Does urbanization lead to less energy use on road transport? Evidence from municipalities in Norway

Yongping Liu (Corresponding author)

Faculty of Technology, Economy and Management,

NTNU, Norwegian University of Science and Technology, Gjøvik, Norway

Teknologivn. 22, 2815 Gjøvik, Norway

T: +47 46 88 92 50

Email: yongping.liu@ntnu.no

Lizhen Huang

Faculty of Technology, Economy and Management,

NTNU, Norwegian University of Science and Technology, Gjøvik, Norway

Teknologivn. 22, 2815 Gjøvik, Norway

Email: lizhen_huang@ntnu.no

Aristidis Kaloudis

Faculty of Technology, Economy and Management,

NTNU, Norwegian University of Science and Technology, Gjøvik, Norway

Teknologivn. 22, 2815 Gjøvik, Norway

Email: aristidis.kaloudis@ntnu.no

Marit Støre Valen

Department of civil and transport engineering, Norwegian University of Science and Technology,

Høgskoleringen 7A, NO-7491, Trondheim, Norway

Email: marit.valen@ntnu.no

Abstract

The relationship between urbanization, energy use, and CO2 emissions has been extensively studied in recent years, however little attention paid to the differences in urban forms. Previous studies implicitly assume that the urban form is homogenous across different urban areas. Such an assumption is questionable as urban form can have many different facets. This paper investigates the effects of urbanization on the road transport energy use by considering different urban forms from a dataset of

386 Norwegian municipalities from 2006 to 2009. Using the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model with an energy use identity equation, the main findings (1) confirm the well-established result that urban density has a negative and significant influence on road transport energy use, and (2) demonstrate that the effect of urbanization partly depends on the level of urban density. These results imply that additional increases in urbanization in dense areas yield greater decreases in road transport energy use per capita. Additional findings posit that (3) there is a non-linear (quadratic) relationship between road energy use per capita and urban population. This implies that an increase in total municipality population over a specific turning point can result in a decrease in road energy use per capita. However, (4) the ratio of urban residential buildings with private gardens has a negative and significant influence on road transport energy use. This implies that there may be a trade-off between compact and sprawl city development strategies, highlighting that sustainable energy use requires further investigation.

Keywords: Dwelling Type, Norway, Road Energy Use, Urban Density, Urbanization

1. Introduction

Around 54% of the world's population lives in urban areas. This is projected to increase to 66% by 2050 with an extra 2.5 billion inhabitants occupying urban spaces (UN, 2014). Such rapid urbanization has generated a multitude of problems and opportunities for not only the economy, but also the environment as urban transport accounts for more than one-fifth of global carbon dioxide emissions (Liddle, 2013). The growth rate of transport energy use – three quarters of which consumed on the road – is projected to increase 2% annually (Saboori et al., 2014). This means that good understandings of road energy use are required to provide insight into the development of more sustainable cities, although the connections between urbanization and environmental impacts are not clear (Brian C O'Neill, 2012; Ergas et al., 2016; Li and Lin, 2015; Liddle, 2014; Ponce De Leon Barido and Marshall, 2014; Poumanyvong and Kaneko, 2010; Ramana Gudipudi and Kropp, 2016).

Some scholars claim that urbanization has positive environmental impacts by decreasing road energy use (Gudipudi et al., 2016; Liddle, 2013) while others claim it generates more emissions (Poumanyvonga et al., 2012). These conflicting results make the real effects of urbanization on the environment inconclusive (Poumanyvonga et al., 2012), leading to the need for more studies regarding the potential detrimental effects of urbanization on the environment. Such disagreements in the extant literature may be due to the quality of data used, as well as the deployment of different methodologies. Specifically, the failure to consider urban form differences could be one reason as most studies implicitly assume that it is homogenous across different areas. This is questionable due to its multiple facets (e.g., urban area, urban density, residential dwelling spatial structure) across countries and geographical regions. In addition, many recent empirical studies have found that some urban form variables (e.g., urban area, residential density, housing sizes and types, urban structure) can have significant impacts on environment (i.e., carbon emission, energy use) (Boyko and Cooper, 2011; Fang et al., 2015; Lee and Lee, 2014; Norman et al., 2006; Perkins et al., 2009; Reingewertz, 2012 ; Yang et al., 2015; Yin et al., 2015). Therefore, further studies with careful considerations of the different urban forms become imperative. Specifically, there have been few studies that examine urbanized area level spatial form impact on the environment due to the lack of appropriate measures (Lee and Lee, 2014). As such, the objective of this paper is to investigate the effects of urbanization on road transport energy use. This is achieved by considering a variety of urban forms taken from available municipality level information on urban residential building spatial structures across 386 Norwegian municipalities from 2006 to 2009. Based on the cross section analysis, the findings demonstrate that the effect of urbanization partly depends on the level of urban density, implying that additional increases in urbanization of already densely populated areas yield greater decreases in road transport energy use per capita.

The paper is structured as follows. First, the related literature is explained. Second, the model, data, and empirical strategy are presented. Third, the main estimation results and discussions are given. Finally, the conclusions are offered.

2. Literature review

A popular framework used to distinguish the impact of population and income on the environment is stochastic impacts by regression on population, affluence, and technology (STIRPAT). This was developed by Dietz and Rosa (1997) and exhibited in the following equation (2.1) where *I* is the environmental impact, *P* is population, *A* is affluence, consumption per capita or income per capita, and *T* is the technology or impact per unit of consumption. The subscript i denotes cross sectional units; a, b, c, and d are the parameters to be estimated; and e is the error term in the regression model:

$$I = aP_i^b A_i^c T_i^d e_i \tag{2.1}$$

Thus, Equation 2.1 leads to the following linear log-function (2.2):

$$\ln(I_i) = a + b\ln P_i + c\ln A_i + d\ln T_i + e_i \tag{2.2}$$

Researchers applying the STIRPAT frame to carbon emissions or energy use typically include data on population, income, urbanization level, urban density, and age compositions in their analyses, summarized in the appendix A1 (Boyko and Cooper, 2011; Fan et al., 2006; Hossain, 2011; Liddle, 2004; Liddle and Lung, 2010; Martínez-Zarzoso et al., 2007; Martínez-Zarzoso and Maruotti, 2011; Menz and Welsch, 2012; Norman et al., 2006; Perkins et al., 2009; Poumanyvong and Kaneko, 2010; Poumanyvonga et al., 2012; Yang et al., 2015; Zhu and Peng, 2012). The common feature in these studies is the lack of information on the urban form which may be ascribed to the deficiency of appropriate measures of urban area level spatial structure (Lee and Lee, 2014) as well as the limited variables in the STIRPAT framework. Indeed, many variables describing urban form (e.g., area, share of residential building type, urban density) are identified as important driving forces with environmental impacts (Boyko and Cooper, 2011; Norman et al., 2006; Perkins et al., 2009). Further, there are two arguments supporting the idea of controlling the ratio of residential building type in a municipality space area from empirical observations. First, it is reasonable to believe that distance from city center is a determinant factor of road transport energy use. According to urban theory, the density of residential housing has a negative relationship with the distance to the city center (Gaigné et al., 2012). Therefore, it is hypothesized that more compact urban areas lead to less transport energy use. Second, it has been empirically verified that age-structure plays a critical role in housing location decisions (Lee et al., 2016). At the same time, there is the implicit idea of housing hierarchy in which low- and moderate-income tenants move into more comfortable quarters while the wealthier tenants save to become first-time homebuyers who thereafter trade up to bigger and better homes (Morrow-Jones and Wenning, 2005). It therefore seems appropriate to assume that the density of housing has a negative connection with age structure and that the omission of these variables, given that they have significant explanatory power, may lead to different estimation results. Thus, by introducing the variables of urban building type, urban area (or urban settlement area), and urban density into the equation, the estimations in this paper may provide greater understanding of the factors that influence road energy use in geographical spaces.

3. Data and models

The municipality data stem from Statistics Norway (SSB) where the definition of municipalities follows the Norwegian nomenclature from 2012. These data include: energy use from road transport, age compositions[1], urban population[2], urban area[3], median household income after tax, household sizes[4], and each type of residential housing stocks. The total population is calculated according to the data from age compositions divided into four groups based on both spatial parameters and extant literature (<16, 16-44, 45-66, and 67 ≥). In Norway, the under 16s are not allowed to drive and the retirement age is 67. Further, the middle groups are assumed workers who are divided into two subgroups for three reasons. As the stock of wealth is assumed different within and between these subgroups according to the life-cycle hypothesis that poses individuals build up assets at the initial stages of their working lives to be used during retirement,[5] it is reasonable to believe the older working group (45-67) have smaller households and larger asset stocks than the younger one (16-44). Nevertheless, there are no united classifications for age structures within the literature. For example, Liddle (2011) divided the population into five age groups (< 20, 20-34, 35-49, 50-69, and 70 ≥) whereas Zhu and Peng (2012) integrated the working population into one group. Further, Cao and Yang (2017) classified the age of 44 as an important node (16-24, 25-34, 35-44, 45 >). The classifications of Cao and Yang (2017) and Zhu and Peng (2012), combined with the Norwegian factors, resulted in our division into four groups. The study period (2006-2009) was determined as the data of housing stock at the municipality level[6] are available from 2006 to 2016, however energy use from road transport[7] only from 2005 to 2009. Hence, the data used consist of a balanced panel over a period of four years (2006-2009) and 386 municipalities, containing in total 1540 observations.

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[1] Age structure data are from SSB Table 07459 (population by sex and age groups).

[2] Urban population is the population of urban settlements from SSB Table 04861 (land use in urban settlements).

[3] Urban area is the area of urban settlements from SSB Table 04861 (land use in urban settlements).

[4] Household unit and median household income after tax data are from SSB Table 06994 (income after tax by household type, number, and median).

[5] The net source comes from: https://en.wikipedia.org/wiki/Life-cycle_hypothesis.

[6] Housing stock data are from SSB table number 06265 (dwellings by building type).

[7] The source of energy use on road data come from SSB Table 06926 (energy use by source and user group). SSB divides transport energy use into four consuming groups: road traffic, air traffic (below 100 meters), shipping (inclusive 1/2 nautical mile from the harbors), and other mobile energy uses (railway, small boats, snow scooters, and motor equipment). Therefore, the energy use on road is calculated based on the road traffic energy consumption.

Figure 1 shows the energy use on road per capita for each municipality plotted against urbanization level (the ratio of urban population to the total population) with a frequency weight of urban density (the ratio of urban population to the urban area) in 2009. When the circle is larger, the urban density in that municipality is more compact. There are two interesting observations. First, there is a negative relationship between energy use on road per capita and urbanization level. Second, the average level of urbanization is around 0.5. When the urbanization level is below this average, there is greater energy use on road per capita with a smaller urban density. Alternatively, there is smaller energy use on road per capita with a larger urban density which implies that the impact of urbanization on the environment partly depends on urban density levels. Figure 2 plots the urbanization level against urban density with a frequency weight of the total population in each municipality for 2009. It highlights that the urban population density can greatly vary although urbanization levels remain the same. This implies that the assumption of homogenous urban forms is questionable. Actually, the urban density is usually treated as a policy variable on city level, while the urbanization can be treated as policy variable on the national level. For example, new urbanization policy is encouraged in Norway by merging the municipalities into the large ones (Parliament, 2017). Further, it is also seen that some researchers try to distinguish the effects of urbanization from the impacts of urban density (e.g., see Liddle (2004), Wang et al. (2017)). Figure 3 shows the natural logarithm of energy use on road per capita for each municipality plotted against the natural logarithm of population for 2009. It seems that there is a quadratic relationship between population and road energy use per capita. According to new economic geography theory, the agglomeration effects occur in urban economics during the process of population concentration (Krugman, 1991) which can lead to energy efficiency improvements. Specifically, figure 3 implies that there may be an economic scale effect of population on the road energy use in cities. Indeed, this effect has been empirically verified in Italian cities (Burgalassi and Luzzati, 2015).

Insert Figure 1, 2, and 3 here

3.1 Variables and model analyses

The analysis begins with a simple identity:

$$energy\_use = \frac{energy\_use}{GDP} * \frac{GDP}{household} * \left(\frac{household}{population}\right) * \frac{population}{urban\_population} * \frac{urban\_population}{urban\_area} * urban\_area$$

The identity can be rewritten as:

$$\frac{energy\_use}{\text{population}} = \frac{energy\_use}{GDP} * \frac{GDP}{household} * \left(household\_size\right)^{-1} * (urbanization)^{-1} * urban\_density * \frac{urban\_area}{\text{population}}$$ [8]

The per capita energy consumption is treated as the independent variable for two reasons.[9] First, the urban area is an important variable but varies very little in this data and therefore it is difficult to precisely estimate the relationship between urban area and road energy use. However, by using the term per capita such considerations are avoided because of the perfect collinearity among urbanization, urban density, and urban-area per capita in log estimation form. Second, the energy use per capita is more important than the total energy use when we consider the energy use efficiency. Thus, the equation can be rewritten as follows (Equation 3.1):

$$\begin{aligned} \ln energy\_use\text{-per capita} &= \ln \frac{energy\_use}{GDP} + \ln \frac{GDP}{household} - \ln household\_size - \ln urbanization \\ &+ \ln urban\_density + \ln urban\_area - percapita \end{aligned} \tag{3.1}$$

Regarding energy (or energy use/carbon emission), many researchers identify variables such as population, economic growth rates, urbanization, and age composition as key drivers of road energy demand (Belloumi and Alshehry, 2016; Liddle, 2004; Liddle, 2013; Okada, 2012; Perkins et al., 2009; Poumanyvonga et al., 2012). In addition to the aforementioned factors, urban formation patterns and urban density relative to urbanization levels are also acknowledged as important in explaining

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[8] Household-size=household/population; urbanization=urban-population/population; urban-density=urban-population/urban-area.

[9] The choice of dependent variable per capita was suggested by an anonymous reviewer and the authors are grateful for this helpful suggestion.

transport energy use (Boyko and Cooper, 2011; Martínez-Zarzoso and Maruotti, 2011; Norman et al., 2006; Perkins et al., 2009). These considerations suggest that energy may have the following relationship where y denotes income or GDP, p denotes population, AC denotes age composition, UR denotes urbanization level, HS denotes household size, and UD denotes urban density (Equation 3.2):

$$energy = f(y_i, p_i, AC_i, UR_i, UD_i, HS, other\_controls), \tag{3.2}$$

Following relative literature such as STIRPAT analysis model, the log-log function is chosen for $f(.)$. The specification is stated as follows where β_i are estimated parameters (Equation 3.3):

$$\ln energy_i = \beta_0 + \beta_1 \ln y_i + \beta_2 \ln p_i + \beta_3 AC_i + \beta_4 \ln UR_i + \beta_5 \ln UD_i + \beta_6 \ln HS_i + \varepsilon_i \tag{3.3}$$

This can be transformed as follows (Equation 3.4):

$$\ln energy_i - \ln y_i = \beta_0 + (\beta_1 - 1)\ln y_i + \beta_2 \ln p_i + \beta_3 AC_i + \beta_4 \ln UR_i + \beta_5 \ln UD_i + \beta_6 \ln HS_i + \varepsilon_i$$

(3.4)

The right side of equation is the log of energy intensity, or energy per GDP. Integrating Equation 3.4 into Equation 3.1, the following is obtained where ENU denotes energy use per capita in road transport sector, HS denotes household size, and α_i are estimated parameters (Equation 3.5):

$$\ln ENU_i = \alpha_0 + \alpha_1 \ln y_i + \alpha_2 \ln p_i + \alpha_3 AC_i + \alpha_4 \ln HS_i + \alpha_5 \ln UR_i + \alpha_6 \ln UD_i + \varepsilon_i \tag{3.5}$$

Here, income y is substituted by the median household income after tax. There are two reasons for this. First, it is sensible to consider that road transport, especially passenger car transport, is more relative to household unit than per capita. This accords with Liddle (2004) who posits that the household is an important level of analysis for road transport. Second, it is more convenient to combine urbanization rate and household size into the analysis when the household unit is considered as shown in Equation 3.1. In addition, because it is assumed that residential building type has strong relationships with age composition (Lee et al., 2016), urbanization, and urban density (Perkins et al., 2009), the share of residential building type is introduced into the estimated equation to mitigate potential bias. Furthermore, with the same urbanization rate and urbanization density, there may be different urban forms due to the differences in urban area. Therefore, the interaction term of urbanization rate and urban density is also considered. Further, it is hypothesized that the effects of age composition partly depend on income level. Thus, the interaction terms of income and age composition are also included in the equation. Due to the economic scale of the population, the quadratic relationship between population and road energy use is tested. Finally, although studies (Poumanyvonga et al., 2012) use industry share and services as proxies of technology factors, these are not controlled for in this equation because the road transport sector is one of many service sectors, and compared with other industries is relative small. Moreover, given the data structure for four time periods it seems appropriate to assume the technology of energy use efficiency factors remains comparatively stable during the analysis. Therefore, the estimation equation is (Equation 3.6):

$$\begin{aligned} \ln ENU_i &= \alpha_0 + \alpha_1 \ln y_i + \alpha_2 \ln p + \alpha_3 (\ln p)^2 + \alpha_4 AC_i + \alpha_5 (\ln y_i) \times AC_i \\ &+ \alpha_6 (\ln UR_i) \times (\ln UD_i) + \alpha_7 \ln HS_i + \alpha_8 \ln UR_i + \alpha_9 \ln UD_i + \alpha_{10} LR_i + \varepsilon_i \end{aligned} \tag{3.6}$$

Here, α are estimated parameters and LR denotes the share of individual households with private gardens of total residential housing stock. The variable “urban area per capita” is not included to avoid perfect collinearity in the estimations as is shown in equation (3.1). Table 1 lists the variables used, their definitions, and model units.

Insert Table 1 here

3.2 Empirical models

Several estimation methods are used, namely ordinary least squares (OLS) for the year 2009 with robust standard errors, the pooled OLS with cluster-robust standard errors, fixed effect estimation

(FE),[10] random effect estimation (RE),[11] and OLS with panels-corrected standard errors (PCSE). As the time-series dimension of four periods is much smaller than the cross-sectional dimension of 386 municipalities, it seems reasonable to assume that the non-stationarity issue is not of concern (see e.g., Menz and Welsh, 2012; Liddle and Lung, 2010). Because the pooled OLS treats the unobserved, time-constant factors (e.g., climate) as constant terms in the regression equation, the setting is limited. To tackle this problem, FE and RE estimators are applied. The Hausman test is employed to show whether the FE or RE estimator is preferred for this static model. Further, the Wooldridge test for autocorrelation (Wooldridge, 2002) and the Modified Wald test for group-wise heteroskedasticity (Greene, 2000) are also applied in the fixed panel model. Finally, the PCSE (panel-corrected standard errors) method is used. Table 2 shows the estimation results for each model.

Insert Table 2 here

4. Empirical results and discussion

4.1 Results

Table 2 shows the estimation results of Equation 3.6 by pooled OLS, OLS for 2009, FE, RE, and OLS with panels corrected standard errors. Because of the presence of heterogeneity bias, the estimation of pooled OLS is only used for comparison. In the model of OLS for 2009, it is against functional form misspecification (the p-value for the Ramsey's test is 0.27). The results of the FE and RE estimators show large differences. The Hausman test (P value is 0.0000) demonstrates that the FE estimator is preferred. However, the FE model has the presence of serial correlation[12] and heteroskedasticity[13]. To address these two issues, the PCSE method is applied.

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[10] Fixed effect estimation assumes the unobserved, time-constant factors are correlated with the explanatory variables.

[11] Random effect estimation assumes the unobserved, time-constant factors are uncorrelated with the explanatory variables.

[12] The P value is below 0.0000 which shows a strong rejection of no serial correlation.

[13] The P value is below 0.0000 which shows a strong rejection of no heteroskedasticity.

Table 2 reveals that the results obtained from the three models of pooled OLS, OLS, and PCSE OLS are not sensitive to the choice of estimating method and all variables have the same sign. As the results do not indicate major differences between these models, the discussion focuses on a series of OLS alternative models in 2009 which contain all significant variables and the most recent data. These alternative OLS models are used to test the sensitivity of the observed results. Table 3 shows the alternative estimation results for energy use per capita from road transport which are based on the OLS method and the data for 2009. The main interpretations focus on columns 2, 6, and 7, while the others are used for comparison.

Insert Table 3 here

This study finds several interesting results.[14] All seven models in Table 3 show there is a quadratic relationship between population and energy use per capita, statistically significant at the 1% threshold. These results are consistent and imply there is a turning point in the population; i.e., column 2 is 9.27 (1.16/ (2×0.06)). In this example, the average of the logged population is 8.48 (the minimum value is 5.37 and the maximum 13.26, see appendix Table A2) which implies that an increase of a municipality's total population over its turning point (10614)[15] can result in a decrease of road energy use per capita. Moreover, the elasticity for household income is partly decided by the share of age structure. For example, using the point estimates in column 6, extra income increases road energy use per capita by 0.06[16] which means there is positive elasticity between household income and road energy use per capita[17]. Further, the elasticity of the road energy use per capita with respect to urban

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[14] All the interesting results are obtained from the table 3. We also establish the same estimation for the other years (2006-2008) in appendix Table A3 and the main results are consistent.

[15] $e^{9.27} = 10614$, which is the turning point value of municipality population.

[16] According to the equation in column 6 in table 3, $\partial enu / \partial income = -22.04 + 48.94 * ac16\_44 + 30.54 * over67$. In this sample, the average of age 16-44 and age >67 are 0.356 and 0.153 (see the Table A2). Thus, the elasticity of income relative to road energy use per capita is 0.06.

[17] Compared the column 5 in table 3, it is seen that the new-added interaction terms of income and age groups (age 16-44 and age >67) in column 6 increase the statistical significance greatly, while the signs of parameters for other variables keep unchanged. This results imply that the high collinearity problem in column 6 is not a serious issue. The logic is simple. If the high collinearity problem really matters in this column 6, it is expected

density is negative and statistically significant which implies a compact city is more sustainable, and the elasticity for the interactive variable between urbanization and urban density is negative and significant. This implies that the effect of urbanization partly depends on the level of urban density. In column 6, the net impact of the urbanization is negative,[18] implying that additional urbanization can decrease energy use in the denser area. Indeed, the elasticity for urbanization is negative and significant at 5% (P value is 0.026) in column 3 without considering the interactive term between urbanization and urban density. The net effect of urbanization is consistent with the argument that urbanization contributes to a decrease in road energy use (Liddle, 2004, 2013). Finally, it is also interesting to note that the variable of residential building type has a negative and significant effect on road energy use per capita. Of this table 3, the magnitudes of coefficient and statistical significance in column 2 greatly increase (e.g., the coefficient of population, urban density, and urbanization rate increase by 52%, 61%, and 55% respectively, and the statistical significances also improve to under the 1% threshold) when compared with column 3. This implies that the variable of residential building type strongly relates to population, urban density, and urbanization rate, and therefore cannot be ignored. Moreover, in column 7 the coefficient of the interaction term between urban density and the sum ratio of households with private gardens over the total residential housing stock is negative and statistically significant at the 1% threshold. This implies that the residential development policy for energy deduction should focus more on dense areas.

4.2. Discussion

Studies comparable to this one include Poumanyvonga et al. (2012), Okada (2012), and Liddle (2004). Liddle (2004) uses a semi-log model with the level of per capita road energy use as the dependent variable. It is, however, difficult to compare our results with that because the estimated model here

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that model will become to perform more badly by introducing the new interaction term of income and age structures (the high correlation among income, age structures, and the interaction terms of them). However, the column 6 shows different picture.

[18] $-0.32 = 2.846 - 0.462\times6.86$(the average value for urban density) < 0. Similar negative results can be obtained from column 2 and 7. Both have similar negative signs for urbanization.

uses logged per capita road energy use as the dependent variable. Although this study has controlled the relative variables that Liddle includes, the meaning of explanation to the dependent variable is different. The same problem arises when the results are compared with those of Okada (2012) who considers the difference of road energy use as the dependent variable. The study with the most comparable dependent variable is the logged road energy use considered in Poumanyvonga et al. (2012) that suggests urbanization has a positive elasticity on road energy use. However, the findings of this study show the elasticity of urbanization with respect to per capita road energy use is negative, similar to the findings of Liddle (2004, 2013). The differences, however, may lie in the various estimated models as variables considered include those used by Poumanyvonga et al. (2012), but also some that were not, for example, residential building type and age compositions.

This paper verifies that there is a quadratic relationship between population and road energy use per capita. This result is consistent with the findings in (Burgalassi and Luzzati, 2015). However, in the current situation, the average urban population is not yet at its peak, and its effect is positive. This implies that road energy use per capita would keep increasing with urban population growth. On the other hand, it also implies that the urban policy should focus more on those communities with populations above the turning point to realize a decrease in road energy use per capita.[19]

The paper also suggests that the effects of age structures (16-44, 45-66, and 67 ≥) on road energy use per capita are 5.028, 7.608, and 1.121 respectively,[20] and that all coefficients are statistically significant. The results imply that the age group 45-66 has the largest effect on the environment. At the same time, the combined working groups (age 16-66) have greater environmental effects than the young (0-15) and older groups (67 ≥). Our results are different to those of Liddle (2011) and Liddle and Lung (2010) because different data and models are used. However, it is reasonable to expect that the level of activities and stock of assets are two important driving factors influencing the household's

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[19] In Norway there were only 97 municipalities with the total population above turning point in 2009.

[20] According to column 6 of Table 3, $5.028 = -287.6 + 48.94 \times 5.983$ is the effect value of age 16-44; $1.121 = -181.6 + 30.54 \times 5.983$is the effect value of age above 67. 5.983 is the average value of the log of household income after tax for different municipalities.

driving behaviors. In other words, the higher level of activities (or the younger age groups), the more energy use on road. Moreover, economic behaviors are constrained by assets condition. Essentially, the wealthier age groups are, the more they can afford relaxation activities. Therefore, Liddle's papers (2010, 2011) which focus on the effects of activity level show that the age group 20-34 has a positive, and 35-69 a negative, effect on the environment. Our results are different from Liddle's papers from the point of life-cycle hypothesis that suggests wealth grows with the development of age during working time. Compared with other cohorts, the wealthier age group (45-66) can afford more relaxation activities. Therefore, this group consumes the most energy on road. Our results verify the assumption that the effects of age structure are partly decided by household income or wealth levels and are consistent with the findings from Cao and Yang (2017) and Zhu and Peng (2012). For example, Cao and Yang (2017) suggest that age has a positive effect on environment, and Zhu and Peng (2012) suggest that the working group (age 16-64) has more positive effects on the environment than other cohorts. Furthermore, the elasticity of urban density with respect to per capita road energy use is negative given the urbanization rate and the ratio of low residential housing stock which implies that compact cities contribute to decreases in road energy use per capita. Moreover, the interaction terms among urban density, urbanization, and the ratio of low density dwelling types are negative and significant which may provide some insightful information for policymakers on energy reduction. The interaction term between urban density and urbanization rate is negative which infers that increasing urban density in areas with high urbanization rates would contribute more to decreasing the road energy use per capita than in areas with lower rates.[21] It also implies that the urbanization policy in a sprawl city (low level of urban density) may increase the energy use on road per capita.

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[21] According to the partial derivation of model in column 7 of Table 3: $\partial enu / \partial ud = \alpha_6 \times ur + \alpha_9 + \alpha_{11} \times LR$. Here, all the coefficients are negative and significant. Because the urbanization rate is between 0 and 1, the logged urbanization rate (ur) is negative and the first item is positive. Moreover, the smaller the level of urbanization rate, the larger the absolute value of logged urbanization rate or ur, and the larger value of the first item. Given the other variables and parameters, there would be a smaller effect of the urban density on road energy use per capita in an area with less urbanization.

As the interaction term between urban density and ratio of low density residential dwelling stock is negative and significant, an increase in the share of houses with private gardens can curb the growth rate of energy use on road per capita. Moreover, it seems to be better effects in reducing road energy use in higher urban density areas than lower ones[22], which may not be a surprise. The result implies that the people living in high-density houses consume more energy on road than people living in low-density ones. In fact, a low-density house has some special characteristics (e.g., access to private green gardens) which high-density residential buildings do not. Therefore, it is reasonable to expect that people living in low-density housing may spend more time in their detached homes, both for relaxation purposes and necessary gardening. This empirical result supports the so-called compensatory mechanism hypothesis which suggests that people living in densely populated urban areas (i.e., inner city apartments) with limited needs for everyday transport tend to undertake longer travel in their leisure time as a compensation for limited access to green/outdoor areas (Holden and Norland, 2005). However, the casual mechanism is not evident, and it is therefore not clear that the negative relationship between energy use on road transport and low density housing rate is due to these reasons. As such, future studies should aim for a better understanding of such leisure-time behaviors.

Taken together, the findings of this study have some policy implications for reducing energy use on road transport per capita in Norway. First, many municipalities that have the total population below turning point value should be encouraged to merge in order to use the economic scale of population, which can make public transportation play more important role. This finding supports the current ongoing municipality reform in Norway, which aims to reform current 428 municipalities to be 354 ones by 2020 (Parliament, 2017). Second, as the maximum value of urban density in Norwegian

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[22] According to the partial derivation of model in column 7 of Table 3: $\partial enu / \partial LR = \alpha_{13} \times ud$. Here, the coefficient is negative and statistically significant. Therefore, given other conditions, the greater the urban density value, the greater the decreased effect of the low residential house share on road energy use per capita.

municipalities is 42.26 per hectare [23] (see appendix Table A2) which is comparatively smaller compared to data from other countries,[24] a more compact city is preferred. Third, the verification of compensatory mechanism hypothesis suggests that it would be effective to reduce the road energy use per capita by providing more public green spaces and entertainment infrastructures in dense urban areas.

5. Conclusions

This article examines the influences of urbanization on the road transport energy use with the consideration of different urban forms by using 386 Norwegian municipality-level data from the period 2006 to 2009. After controlling for household income , population, average household sizes, age compositions, urbanization level, urban population density, and the urban residential building structure (the ratio of residential building unit with private garden to the total residential building unit), this paper reveals that (1) urban density has a negative and significant effect on road transport energy use. This implies that the process of population concentration can contribute to curbing the growth rate of road energy use per capita and that (2) the impact of urbanization partly depends on the level of urban density. This result suggests that additional urbanization increases in areas of higher density levels would contribute more to decreasing road energy use per capita than in areas with lower levels. This is important because it highlights that the residence policies of large Norwegian cities should concentrate more on the denser centers. The results further reveal that (3) there is a quadratic relationship between road energy use per capita and urban population which suggests that the latter has a concave effect on the former. In this study, the urban population is not yet at its peak point, and the real effect of urban population is positive. Nevertheless, this implies that policymakers concerned with energy reduction should focus more on cities with larger populations. At the same time, urban policy should encourage municipalities with smaller populations to merge in order to use the economic

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[23] $e^{8.349} = 4226$

[24] The means of urban density in OECD/developed countries in 1995 is 52.6 per hectare (Liddle, 2013, p. 21).

scale of population in reducing the road energy use per capita. Moreover, (4) the interaction term between the ratio of low density dwelling stock and urban density is negative and significant. This result implies that people living in higher urban density areas create more road energy than those in low density areas, supporting the compensation mechanism hypothesis (Holden and Norland, 2005).

Notwithstanding, there are some limitations in this study worthwhile to mention. Predictors for explaining the variance of road energy use per capita are limited and by no means comprehensive. At the same time, the results are obtained under the peculiarity of Norway that is a long-stretched country with low population density. Moreover, the results may only reflect the short-run effects as they are obtained from a very short period (2006-2009) and, therefore, may provide an incomplete empirical relation of certain aspects. Nevertheless, the study provides a foundation for further investigations on the role of urban form in road energy use in rapidly urbanizing areas. Specifically, the co-existence effects of urban density (compact city) and compensation mechanism (sprawl city) suggest that there may be a trade-off between these two different urban development strategies which deserves a follow-up study to decide where the boundary is.

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Table 1 stochastic STIRPAT studies on carbon emissions/energy consumption

Dependent variable	Research method	Recognized Impact factors and Research result					source
		population	urbanization	GDP per capita or income	Age composition	Other variable	
Energy use in traffic per household	Case study					Residential location to city center (positive)	Perkins,A., Hamnett,S., Pullen,S., Zito,R., andTreblicock,D., 2011
GHG emissions per person	Correlation analysis	Population, (not important)	Urbanization (not important)	Income (important)			Satterthwaite, D., 2009
Log(carbon emission)	Time seriesand STIRPAT model	Log(population) +0.55 significant	Log(urbanization) +0.334 significant	Log(expenditure) +0.16 significant	Log(the ratio of working age (16-44) +1.32 , significant	Log (household size) -0.7823, significant	Zhu, Q., and Peng, X., 2012
Log(private transport energy consumption)	Cross section data and STIRPAT model	Log(population) +0.997-+1.335, significant	Log(urban density) -0.679 -0.375, significant	Log(Gdp per capita) +0.220-+0.632, significant			Liddle,B., 2013
Log(carbon emissions)	Panel data and STIRPAT model	Log(population) more than 1, significant		Log(Gdp per capita) +0.9-+1.2, significant			Martinez-Zarzoso,I., Bengochea-Morancho,A., and Morales-Lage,R.,2007
Log(carbon emissions)	Panel data and STIRPAT model	Log(population) 0.319	Log(urban population) 0.755, significant	Log(Gdp per capita) 0.424 significant	Log(age composition) Not		Martinez-Zarzoso,I., and Maruoti, A., 2011

		significant at 5 percent	Square(Log(urban population)) -0.121 , significant		significant		
Log(carbon emissions)	Cross section data and STIRPAT model	Log(population) +1.497-+1.655, significant		Log(Gdp per capita) +0.712-+0.822, significant			Shi, 2003
Energy use in household	Correlation analysis		Urbanization (important)	income (important)			Pachauri,S., and Jiang, L., 2008
Log(carbon emissions)	Panel data	Log(population) +1.81, significant	Log(urbanization) +0.9, significant	Log(Gdpper capita) +0.83,significant	Share of age composition from 45/59 significant at 10 percent, Others are not significant.		Menz,T., and Welsch,H., 2012
Log(carbon emissions)	Panel data		Log(urbanization) +28.02/-12.64, significant, varied by countries	Log(Gdp per capita) +1.0236/-1.1871, significant	.		Hossain, M, S., 2011
Road Energy use per capita	Panel data		Population density Negative, and significant urbanization, Negative, and significant	Log(Gdp per capita), +0.21, significant	Share of age composition from 20/39 ,significant positive	Household size, significant negative, but highly auto correlation	Liddle,B., 2004

						with age composition, when both are included, one of them will be not significant.	
The difference of Road Energy use per capita	Panel data			The difference of Gdp per capita, positive, significant	The difference ofthe share of aged population, positive, significant, Square(The difference ofthe share of aged population) negative , significant		Okada,2012
Log(road energy use)	Panel data and STIRPAT model	Log(population) +0.76-+1.3, varied by income level, significant	Log(urbanization) +0.3-+1.1, varied by income significant,	Log(Gdp per capita), +0.6-+1.07, varied by income group significant			Poumanyvong, P., Kaneko, S., and Dhakal,S., 2012
Log(carbon emissions per capita)	Panel data		Log(urbanization) positive, not significant,	Log(Gdp per capita), Positive, significant			Du,L., Wei,C., and Cai,S.,2012

Log(carbon emissions)	Panel data and STIRPAT model	Log(population) More than unit, significant	Log(urbanization) positive, significant,	Log(Gdp per capita), +0.9-+2.49, varied by income group significant			Poumanyvong, P., and Kaneko, S., 2010
Log(energy use)	Panel data and STIRPAT model	Log(population) More than unit, significant	Log(urbanization) positive, significant at 5 percent,	Log(Gdp per capita), +0.5, Significant Square of Log(Gdp per capita) Negative significant	Share of age composition over65 ,significant positive		York, R., 2007
Log(carbon emissions)	Panel data and STIRPAT model	Log(population) More than unit, significant within high income	Log(urbanization) negative, significant within high income, upper middle and low income level but positive and significant within lower middle income at 5%	Log(Gdp per capita), Positive, significant	Share of age composition over65 ,Within high income Negative significant		Fan, Y., Liu,L,C., Wu,G., and Wei,Y,M., 2006
Log(carbon emissions from transport)	OLS	Log(population) 0.28, significant at 5 percent	Log(urbanization) positive, significant within 5 percent,	Log(Gdp per capita), Positive, significant	Log(Pop3564), negative, significant at 5 percent. Log(Pop2034), positive, not significant.		Liddle,B., and Lung, S., 2010

Table 2 Definition of variables used in the estimated equation

Variable	Definition	Unit/notes
Energy use on road (ENU)	Energy consumption from road transport divided by total population	kWh per capita
Enu	Logged (ENU)	
Y	Median household income after tax	100 kroner
Income	Logged (y)	
hs(Household Size)	Log(total population divided by gross household number)	Number
ur(Urbanization Rate)	Ln(population living in urban areas divided by total population)	Percent
ud (Urban population Density)	Ln(Gross population living in urban area divided by total urban settlement area)	Number per square Km
ac45_66	The share of population aged from 45 to 66 over the total population	Percent
LR (Low density residence rate)	The share of detached house stock plus semidetached house stock divided by total housing stock	Percent
P	Total population	Number
Po	Logged (p)	
Po2	$(\ln p)^2$	Square term
ac0_15	The share of population aged from 0 to 15 over the total population	Percent
ac16_44	The share of population aged from 16 to 44 over the total population	Percent
ac_over67	The share of population aged above 67 over the total population	Percent
Income16_44	$income \times ac16\_44$	Interaction term
Income45_66	$income \times ac45\_66$	Interaction term

Incomeover67	$income \times ac\_over67$	Interaction term
Ud1	$ud \times ur$	Interaction term
udLR	ud*LR	Interaction term

Table 3 Estimation results for energy use per capita from road transport

	(1) pooled_ols	(2) ols_2009	(3) FE	(4) RE	(5) PCSE
po	1.167***	1.163***	3.053***	1.115***	1.163***
	(0.360)	(0.365)	(1.035)	(0.240)	(0.0134)
po2	-0.0629***	-0.0627***	-0.213***	-0.0619***	-0.0628***
	(0.0196)	(0.0199)	(0.0612)	(0.0137)	(0.000855)
income	-9.642	-18.99*	2.974*	4.469***	-10.13***
	(9.045)	(10.96)	(1.779)	(1.723)	(2.844)
income16_44	28.53*	44.87***	-2.415	-5.444**	29.76***
	(14.78)	(17.26)	(2.804)	(2.680)	(6.787)
income45_66	-13.66	-4.961	-5.239**	-6.816***	-13.24***
	(11.45)	(16.23)	(2.241)	(2.206)	(1.913)
incomeover67	20.35*	29.61**	-3.588	-3.469	21.36***
	(10.62)	(12.15)	(2.269)	(2.136)	(5.210)
hs	1.393**	1.081	-0.395**	-0.348**	1.189***
	(0.600)	(0.818)	(0.177)	(0.164)	(0.225)
ud1	-0.351***	-0.457***	0.302**	-0.0648	-0.358***
	(0.127)	(0.139)	(0.139)	(0.0932)	(0.0535)
ud	-0.702***	-0.816***	0.255	-0.302***	-0.713***
	(0.145)	(0.156)	(0.179)	(0.102)	(0.0432)
ur	2.127**	2.814***	-2.027**	0.256	2.172***
	(0.841)	(0.919)	(0.895)	(0.613)	(0.355)
ac16_44	-163.5*	-263.3**	15.94	34.02**	-170.5***
	(87.61)	(102.8)	(16.52)	(15.79)	(40.04)
ac45_66	89.37	37.24	30.82**	41.65***	87.14***
	(68.03)	(97.17)	(13.23)	(13.01)	(11.93)
ac_over67	-119.6*	-176.0**	20.34	20.62	-125.0***
	(62.88)	(72.27)	(13.26)	(12.60)	(30.61)
LR	-2.060***	-2.292***	0.325	-0.0412	-2.085***
	(0.553)	(0.594)	(0.450)	(0.330)	(0.129)
middle	0.258***	0.243***		0.250***	0.257***
	(0.0789)	(0.0802)		(0.0860)	(0.00759)
south	0.316***	0.291***		0.352***	0.313***
	(0.0757)	(0.0782)		(0.102)	(0.0109)

west	0.0393	0.0148		0.0333	0.0280***
	(0.0883)	(0.0888)		(0.0689)	(0.0107)
east	0.307***	0.272***		0.340***	0.296***
	(0.0682)	(0.0718)		(0.0678)	(0.00918)
year	controlled		controlled	controlled	Controlled
_cons	47.76	105.9	-34.70***	-35.00***	50.71***
	(53.86)	(65.78)	(10.39)	(10.13)	(16.80)
N	1540	386	1540	1540	1540
R^2	0.338	0.343	0.088		0.339

Note: dependent variable: Logged Energy consumption from road transport per capita (KWh per capita). Middle, south, west, east, north are a group of dummy variables to capture the characteristic of region. The base group is north here. The robust standard errors are applied in the OLS for the year in 2009, the cluster-robust standard errors are applied in the pooled ordinary least squares (pooled OLS), the panels-corrected standard errors are applied in the PCSE model. All standard errors are given in parentheses. Statistical significance is indicated by: *** P<0.01, ** P<0.05, and * P<0.10.

Table 4 estimations results for energy use per capita from road transport in 2009 year

	(1) ols_1	(2) ols_2	(3) ols_3	(4) ols_4	(5) ols_5	(6) ols_6	(7) ols_7
po	1.140***	1.163***	0.764**	1.295***	1.256***	1.160***	1.240***
	(0.364)	(0.365)	(0.351)	(0.356)	(0.370)	(0.364)	(0.372)
po2	-0.0619***	-0.0627***	-0.0387**	-0.0712***	-0.0682***	-0.0625***	-0.0671***
	(0.0198)	(0.0199)	(0.0189)	(0.0193)	(0.0202)	(0.0198)	(0.0203)
income	32.66	-18.99*	-17.04	-13.73	0.104	-22.04***	-22.65***
	(51.30)	(10.96)	(11.45)	(11.23)	(0.482)	(6.407)	(6.381)
income2	-3.297						
	(3.180)						
income16_44	28.43	44.87***	39.66**	34.82**		48.94***	50.25***
	(23.97)	(17.26)	(17.89)	(17.40)		(13.37)	(13.33)
income45_66	-16.56	-4.961	-6.414	-9.870			
	(19.17)	(16.23)	(16.79)	(16.79)			
incomeover67	10.39	29.61**	30.94**	27.32**		30.54**	31.36***
	(23.48)	(12.15)	(12.81)	(12.29)		(12.18)	(12.10)
hs	0.942	1.081	0.573	1.082	1.211	1.082	1.080
	(0.835)	(0.818)	(0.772)	(0.828)	(0.833)	(0.818)	(0.813)

ud1	-0.459***	-0.457***	-0.242*		-0.333**	-0.462***	-0.484***
	(0.140)	(0.139)	(0.142)		(0.143)	(0.139)	(0.140)
ud	-0.810***	-0.816***	-0.506***	-0.514***	-0.692***	-0.819***	-0.545***
	(0.157)	(0.156)	(0.143)	(0.120)	(0.157)	(0.156)	(0.145)
ur	2.827***	2.814***	1.410	-0.184**	2.001**	2.846***	3.004***
	(0.924)	(0.919)	(0.950)	(0.0827)	(0.954)	(0.919)	(0.926)
ac16_44	-165.4	-263.3**	-230.7**	-203.5*	3.943	-287.6***	-295.5***
	(142.7)	(102.8)	(106.9)	(103.7)	(3.533)	(79.57)	(79.32)
ac45_66	106.3	37.24	46.04	66.43	6.799**	7.608***	7.526***
	(114.6)	(97.17)	(100.7)	(100.5)	(2.782)	(2.777)	(2.760)
ac_over67	-61.39	-176.0**	-182.9**	-162.5**	0.571	-181.6**	-186.6***
	(140.0)	(72.27)	(76.36)	(73.07)	(3.130)	(72.37)	(71.91)
LR	-2.345***	-2.292***		-1.720***	-1.976***	-2.296***	
	(0.592)	(0.594)		(0.587)	(0.580)	(0.596)	
Ud*LR							-0.319***
							(0.0823)
middle	0.237***	0.243***	0.281***	0.258***	0.193**	0.243***	0.246***
	(0.0802)	(0.0802)	(0.0835)	(0.0815)	(0.0817)	(0.0801)	(0.0801)
south	0.280***	0.291***	0.355***	0.320***	0.284***	0.292***	0.298***
	(0.0789)	(0.0782)	(0.0819)	(0.0781)	(0.0811)	(0.0782)	(0.0781)
west	0.0119	0.0148	0.0773	0.0444	-0.00742	0.0193	0.0223
	(0.0885)	(0.0888)	(0.0896)	(0.0889)	(0.0895)	(0.0872)	(0.0872)
east	0.270***	0.272***	0.327***	0.281***	0.240***	0.271***	0.273***
	(0.0719)	(0.0718)	(0.0718)	(0.0718)	(0.0718)	(0.0718)	(0.0715)
_cons	-84.59	105.9	91.35	71.51	-9.225**	124.1***	125.5***
	(196.6)	(65.78)	(69.04)	(67.25)	(4.586)	(38.25)	(38.04)
N	386	386	386	386	386	386	386
R^2	0.345	0.343	0.314	0.328	0.316	0.343	0.343

Note: dependent variable: Logged Energy consumption from road transport per capita (KWh per capita). Robust Standard errors are given in parentheses. Statistical significance is indicated by: *** P<0.01, ** P<0.05, and * P<0.10.