A Spatially Disaggregated Approach to Commuting Efficiency

Michael A. Niedzielski

Summary. During the past two decades, the concept of commuting efficiency has been used to evaluate the relationships between the journey to work and land use at the regional scale. The common approach of calculating regional statistics masks the intraurban variation of commuting efficiency. This paper develops an alternative approach to commuting efficiency and spatial structure assessments based on spatial disaggregation. The extension of existing regional measures by estimating zonal average trip lengths for workers leaving home and employers attracting workers facilitates analysis of intrametropolitan commuting efficiency. Spatially disaggregated metrics are formulated and applied to journey-to-work data for the cities of Warsaw, Poznań, Łódź and Kraków in Poland. At the regional scale, excess commuting varies from 48 per cent (Warsaw) to 67 per cent (Łódź). Intraurban variations in excess commuting indicate that estimates of commuting efficiency are impacted by the jobs–housing balance and are sensitive to locations of zones within the study area.

Introduction and Purpose

The work commute is a means by which urban residents engage in one of the fundamental activities of modern life. Income-generating employment allows them to sustain the necessities of everyday life and to pursue leisure-related activities. The journey to work is an important and unavoidable part of the modern economic system and its intensity may be viewed as a sign of the economic vitality of a region. When the intensity of work trips and their distance reach a critical level, urban areas are confounded by problems such as urban sprawl, congestion, pollution and social costs. If residents could exchange home or job locations with each other to minimise the work commute, many of the negative externalities could be dramatically reduced or even eliminated.

The idea of commuting efficiency is to compare observed and theoretical commuting patterns by evaluating the spatial relationships between residential and employment locations, thus relating the journey to work to issues of urban commuting, accessibility, spatial mismatch and sustainability (Horner, 2004). Urban area workers engage in commuting and their commuting behaviour is quantified by the observed average trip length, whereas under the commute minimisation strategy their commuting behaviour is expressed by the transportation-problem-derived minimum average trip length. The difference between the observed and theoretical average trip lengths is known as excess commuting.
Excess commuting quantifies the fact that workers engage in work travel patterns above the minimum work travel pattern, based on the urban composition of residences and workplaces (Hamilton, 1982; Small and Song, 1992; White, 1988).

In this context, the excess commuting framework has been used to evaluate the efficiency with which urban residents travel to work at the city or regional scale. Armed with findings often indicating potential for reductions in commuting, analysts propose solutions for more sustainable commuting patterns, primarily focusing on multiuse communities, where jobs and housing are balanced. The effectiveness of the jobs–housing balance policy in reducing commuting is supported by some (Cervero, 1991; Sultana, 2002) and questioned by others (Giuliano and Small, 1993; Levine, 1998). Further exploration of this issue requires investigation of commuting data at the intrametropolitan scale.

Standard analyses to date of excess commuting and land-use-related topics report a single regional efficiency statistic. Regional measures of excess commuting provide limited information, summarising commuting efficiency and the jobs–housing balance for the urban region as a whole (Horner, 2002). Consideration of zonal commuting efficiency allows analysis of the relationship between the journey to work and urban structure in greater spatial detail. The spatially disaggregated commuting efficiency approach can answer basic questions such as ‘How far on average does each zone send (or receive) workers?’ or ‘Do workers from one urban area commute more efficiently than workers from another part of town?’ For example, the common perception maintains that suburban residents commute less efficiently than inner-city residents.

The next section of this paper provides a review of the commuting efficiency literature and introduces spatially disaggregated measures of journey-to-work efficiency. This is followed by the description of the data used in the analyses and the presentation of results obtained by the application of the new metrics on commuting data from Poland. Finally, a discussion and conclusions are provided.

**Literature Review**

The relationship between commuting and land use has been studied from three broad perspectives. One group of jobs–housing balance oriented researchers strives to link the spatial distribution of homes and jobs with commute duration. Some studies suggest that a balance of homes and jobs promotes shorter commutes to work (Cervero, 1989; Giuliano and Small, 1993; Horner, 2002; Levinson, 1998; Peng, 1997; Sultana, 2002). The policy implication is that proximally located residential and employment locations reduce journey-to-work lengths and increase sustainability (Cervero, 1989). However, dramatic increases in personal mobility have meant that improved personal choices interfere with the effectiveness of policies promoting mixed-use development and increase in commuting efficiency (Giuliano, 1991; Levine, 1998). The connection between individual location decisions and the work commute is the focus of the second research agenda. The impact of policies aimed at decreasing the spatial separation between homes and jobs is assessed through excess commuting estimates (Giuliano and Small, 1993; Kim, 1995; Levine, 1998; Merriman et al., 1995). Large excess commuting estimates indicate a weak connection between commuting and location decisions, with the implication that policies improving the jobs–housing balance would not be successful in reducing commute lengths, whereas the opposite interpretation is extracted from small excess commuting estimates. Recently, Chen (2000) has called into question this ‘all or nothing’ interpretation. The impact of job–housing balance policies on commuting depends on the type of urban structure (Chen, 2000). Alternatively, excess commuting results are used to measure the commuting efficiency of an urban region (Buliung and Kanaroglou, 2002; Horner, 2002; Scott et al., 1997).
Given the fixed spatial structure of homes and jobs, the efficiency with which residents commute to work is estimated for purposes of intermetropolitan comparisons (Frost et al., 1998; Horner, 2002) or for simulations of various policy scenarios (Horner and Murray, 2003; Merriman et al., 1995).

Recent research activity into the concept of excess commuting—or, more broadly, commuting efficiency—is based on the work of Hamilton (1982) who tested the ability of the urban economic model of monocentricity to predict journey-to-work patterns. Motivated by the deficiencies of Hamilton’s (1982) approach (flawed definition of excess commuting and unrealistic representation of urban form), White (1988) explicitly includes the spatial distribution of residential and employment locations and adapts the linear programming optimisation technique introduced by Hitchcock (1941) to the estimation of the minimum trip length. Given the observed location of supply and demand, the linear programming formulation solves for the optimal distribution of trips from origins to destinations, such that total system cost is minimised and all demand is satisfied. The theoretical minimum and maximum average journey-to-work trip lengths are calculated using the following transport problem formulations

\[
T_{\text{min}} = \min \frac{1}{W} \left( \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} x_{ij} \right) \tag{1a}
\]

\[
T_{\text{max}} = \max \frac{1}{W} \left( \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} x_{ij} \right) \tag{1b}
\]

Subject to

\[
\sum_{j=1}^{m} x_{ij} = D_j \quad \forall j = 1, \ldots, m \tag{2}
\]

\[
\sum_{i=1}^{n} x_{ij} = O_i \quad \forall i = 1, \ldots, n \tag{3}
\]

\[
\text{where, } i = \text{index of origin zones}; \ j = \text{index of destination zones}; \ n = \text{number of origin zones}; \ m = \text{number of destination zones}; \ O_i = \text{number of workers living in zone } i; \ D_j = \text{total employment in zone } j; \ C_{ij} = \text{travel costs between zone } i \text{ and zone } j; \ x_{ij} = \text{journey-to-work trips from zone } i \text{ to zone } j; \text{ and } W = \text{total number of commuters.}
\]

The objective function (1a) minimises or (1b) maximises average commuting costs, where the inclusion of the total number of commuters \((W)\) results in average work-trip costs rather than total work-trip costs. Constraint (2) ensures that all employment demand is satisfied, while constraint (3) limits the supply of workers to the number residing in each zone. Non-negativity constraints for the decision variables are maintained by constraint (4). Since zones are simultaneously origins and destinations, the number of origins, \(n\), is equal to the number of destinations, \(m\). The impedance factor, \(C_{ij}\), is expressed as the travel time, network travel distance or Euclidean travel distance between zone centroids (Frost et al., 1998; Giuliano and Small, 1993). For complete details of uncertainties surrounding excess commuting estimates due to the modifiable areal unit problem (MAUP), the reader is referred to Horner and Murray (2002). Concise overviews of the development of the concept of commuting efficiency and analytical findings are found in Frost et al. (1998), Horner (2002) and Rodriguez (2004).

Mathematically, regional excess commuting \((E)\) is the difference between the regional average observed trip length \((T_{\text{obs}})\)—i.e. the non-optimal work trip distribution—and the regional minimum average trip length \((T_{\text{min}})\)—i.e. the optimal journey-to-work pattern when workers exchange home or job location to minimise regional commuting costs. This deviation is expressed as a percentage of the regional observed trip length

\[
E = \left( \frac{T_{\text{obs}} - T_{\text{min}}}{T_{\text{obs}}} \right) \times 100
\]

A normalised version of regional excess commuting incorporates the regional maximum average commute \((T_{\text{max}})\) as the upper limit.
to commuting (Horner, 2002) and is given by
\[ C_u = \left( \frac{T_{obs} - T_{min}}{T_{max} - T_{min}} \right) \times 100 \]

The fundamental unit of analysis in commuting research is a sub-regional zone, such as the traffic analysis zone (TAZ) or the census block. Other transport and land-use-related studies utilise the journey-to-work data disaggregated by zone that is found in the Census Transport Planning Package (CTPP) to evaluate intraurban or interzonal (i.e. at the sub-regional scale) variations of accessibility (Horner, 2004; Wang, 2000) or the jobs–housing balance (Horner and Murray, 2003; O’Kelly and Lee, 2005; Peng, 1997; Sultana, 2002). Few excess commuting studies have addressed the sub-regional or intraurban variation in commuting efficiency, despite the zonal format of available travel data. Giuliano and Small (1993) identify variations in commuting for 8 sub-areas and 32 large employment centres in the Los Angeles metropolitan area. Chen (2000) analyses excess commuting for 30 municipalities in the Taipei metropolitan region. However, a systematic region-wide intraurban analysis of commute generator and commute attractor variation in efficiency at a more local level is not attempted. However, the process of calculating zonal estimates of commuting efficiency from the transportation-problem-derived predictions is straightforward and is presented in the following section.

**Developing the Spatially Disaggregated Approach**

There are two outputs from the application of linear programming to the optimisation of work travel: the regional trip length and the optimised journey-to-work matrix. The former is used to calculate regional efficiency metrics (Horner, 2002; Small and Song, 1992). The latter is the building block of the spatially disaggregated framework for the analysis of intrametropolitan differences. The theoretical maximum journey-to-work matrix (\(X_{ij}^{\text{max}}\)), observed work travel matrix (\(X_{ij}^{\text{obs}}\)) and theoretical minimum spatial interaction matrix (\(X_{ij}^{\text{min}}\)) along with the cost matrix (\(C_{ij}\)) are used in the calculation of the intrametropolitan commuting efficiency components (Table 1).

The spatially disaggregated approach allows commuting patterns to be analysed from the two ends of the work trip. It is now possible to investigate the lengths of work trips for workers leaving their homes and the distance of workers attracted to employers. For workers, commuting cost is a major factor in the process of matching home and job locations, although non-transport factors are important, too. Thus, excess commuting measures the savings possible, if journey-to-work lengths are reduced. For employers, the importance of the commute distance of employees is vastly overshadowed by the need to attract an appropriate workforce. Therefore, deficit commuting is proposed as a measure that reduces the importance of commuting efficiency in the process of matching workers to jobs.

The value of calculating deficit commuting is as follows (Figure 1). The line segment

<table>
<thead>
<tr>
<th>Table 1. Spatially disaggregated average trip lengths</th>
</tr>
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<tbody>
<tr>
<td><strong>Origin-specific</strong></td>
</tr>
<tr>
<td>(5) Minimum (O_{i}^{\text{MIN}}) = ( \sum_{j} X_{ij}^{\text{MIN}} C_{ij} ) / ( \sum_{j} X_{ij}^{\text{MIN}} ) = ( \sum_{j} X_{ij}^{\text{MIN}} C_{ij} ) / ( O_{i} )</td>
</tr>
<tr>
<td>(6) Observed (O_{i}^{\text{OBS}}) = ( \sum_{j} X_{ij}^{\text{OBS}} C_{ij} ) / ( \sum_{j} X_{ij}^{\text{OBS}} )</td>
</tr>
<tr>
<td>(7) Maximum (O_{i}^{\text{MAX}}) = ( \sum_{j} X_{ij}^{\text{MAX}} C_{ij} ) / ( \sum_{j} X_{ij}^{\text{MAX}} ) = ( \sum_{j} X_{ij}^{\text{MAX}} C_{ij} ) / ( O_{i} )</td>
</tr>
<tr>
<td><strong>Destination-specific</strong></td>
</tr>
<tr>
<td>(8) Minimum (D_{j}^{\text{MIN}}) = ( \sum_{i} X_{ij}^{\text{MIN}} C_{ij} ) / ( \sum_{i} X_{ij}^{\text{MIN}} ) = ( \sum_{i} X_{ij}^{\text{MIN}} C_{ij} ) / ( D_{j} )</td>
</tr>
<tr>
<td>(9) Observed (D_{j}^{\text{OBS}}) = ( \sum_{i} X_{ij}^{\text{OBS}} C_{ij} ) / ( \sum_{i} X_{ij}^{\text{OBS}} )</td>
</tr>
<tr>
<td>(10) Maximum (D_{j}^{\text{MAX}}) = ( \sum_{i} X_{ij}^{\text{MAX}} C_{ij} ) / ( \sum_{i} X_{ij}^{\text{MAX}} ) = ( \sum_{i} X_{ij}^{\text{MAX}} C_{ij} ) / ( D_{j} )</td>
</tr>
</tbody>
</table>
$D_j^{\text{MAX}} - D_j^{\text{OBS}}$ represents deficit commuting, the unused portion of the commuting capacity or the commuting deficit from the maximum work travel pattern. While the scenario of short-distance work trips—where employment demand is satisfied by workers residing in proximity to the job site—is ideal, the traditional excess commuting definition of deviation from the minimum trip length penalises employment locations for their success in attracting workers. Large deviation from the optimal is considered inefficient based on the standard definition, but from the destination perspective this may be seen as efficient due to agglomeration effects. The positive effects of clustering may produce longer work trips than necessary but this is a desired side effect of the clustered location of economic activity. Therefore, as $D_j^{\text{MAX}} - D_j^{\text{OBS}}$ increases relative to maximum average commute, $D_j^{\text{MAX}}$, employers are able to satisfy their demand for workers as well as approach the most efficient work travel pattern. Applying this concept to the sub-regional level, the degree to which workers attracted by employers deviate from the maximum amount of travel is a valuable approach in benchmarking the trade-off between commuting distance and worker-attraction success. Moreover, this new definition of deficit commuting is consistent with the concepts of growth pole effects and economies of scale and agglomeration economies.

The spatially disaggregated commuting efficiency components derived by equations (5)–(10) in Table 1 are used to develop the intrametropolitan versions of excess

![Figure 1. Spatially disaggregated approach to commuting: excess commuting and deficit commuting.](image-url)
commuting and capacity used metrics (Table 2). Quantitatively, each statistic is the difference between the observed zonal average commute and the minimum zonal average commute \((E_i^O, C_i^O)\) or the maximum zonal average commute \((E_j^D, C_j^D)\). These differences are expressed as a percentage of the observed \((E_i^O)\) or maximum zonal average commute \((E_j^D)\) or the zonal commuting potential range \((C_i^O, C_j^D)\).

To clarify, the spatially disaggregated approach to commuting efficiency involves two steps. First, linear programming is used to estimate the regional minimum and maximum commute flow matrices. Secondly, equations (5)–(14) are used to calculate zonal average trip lengths and zonal commuting efficiency metrics. The main idea is that the zonal measures are calculated using the LP predicted theoretical flow patterns and the distance matrix. Therefore, the intraurban commute metrics (5)–(10) are based on the flow patterns optimised for the entire region as a whole incorporating residential and employment competitor effects.

**Data Selection**

To date, most research involving the analysis of work travel patterns in Poland has been focused on single regions with the goal of identifying regional commuter sheds, such as the Warsaw Province (Bergel, 1987; Potrykowska, 1983; Rakowski and Gocał, 1989), the Katowice Province (Runge, 1988), the Łódź Province (Jakóbczyk-Gryszkiewicz, 1991; Michalski and Pasikowska, 1991) and the Olsztyn Province (Rakowski and Gocał, 1990), on industrial towns to examine the effects of large industrial plants on commuting (Dziadek, 1981; Gocał, 1992; Marczyńska-Witczak and Michalski, 1983) and on the objective of delineating urban functional regions at the national scale by identifying commuting hinterlands and commuting hierarchies (Korcelli et al., 1981). One exception is the work of Dzieciuchowicz (1979) and his analysis of the journey to work at the urban scale in the city of Łódź, although commuting efficiency was not the focus of his research. However, during the 1990s, major cities in Poland performed traffic surveys that provide origin–destination commuting flows allowing the analysis of interurban and intraurban commuting patterns.

Every major metropolitan government in Poland collects origin–destination flow data for local transport planning, the dissemination of which is channelled through a planning package known as the Comprehensive Traffic Survey (CTS) (Kompleksowe Badanie Ruchu, KBR). Given the fact that the data are collected and maintained by various agencies, the compilation of commuting data from cities in

<table>
<thead>
<tr>
<th>Table 2. Spatially disaggregated commuting efficiency metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Origin-specific</strong></td>
</tr>
<tr>
<td>(11) Excess commuting (E_i^O = \left(\frac{O_i^{OBS} - O_i^{MIN}}{O_i^{OBS}}\right) \times 100)</td>
</tr>
<tr>
<td>(13) Capacity used (C_i^O = \left(\frac{O_i^{OBS} - O_i^{MIN}}{R_i^O}\right) \times 100 = \left(\frac{O_i^{OBS} - O_i^{MIN}}{O_i^{MAX} - O_i^{MIN}}\right) \times 100)</td>
</tr>
<tr>
<td><strong>Destination-specific</strong></td>
</tr>
<tr>
<td>(12) Deficit commuting (E_j^D = \left(\frac{D_j^{MAX} - D_j^{OBS}}{D_j^{MAX}}\right) \times 100)</td>
</tr>
<tr>
<td>(14) Capacity remaining (C_j^D = \left(\frac{D_j^{MAX} - D_j^{OBS}}{R_j^D}\right) \times 100 = \left(\frac{D_j^{MAX} - D_j^{OBS}}{D_j^{MAX} - D_j^{MIN}}\right) \times 100)</td>
</tr>
</tbody>
</table>
Poland presents challenges. Nonetheless, several factors are important for the selection process of study cities. First, a city is considered for inclusion in the study if it has recently collected data on journey-to-work interaction as part of the CTS package of transport systems data. Datasets collected before 1998, the year of the most recent CTS undertaken in Warsaw, are not considered. Secondly, cities are selected in such a manner that the methodology of calibration of journey-to-work matrices is consistent among the cities. Thirdly, cities are selected if the journey-to-work interactions recorded in the matrices are representative of commuter sheds. Those datasets that record only the commuting interactions of a single city being part of a conurbation are not included in this research. Thus, fairly recent data from Gdańsk and Katowice are excluded. Based on these criteria, the cities of Warsaw, Poznań, Łódź and Kraków are selected for inclusion in this research. The data in the CTSs from these four cities have been collected within the past seven years, are based on consistent methodology and refer to single commuting sheds (Biuro Inżynierii Transportu, 2000; Biuro Planowania Rozwoju Warszawy S.A., 1998, 2000; Pracownia Badań Społecznych, 2003). The use of only those CTSs representative of commuter sheds is consistent with other research (Giuliano and Small, 1993; Horner, 2002; Scott et al., 1997).

### Analytical Results

#### Regional Commuting Efficiency

For comparative purposes, traditional excess commuting analyses are performed at the regional level on a selection of four major cities in Poland (Table 3). Excess commuting \((E)\) for the sample of cities varies from 48 per cent (Warsaw) to 67 per cent (Łódź), falling within the bounds (11–88 per cent) established by White (1988) and Small and Song (1992). The results of the analyses for Warsaw and Poznań confirm that geographical boundary variations influence estimates of the minimum commute and commuting efficiency. For the Warsaw and Poznań agglomerations, the minimum required commute (5 km and 3.5 km respectively) is much higher than the minimum required commute when boundary-crossing trips area excluded (2.4 km and 2.2 km respectively). When only intracity work trips are taken into consideration, decreases in the optimised trip lengths lead to an increase in the proportion in excess commuting, confirming the findings of Frost et al. (1998).

Furthermore, the minimum required commute tends to be roughly equal across the four central cities of Warsaw, Łódź, Poznań and Kraków. Interestingly, the lowest level of the minimum required commute corresponds to the highest level of excess commuting. The

<table>
<thead>
<tr>
<th>City</th>
<th>Number of work trips</th>
<th>Minimum average metres ((T_{\text{min}}))</th>
<th>Observed average metres ((T_{\text{obs}}))</th>
<th>Percentage excess commuting ((E))</th>
<th>Maximum average metres ((T_{\text{max}}))</th>
<th>Percentage of range used ((C_u))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warsaw I(^a)</td>
<td>533,137</td>
<td>5,007</td>
<td>9,619</td>
<td>47.95</td>
<td>21,143</td>
<td>28.58</td>
</tr>
<tr>
<td>Warsaw II(^b)</td>
<td>348,506</td>
<td>2,376</td>
<td>6,377</td>
<td>62.75</td>
<td>11,498</td>
<td>43.86</td>
</tr>
<tr>
<td>Łódź(^b)</td>
<td>190,554</td>
<td>1,875</td>
<td>5,689</td>
<td>67.04</td>
<td>8,790</td>
<td>55.16</td>
</tr>
<tr>
<td>Poznań I(^a)</td>
<td>186,684</td>
<td>3,517</td>
<td>8,955</td>
<td>60.72</td>
<td>15,585</td>
<td>45.06</td>
</tr>
<tr>
<td>Poznań II(^b)</td>
<td>129,937</td>
<td>2,151</td>
<td>6,276</td>
<td>65.72</td>
<td>9,539</td>
<td>55.83</td>
</tr>
<tr>
<td>Kraków(^b)</td>
<td>135,709</td>
<td>2,992</td>
<td>7,073</td>
<td>57.70</td>
<td>11,302</td>
<td>49.11</td>
</tr>
</tbody>
</table>

\(^a\)City and suburbs.  
\(^b\)Central city.
spatial structure of Łódź and Poznań allows the shortest journeys to work in this sample of cities and yet the residents of these cities do not take advantage of these commute-minimising opportunities and are the least efficient commuters. Not surprisingly, results in Table 3 and Figure 2 confirm Horner’s (2002) findings of the relationship between commuting efficiency and theoretical trip lengths for larger and smaller cities. Efficiency is higher in larger cities than in smaller cities due to more commuting possibilities. Clearly, the capacity used statistic provides a more accurate description of commuting efficiency, because it fully captures the extent of urban structure.

**Spatially Disaggregated Commuting Efficiency**

The intrametropolitan framework proposed in equations (5)–(14) produces zonal average trip lengths and commuting efficiency metrics for the four sample cities—Warsaw, Poznań, Łódź and Kraków. For comparative purposes, the minimum and maximum values of theoretical commutes components and metrics are presented in Table 4. Not surprisingly, there is substantial intraurban variation in the average trip length of commuters. Across the six study areas, minimum commutes vary from just a few hundred metres up to 28 km, and maximum commutes vary from a few km up to 78 km. The wide range of these benchmark values results in extreme cases of almost perfect efficiency and perfect inefficiency in work travel. Interestingly, the average minimum distance is shorter for workers travelling to work than the average minimum distance for workers attracted by employers. The urban structure of the four cities suggests that jobs are more accessible to workers than workers to jobs.

Due to space limitations only the zonal results for Warsaw II (Figure 3) are presented, although similar spatial patterns and generalisations are applicable to the other three cities. Minimum average trip lengths vary from 0.3 km to 10.7 km for workers travelling to work ($O_{i}^{\text{min}}$) and from 0.37 km to 6.5 km for employers drawing upon a workforce ($D_{j}^{\text{min}}$). For $O_{i}^{\text{min}}$ (Figure 4), the zones with the shortest minimum work trips are located in the Śródmieście, Ochota and northern Mokotów districts. The longest minimum commutes are detected for zones in the eastern Ursynów, eastern Praga Północ, Wawer and western Białołęka districts. For $D_{j}^{\text{min}}$ (Figure 5), employers in zones in the eastern Ursynów and Bemowo districts in addition to those on the boundary of southern Ochota and northern Włochy districts appear to attract workers from the shortest minimum distances. At the other end of the spectrum, employers in zones in Śródmieście, northern Włochy, southern Białołęka, eastern Praga Południe and northern Praga Północ tend to draw upon a workforce travelling the longest minimum distances.

![Figure 2. Comparative regional commuting results.](image-url)
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</thead>
<tbody>
<tr>
<td>$O^\min_i$</td>
<td>297</td>
<td>27 828</td>
<td>297</td>
<td>10 731</td>
<td>232</td>
<td>25 180</td>
<td>302</td>
<td>11 066</td>
<td>338</td>
<td>5 497</td>
<td>423</td>
<td>12 175</td>
</tr>
<tr>
<td>$O^\max_i$</td>
<td>4 178</td>
<td>65 151</td>
<td>4 736</td>
<td>28 306</td>
<td>2 949</td>
<td>68 135</td>
<td>2 999</td>
<td>28 179</td>
<td>3 822</td>
<td>22 000</td>
<td>4100</td>
<td>30 900</td>
</tr>
<tr>
<td>$E_i^O$</td>
<td>2.47</td>
<td>94.38</td>
<td>0.07</td>
<td>93.08</td>
<td>5.15</td>
<td>96.86</td>
<td>12.01</td>
<td>95.01</td>
<td>34.20</td>
<td>91.01</td>
<td>9.24</td>
<td>90.49</td>
</tr>
<tr>
<td>$C_i^O$</td>
<td>0.93</td>
<td>98.71</td>
<td>0.16</td>
<td>98.55</td>
<td>2.78</td>
<td>96.85</td>
<td>11.36</td>
<td>97.88</td>
<td>18.09</td>
<td>99.72</td>
<td>8.90</td>
<td>97.89</td>
</tr>
<tr>
<td>$D^\min_j$</td>
<td>423</td>
<td>26 212</td>
<td>365</td>
<td>6 520</td>
<td>453</td>
<td>18 272</td>
<td>325</td>
<td>10 125</td>
<td>432</td>
<td>7100</td>
<td>508</td>
<td>11 094</td>
</tr>
<tr>
<td>$D^\max_j$</td>
<td>7 872</td>
<td>77 859</td>
<td>6 093</td>
<td>31 692</td>
<td>5 683</td>
<td>72 399</td>
<td>5 027</td>
<td>25 858</td>
<td>4 884</td>
<td>24 400</td>
<td>6308</td>
<td>32 200</td>
</tr>
<tr>
<td>$E_j^D$</td>
<td>0.19</td>
<td>84.39</td>
<td>1.64</td>
<td>80.93</td>
<td>0.12</td>
<td>95.74</td>
<td>1.98</td>
<td>79.61</td>
<td>7.73</td>
<td>91.40</td>
<td>6.55</td>
<td>73.29</td>
</tr>
<tr>
<td>$C_j^D$</td>
<td>0.21</td>
<td>99.96</td>
<td>2.72</td>
<td>95.07</td>
<td>0.14</td>
<td>99.79</td>
<td>2.25</td>
<td>98.08</td>
<td>13.52</td>
<td>96.56</td>
<td>7.65</td>
<td>95.43</td>
</tr>
</tbody>
</table>

Note: Excludes cases where minimum commutes are longer than observed (resulting in negative excess commuting and capacity used) and where observed commutes are longer than maximum commutes (resulting in excess commuting and commuting efficiency values greater than 100 per cent) due to regional optimisation.
From the commuting efficiency perspective, excess commuting can explain whether workers in one area of the city commute to work more or less efficiently than workers in another part of town. Excess commuting for workers travelling to work ($E^O_i$) varies from 0.07 per cent to 93.08 per cent. The most efficient travel patterns are detected for workers leaving their homes in zones located in the Ursynów, Wawer and western Bielwalka districts. Workers leaving for work in zones in the Śródmieście, Ochota and Mokotów districts tend to be most inefficient in their commute. In terms of the commute potential consumed in terms of capacity imposed by the introduction of the maximisation concept (Horner, 2002), more zones are considered to be more efficient in generating trips to work than the unstandardised excess commute metric. Zones in western Wola, southern Bemowo, southern Praga Południe and south-eastern Mokotów in addition to the zones that are considered efficient using $E^O_i$ show the lowest consumption of commute generator potential. The opposite relationship occurs for workers with the highest consumption of commute generator capacity. Although $E^O_i$ identified almost all of the zones in the Śródmieście, Ochota and Mokotów districts as the most inefficient, $C^O_i$ (Figure 6) shows that a much smaller number of zones in these three districts are highly inefficient.

Deficit commuting can explain whether employers in one area of the city attract a workforce with more or less efficient commuting patterns than employers in another

Figure 3. Warsaw districts in 1998.
part of town. $E^D_j$ varies from 1.64 per cent to 80.93 per cent. Employers attracting workers with more efficient commuting patterns are found on the city periphery (Bemowo, southern Mokotów, Bielany, south-eastern Wola, Ursus and Białołęka districts). Not surprisingly, inefficient commuting is detected for areas with a large number of jobs, mostly in the Śródmieście and Ochota districts but also in eastern Targówek district. Including the maximisation concept (Horner, 2002), we can explore the success of employers in attracting a workforce with shorter commutes by investigating how much commute potential remains or is not used in terms of capacity. The higher the commute potential remaining, the more efficient commuting occurs in the city, because the observed trip length is closer to the lower capacity limit. For $C^D_j$ (Figure 7),

Figure 4. Origin-specific minimum average commute in Warsaw.
more employers are found to attract workers with more efficient work trips, both within the zones identified by $E^D_i$, and also in additional zones in Rembertów and Wawer districts. Once again, efficiency improves when the commuting potential capacity is incorporated in the analysis. Fewer inefficient employer-attracted workers are detected in the Sródmieście, Ochota and Mokotów districts by the use of $C^D_i$.

Several statements can be made regarding the analytical results illustrating the variation in average trip lengths and commuting efficiency. First, the variation tends to occur with respect to the residential and employment clusters. Workers travelling from homes located in job-rich areas make the shortest minimum commute, whereas workers living in housing-rich areas make the longest minimum commutes. However,
the lowest commuting efficiency is found for job-rich areas and the highest for housing-rich areas. Employers in job-poor areas attract workers with the shortest minimum commutes, whereas those in job-rich attract employees with the longest minimum trip lengths. Commuting efficiency is higher in job-poor areas and lower in job-rich areas. Secondly, the variation in average trip lengths and commuting efficiency reflects the geometric possibilities of commuting within the urban structure. Since journey distances are limited by the study boundary, the longest work trips originating in the city centre are much shorter than the longest journeys originating in edge zones. Figures 8 and 9 illustrate the relationship between the three average trip lengths and reflect the

Figure 6. Origin-specific capacity used in Warsaw.
implications for commuting efficiency with increasing distance from a central zone (refer to zone 13 in figure 3). In both cases, the increase in the maximum travel distance is greater than the increase in the observed trip length which is greater than the increase in the minimum commute. In mechanical terms, this explains the higher commuting efficiency of edge workers (edge employers) than central workers (central employers). Intuitively, we would expect that commuting over longer distances is less efficient than work travel over shorter distances. The implication is that commuting efficiency results are highly sensitive to the location of commute generator (commute attractor) zones within the study boundary based on the model specification.

Figure 7. Destination-specific capacity remaining in Warsaw.
Discussion and Conclusions

By developing a framework that disaggregates journey-to-work data by intrametropolitan zone, the issue of the lack of spatial detail in commuting efficiency analysis to date is addressed. The spatially disaggregated framework calculates the minimum, observed and maximum trip lengths for each zone in the study area. The examination of spatial variation in commuting efficiency indicates a strong sub-regionally imbalanced urban structure in which workers (employers) in some locations commute to jobs (attract workers from homes) more efficiently than workers (employers) in other locations. In the results obtained from the four sample cities (Warsaw, Poznań, Łódź and Kraków), commuting efficiency is higher for peripheral locations than for centrally located sites and higher for job-poor areas than job-rich areas. From the urban policy perspective, knowledge of the distribution of commuting efficiency across the region provides useful information for evaluating where workers and jobs need to be relocated in order potentially to reduce commuting thus motivating improvements in quality of life (Helling, 1998).

The proposed approach enhances the standard framework by addressing intrametropolitan differences in commuting efficiency. Thus, it can be widely applied to analyses involving data disaggregation by various socioeconomic dimensions such as occupation types, transport mode or race/ethnicity. Extending this work to urban settings in the US can test for the generality of the findings made in this paper, especially given the different urban context of US cities. By investigating urban structure in great detail, relationships between commuting efficiency and (de)centralisation of employment and residences at the intraurban scale can be analysed. As dispersion and concentration invariably affect the efficiency of journeys to work, a more sophisticated understanding of commuting patterns is necessary for informed decision-making.

The focus in this paper is on examining the efficiency of work trips, but perhaps a reinterpretation of this approach and the statistics is needed for improved policy decision-making. Although this framework is useful for benchmarking the levels of commuting in a city, it assigns blame on workers and employers in matching homes and jobs based on the
assumption of commuting cost minimisation. However, an unintended side effect of commute minimisation is significantly reduced interaction, which is expressed geographically through residential and employment exclusion clusters. Commuting efficiency statistics can be reinterpreted as reporting on the amount of segregation or exclusion in the region and, thus, benchmarking social exclusion (Horner, 2004; Lyons, 2003). Thus, minimum commutes can not only measure the minimum level of commuting required in a region, but also the maximum level of exclusion. Moreover, an estimate that implies high commuting efficiency also implies increased exclusion and limited interaction, as workers commute short distances between homes and jobs. Interpreting commuting data in this light implies that longer commutes than necessary given the urban structure are not ‘wasteful’ due to positive social effects of journey-to-work interaction.

The current framework strives to understand relationships between spatial structure, commuting and urban sustainability, based solely on the commute minimisation behaviour. The results presented in this and other related papers indicate that, although commuting costs are important, there are other factors involved in urban location decisions. This single objective modelling of commuting patterns is a limitation of this paper and previous excess commuting studies. Continuing efforts should be directed towards understanding additional factors influencing spatial matching of homes and jobs by considering workers’ utility constraints. Ultimately, future research should extend the current approach to incorporate non-transport factors in the investigation of conflicting objectives of deciding where to live and where to work.

References

Figure 9. Comparative intraurban trip lengths for commutes arriving in zone 13.
COMMUTING EFFICIENCY


