative and traffic state (i.e., *A* & *θ*) combination exhibits the same relative position as travel time saving. The reason is that these savings are attributable to travel km reduction and driving conditions. Saving of parking charges may not materialize for two reasons. In the central business district, employees usually arrange a low rate yearly contract with a parking garage or a parking lot. Also, some employers provide parking spaces as an employment benefit.

The variable of "physical presence in the office" is quantified on a relative value (i.e., utility) scale of 0 to 1. Under *θ1*, *A1* is given 1.0 due to the absence of telecommuting. The *A2* and *A3* alternatives initially receive 0.7 and 0.5 in accordance with the extent of physical presence in the office. These relative value scores are adjusted under *θ2* and *θ3* according to time wasted in traffic jams which may result in less time spent in the office.

Next step is to transform the "effects" that are measured in diverse units into a relative value scale so that these can be weighted and then added. Since the physical presence in the office is estimated on the relative value scale, its values can be used directly. But, the travel time saving and travel cost saving have to be transformed from their original units of measurement into relative values, measured on the 0 to 1 relative value or utility scale.

The theoretical basis of scale transformation is described next. A methodology is used here that can treat evaluation factors or "effects" measured on diverse scales (e.g., time, dollars,

subjective ratings) into an overall value score for each alternative. This methodology, based on the principles of multi-attribute utility theory, enables the treatment of multiple "effects", differential weighting of "effects" and diminishing marginal utility property (if applicable).

Weights can be used as indicators of relative importance of the "effects". These weights can express the potential telecommuter's tradeoffs for saving travel time, travel cost, and absence from the office. The weights can be selected from a scale of 1 to 5, which is commonly used in psychological studies. These can be used as raw weights or can also be normalized. Logically, the decision- maker (i.e., the potential telecommuter) has to assign weights to "effects" of telecommuting.

As noted earlier, the levels of various "effects", originally measured in their raw units or in some cases expressed subjectively (e.g., excellent, very good, good, etc.), can be mapped on a relative value or utility scale of 0 to 1.0. A value function with the property of diminishing marginal utility property can be expressed as:

$$u(g) = L[q(g)]^k \quad \text{for } k<1 \tag{1}$$
where
$u(g)$ is the transformed value of a given g
$q(g)$ is the value of g expressed in its original units (e.g., time measured in minutes, cost measured in dollars, lack of physical presence expressed on a face-time expressed on a relative value scale)
L and k are constants.

In case of linear transformation:
$$u(g) = yq(g)+ b$$
where
y and b are constants

Another form of the linear transformation function that was used in this research is
$$u(g) = [q(g)/q(g_{max})]\times 1.0 \tag{2}$$
In this case, g_{max} is assigned the highest value, which is 1.0 and the $q(g)$ under consideration is found by the ratio as shown in equation 2. If the relative value scale used is from 0 to 100, then the above equation becomes $u(g) = [q(g)/q(g_{max})]\times 100.0$.

The "gain" elements can be weighted and then combined.
$$G = w_1u(g_1) +w_2u(g_2) + \ldots +w_mu(g_m) \tag{3}$$
where
G is the combined weighted gain.
w is a scale transformation on $u(g)$ – a relative "weight" reflecting the importance of "gain" g.

The unweighted utility matrix is shown in Table 8. It can be seen that the scores for physical presence in the office are adjusted under *θ2 and θ3* to take into account time wasted in traffic jams. Three scenarios of relative weights were considered and the weighted utilities are presented as three versions of the gain matrix *G(e, z, A, θ)*.

A *gain* matrix represents the value for the course of action defined by *e, z, A, θ* combinations. In accordance with the principles of utility theory, it is assumed that the gains *G(e,z)* and *G(A,θ)* are additive. In this paper, a *G(A,θ)* matrix is used and *G(e,z)* is kept as a variable that is internal to the computation process since no monetary cost is assigned to the experiment. For a comprehensive analysis of the decision problem including the sensitivity analysis, three versions of the *G(A, θ)* matrix are presented as Table 9. On the scale of 1 to 5, the travel time saving was assigned weights of 2,1, and 1 in gain matrix version 1,2, and 3, respectively. Travel cost was given a weight of 1 in all three gain matrix versions. The "office presence" received weights of 5, 5, and 4 in gain matrix versions 1,2, and 3. It should be noted that these weights are used for sensitivity analysis purposes. If the methodology reported in this paper is applied to another case study, the analyst can apply different weights.

We are interested in finding the best course of action. This involves determining the best action and the expected value of information using the probability distributions over the possible states-of-nature. However, to find these answers, a joint probability *P(θ,z|e)* must be assigned to the joint distribution of *θ, z,* for each experiment *e*. This requires the reliability of each possible outcome to be defined for the prediction of the true state-of-nature. In doing so, four other probability measures are determined. These are: prior probability {*P'(θ)*}, conditional probability {*P(z|θ,e)*}, marginal probability {*P(z|e)*}, and posterior probability {*P''(θ|z,e)*}.

Table 8. Effectiveness of Alternatives (relative value unit on a scale of 0 to 1) (unweighted)

	θ1 *Moderate peak period congestion*	*θ2* *Congested peak period*	*θ3* *Very congested peak period*
Alternative *A1* (0% telecommuting time)			
Travel time savings	0	0	0
Travel cost savings	0	0	0
Physical presence in the office	1.0	0.85	0.75
Alternative *A2* (30% telecommuting time)			
Travel time saving	0.46	0.54	0.60
Travel cost saving	0.46	0.54	0.60
Physical presence in the office	0.70	0.60	0.53
Alternative *A3* (50% telecommuting time)			
Travel time saving	0.76	0.90	1.00
Travel cost saving	0.76	0.90	1.00
Physical presence in the office	0.50	0.43	0.38

The probability distributions of *P'(θ)* and *P(z|θ ,e)* provide a starting point for the estimation of the joint probability measure *P(θ,z|e)* for each information acquisition activity *e.* The *P'(θ)* represents the decision maker's judgment about the relative likelihood of values of *θ*, and *P(z|θ,e)* characterizes each information acquisition activity and is the probability that the outcome *z* will be observed if the experiment *e* is performed and *θ* is the state-of-nature.

Table 9. Gain matrix *G(A, θ) (relative value units)*

	θ1	θ2	θ3
Version 1			
A1	5.00	4.25	3.75
A2	4.88	4.62	4.45
A3	4.78	4.85	4.99
Version 2			
A1	5.00	4.25	3.75
A2	4.42	4.08	3.85
A3	4.02	3.95	3.90
Version 3			
A1	4.00	3.40	3.00
A2	3.72	3.48	3.32
A3	3.52	3.52	3.52

8.3 Solving the Telecommuting Decision Problem

The basic data of the decision problem can be represented by a sequence of experiment, outcome, action, and state of nature. The desirability of that sequence or course of action (*e, z, A, θ*) or (*e_0, z_0, A, θ*) is completely described by the gain matrix *G(e, z ,A, θ)* or *G(A, θ)*.

Given the prior probability and the conditional probability, the marginal probability can be computed as follows:

$P(z|e) = \sum P'(\theta)P(z|\theta,e)$ (4)

The posterior probability is computed using the Bayes theorem:

$$P''(\Theta | z, e) = \frac{P'(\Theta)\, P(z|\Theta, e)}{\sum P'(\Theta)\, P(z|\Theta, e)}$$ (5)

The assumption is that each experiment option (*e_0, e_1*) can be characterized by a conditional probability of *P(z|θ,e)*, such that the relationship between the prior and posterior probabilities is as given by the Bayes Theorem.

In order to find the optimal course of action, an extension of this analysis is required. This involves determining a relative value of gain with each combination (i.e. *G (e, z, A, θ)*). The

gain matrix *G(e,z,A,θ)* represents the decision maker's preferences for all *e,z,A,θ* combinations.

The sequence of a course of action is as follows. The decision maker selects an information acquisition activity *e*, observes a result *z*, selects a particular *A*, and then a particular state of nature, *θ*, occurs.

The gain functions should reflect the value structure of the decision maker (i.e., the potential telecommuter). For this reason, it is not possible to generalize the characteristics of these functions. Depending on circumstances, in some cases, the diminishing marginal gain property may be applicable. In other cases, step functions (with well defined threshold values) may be relevant. Owing to much diversity in the estimation of gain functions, it is left up to the evaluator or analyst to estimate or acquire the applicable gain values.

The expected gain for each act *A*, for each (experiment, outcome) combination can be found as follows.

$$G^*(A,z,e) = \sum \text{for all } \theta \ (P''(\theta|z,e).[G(e,z,A,\theta)] \tag{6}$$

In the case of no experiment, $G^*(A,z_0,e_0) = \sum \text{for all } \theta \ P''(\theta|z_0,e_0).[G(e_0,z_0,A,\theta)]$

For each (experiment, outcome) combination, an optimal act and its associated maximum gain are found.

$$G^*(z,e) = Max_A \ G^*(A,z,e) \tag{7}$$

For each *e*, the expected gain can be found:

$$G^*(e) = \Sigma_z \ [P(z|e) \ G^*(z,e)] \tag{8}$$

If more than one experiment is to be performed, the optimal experiment is that for which *G*(e)* is maximum.

$$G^*(e^*) = Max_e \ G^*(e) \tag{9}$$

8.4 Value of Information from Trial Period

If the optimal experiment turns out to be any result other than the 'null' one, it could be of interest to know the value of information acquired. This involves determining the increase in the optimal gain which would result for each *z* if the prior choice of terminal action *A* was altered after posterior information was attained.

In operational terms, the expected gain of the optimal alternative under posterior information (*A_z*) is to be subtracted from the expected gain of the optimal alternative under prior probabilities (*A'*). Or,

$$V_t{}^*(e) = \Sigma_z P(z|e) \, [\Sigma_\theta \, P''(\theta|z,e) \, G_t(A_z,\theta) - \Sigma_d \, P''(\theta|z,e) \, G_t(A',\theta)] \qquad (10)$$

Where $V_t{}^*(e)$ is the value of information and subscript "*t*" refers to the terminal gain in terms of the optimal course of action.

It should be noted that the expected terminal gain of a particular experiment is the expected terminal gain of an immediate terminal action plus the expected value of information obtained from the experiment. This can be expressed in equation form as shown below.

$$G_t{}^*(e) = G_t{}^*(e_0) + V_t{}^*(e) \qquad (11)$$

Now, the expected net gain of information acquisition is therefore determined to be the expected value of new information less the expected cost of obtaining it. In equation form:

$$v^*(e) = V_t{}^*(e) - c_s{}^*(e) \qquad (12)$$

where,

$$c_s{}^*(e) = G_s{}^*(e) = \sum_z P(z|e) \, G_s(e, z) \qquad (13)$$

From the above, it can be inferred that the expected cost of the telecommuting experiment in relative value units should not exceed the expected value of information $V_t{}^*(e)$.

8.5 Bayesian Methodology Application

The Bayesian methodology was applied to the telecommuting decision problem as follows. First, the prior probability distributions were specified as shown in Table 10. Experience of traffic engineers points in the direction of the use of the normal probability distribution function for the states of traffic congestion.

Further, the amount of deviation from the mid point that is commonly observed in the data suggests a standard normal deviate equal to 1. Therefore, these were used as a basis to specify prior probabilities. Alternatively, discrete prior probability distributions can be specified subjectively.

The conditional probabilities, which represent reliability of the experiment (i.e., the trial telecommuting period), shown in Table 10 were assigned on the basis of experience with traffic studies in general. The posterior probabilities and marginal probabilities were computed by using equations noted above. These results are shown in Table 11.

The decision problem was solved by using the probabilities (presented in Table 11) and the gain matrix shown in Table 9. Table 12 presents the results of posterior and pre-posterior analysis. The telecommuting alternative *A3* turns out to be the choice when gain matrix versions 1 and 3 are used. These are based on favourable weights assigned to travel time saving or slightly reduced weights given to office presence. From a behavioural perspective,

these results appear logical. The value of information results show the $V_t^*(e)$ to be positive. Therefore, an experiment can be carried out.

Table 10. Input probabilities

Prior probability P'(θ)		Conditional probability $P(z\|\theta,e)$			
			$\theta 1$	$\theta 2$	$\theta 3$
P'($\theta 1$)	0.16	z1	0.7	0.15	0.1
P'($\theta 2$)	0.68	z2	0.2	0.7	0.2
P'($\theta 3$)	0.16	z3	0.1	0.15	0.7
	1.00		1.0	1.0	1.0

Table 11. Computed probabilities

Marginal probability P(z|e)		Posterior probabilities $P''(\theta\|r,e)$				
			$\theta 1$	$\theta 2$	$\theta 3$	Sum
z1	0.23	z1	0.487	0.443	0.070	1
z2	0.54	z2	0.059	0.882	0.059	1
z3	0.23	z3	0.070	0.443	0.487	1
	1.00					

Table 12. Bayesian analysis results

Prior branch, e_0	Posterior branch, e_1	Value of Information
Gains Matrix Version 1		
Optimal decision: A3	Optimal decison under:	Vt* +ve
	z1: A3	
	z2: A3	
	z3: A3	
Gains Matrix Version 2		
Optimal decision: *A1*	Optimal decison under:	Vt* +ve
	z1: A1	
	z2: A1	
	z3: A1	
Gains Matrix Version 3		
Optimal decision: *A3*	Optimal decison under:	Vt* +ve
	z1: A1	
	z2: A3	
	z3: A3	

9. FUEL AND EMISSION EFFECTS

Analyses presented in Sections 7 and 8 show that telecommuting saves travel time, travel cost, and vehicle-kms. The level of telecommuting reviewed in Section 6 points out a wide range of 3 to 33 percent, depending on the location, employment sector and enthusiasm of the employer. The case study of telecommuting carried out in the National Capital Region (Canada), presented in Section 7 shows that 25% of the sample were telecommuters and if given the opportunity, 69% of non-telecommuters would either definitely or probably participate in a telecommuting program.

The Bayesian model presented in Section 8 shows that under high and very high traffic congestion conditions and if the human factors are favourable, the telecommuting option will be acceptable to an employee.

Forecasts of the level of telecommuting presented in Section 6 suggest that under well defined traffic and human factor conditions, for the job types defined in this paper and with strong employer support, a substantial proportion of commuters will telecommute. Of course it is assumed that public policy has to be supportive.

Considering the above information, particularly the results of the Bayesian model and assuming favourable conditions, it is likely that 10% to 20% of commuters will telecommute in the future. Going forward with this range, next we estimate the corresponding reduction in fuel consumption and greenhouse gas emissions.

 It was found in Section 7 that 14.7% saving of vehicle-kms can be achieved due to telecommuting. For 25% telecommuters out of total workers, saving of vehicle-kms=(0.25)(14.7%) = 3.7%. For 10% telecommuting level in the region, saving of vehicle-kms=(0.1)(14.3%) = 1.4%.

Saving of fuel and reduction of greenhouse gas emissions are directly proportional to a reduction in vehicle-km of travel. As a result of fuel consumption, emissions are produced. In addition to other emissions, the following GHG emissions result from the combustion of petroleum fuels. The GHG emissions of interest are: carbon dioxide (CO_2), methane (CH_4), and nitrogen oxide (N_2O). The magnitudes of these emissions per litre of fuel vary by type of fuel, engine and emission control technologies. In order to find the CO_2 equivalent of these gases, equivalency factors are used which reflect their relative long term greenhouse effect. The equivalency factors are 1 for CO_2, 21 for CH_4, and 310 for N2O.

The overall relationships between vehicle-kms, fuel consumption and GHG emissions are shown below.

Fuel Consumption (litres) = Vehicle-kms x (Fuel Consumption/Vehicle-km)   (14)

GHG Emission Factor (million tonnes/giga litre) =
    $\sum$(Emission Level)x(CO_2 Equivalency)]   (15)

GHG Emissions (million tonnes) =
    (giga litres of fuel consumed)x(GHG Emission Factor)   (16)

In this study, we are not estimating the absolute magnitudes of vehicle-kms, litres of fuel and tones of GHG emissions. Our interest is in percent reduction as shown in Table 13.

Table 13. Fuel consumption and GHG emission reduction

	25% of workers Telecommute	10% of workers Telecommute
Reduction in peak-period work trips	7.5%	3.0%
Fuel consumption and greenhouse gas emission reduction*	3.7%	1.4%

 * Assumption: 30% of vehicle-kms saved due to telecommuting are offset by increased non-work travel due to the effect of travel time budget

10. CONCLUSIONS AND POLICY IMPLICATIONS

Telecommuting has the potential to contribute to urban sustainability. However, this potential cannot be realized unless conditions favourable to telecommuting are created. In multi-nucleated urban regions, favourable conditions can be achieved with the policy of offering telecommuting incentives, should potential telecommuters decide to locate or re-locate in satellite communities. These incentives can take the form of ensuring the availability of broad band network, as visualized by the City of Ottawa's strategic plan.

Employer-initiated telecommuting program is the pre-requisite for telecommuting. Also, a potential telecommuter has to perceive the benefits of telecommuting under prevailing circumstances, including traffic congestion, which plays a role.

Given that telecommuting is a significant factor in the residential location choice decision, therefore, in estimating benefits of telecommuting, the additional distance covered by telecommuters vis-à-vis non-telecommuters should be taken into account. Likewise, benefits of telecommuting should be discounted somewhat owing to the effect of the concept of travel time budget. This was done in the case study reported in this paper.

On the basis of the case study presented in this paper, it can be concluded that at 25 percent level of telecommuting, 3.7% saving of fuel and reduction of greenhouse gas emissions can be achieved. At 10% level of telecommuting, 1.4% reduction in fuel consumption and GHG emissions can be attained. This level of fuel saving and GHG emissions reduction is significant, given that telecommuting is only one of the many initiatives for energy conservation and GHG emission reduction.

Methods for estimating the extent of telecommuting require refinement. This calls for new research on the substitution of telecommuting for travel to work.

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