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An approach for modelling CO_2 emissions from road traffic in urban areas

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ABSTRACT

An approach that incorporates three modelling components has been developed to estimate road traffic CO_2 emissions for an urban area with street level resolution. The first component enables the determination of the road traffic characteristics using the SATURN (Simulation and Assignment of Traffic in Urban Road Networks) model. The output from this component is then analysed using MATrix LABoratory (MATLAB) programming to provide estimates of CO_2 emissions for the urban area. Finally, ArcGIS is used to illustrate the model output. The three components are integrated using a Loose-Coupling approach in which the individual components each load the necessary data to give an independent output. The model structure is discussed in the current paper and the modelling results for a small city (Norwich, UK) are presented.

1. Introduction

The local impact of various air pollutants, such as CO, NO_x, SO_2, and PM_{10}, has been well documented. However, now there is a growing emphasis on global effects, especially for greenhouse gases and notably CO_2. Road vehicles are acknowledged to be significant sources of a range of pollutants and they have been estimated to contribute around 10% of the total global, and 20% of the European anthropogenic CO_2 emissions (Metz, 2001). In the UK for example, a quarter of all anthropogenic CO_2 emissions are produced by the transport sector (Department for Environment Food and Rural Affairs, 2002), and road transport is the largest single component (85%) of this (Department of Trade and Industry, 2004).

Road transport emissions of CO_2 have received special attention, because they have been rising constantly. Although, there are methods through which they can be reduced, such as better transport infrastructure, advances in vehicle technology and management systems, stabilising CO_2 emissions from road transport is likely to be a complicated task due to the rapidly rising traffic needs around the world. For example, it has been estimated that CO_2 emissions from road traffic worldwide will increase by 92% between 1990 and 2020 (Gorham, 2002).

Traffic emission estimates have been used mostly to allow decision makers to manage local air quality effectively (Carmichael et al., 2008; Escobedo et al., 2008; Mensink and Cosemans, 2008). Some studies (Idso, 1998; Nasrallah et al., 2003) have measured and considered levels of CO_2 to be representative of air quality similar to other pollutants that can have significant health effects (e.g. NO_x, SO_2, O_3, CO and PM_{10}). In this respect, the estimation and modelling of CO_2 can be a powerful tool for air quality managers and environmentalists in order to examine the impact of different transport plans (e.g. reducing personal

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mobility, restructuring urban areas and switching to low carbon vehicles). In addition to this use, there is a growing need to examine how overall emissions of CO_2 can be managed by local transport management, in order to reduce its impact as a greenhouse gas.

There have been two main approaches that have been adopted for estimating road traffic emissions: a macro-scale approach; and a micro-scale approach (Namdeo et al., 2002; Reckien et al., 2007; Tuia et al., 2007; Schrooten et al., 2008). Using the former, emissions are estimated taking into account information such as total fuel consumption, average speed and average distance travelled for a large area (e.g. a county or country) for a lengthy period (e.g. a year). The latter approach involves a finer resolution and emissions might be estimated for individual roads, using detailed traffic data including volume, speed, distance travelled and vehicle type (Namdeo et al., 2002), for periods as short as an hour. Such estimates are then integrated over time and space to provide estimates of emissions on a regional scale.

It has been argued that the use of a micro-scale approach is preferable for predicting emissions in urban areas (Namdeo et al., 2002) because traffic densities and speeds can vary significantly over relatively short distance and time scales. More importantly (especially when predicting CO_2 emissions), this approach enables the impact of changes in local transport infrastructure and patterns to be investigated thus identifying potentially attractive options for CO_2 reduction (e.g. changing fleet composition, low emission zones, congestion charging).

In this paper, we demonstrate how a road traffic model (SATURN) that adopts a micro-scale approach can be coupled with programming software (MATLAB) to predict CO_2 emissions for an urban area. GIS (ArcGIS) has been incorporated into the approach for the spatial display of the results. We then highlight how these emissions might be affected by various management strategies.

2. Road transport CO_2 emission modelling

2.1. The approach: overview

There are two main approaches to integrating computer packages: Loose-Coupling and Tight-Coupling (Sui and Maggio, 1999; Gilliams et al., 2005; Dunfey et al., 2006). Loose-Coupling involves the exchange of data between each package and it has the advantage of not requiring any complex programming. However, the data exchange between the packages can be both tedious and expensive in terms of computer time. A Tight-Coupling approach requires a significant amount of programming in linking the packages together, but it can require less computing time and the overall required knowledge of the different software packages is not as large as in the Loose-Coupling approach (Goodchild et al., 1992). Since a Tight-Coupling approach involves an integrated modelling output only, it has the disadvantage that usually it is not possible to investigate minor adjustments to the individual modelling components separately. Consequently, a Loose-Coupling approach was preferred for the current study. The structure of the modelling approach is shown in Fig. 1.

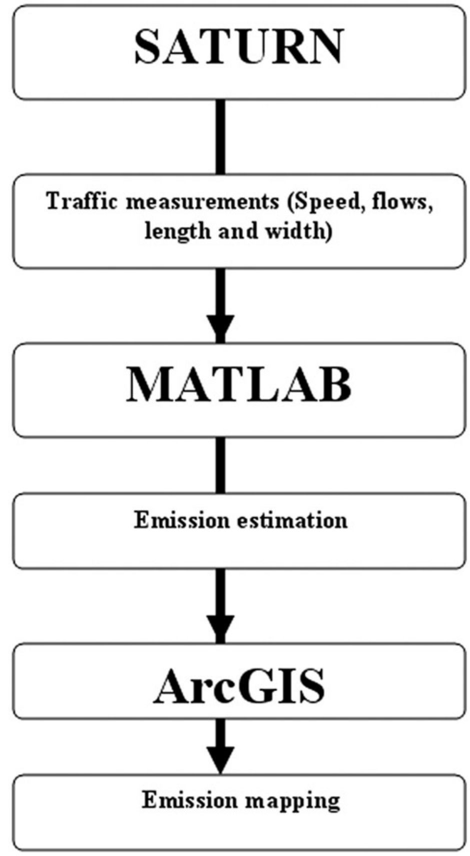

Fig. 1 – The modeling approach.

2.2. Saturn

Much of the basis for road traffic planning is focused on models that simulate real-world traffic flow and conditions. These models are used to monitor and resolve road traffic issues, such as predicting the effect of new roads or developments, and predicting areas of congestion. The output of such traffic models is usually expressed in terms of vehicle speeds and traffic flow at peak hours (i.e. the morning and evening rush hours) for a given length of road (segment). SATURN is one such model and it was developed at the Institute for Transport Studies (ITS), University of Leeds, UK. It is used in thirty countries worldwide. In the UK, it is used by 80 Local Authorities (Van Vliet, 1998) and the model has been validated in small scale studies where results have shown acceptable levels of uncertainty (Namdeo et al., 2002). Given its widespread and generally accepted use, SATURN was chosen as being suitable for the current study.

SATURN requires input data of two types: a trip (or journey) matrix; and a road traffic network (Van Vliet, 1998). The study area is divided into areas of similar land use, called traffic analysis zones (TAZs). Traffic demand data are expressed in Passenger Car Units (PCUs) and represented by the number of journeys that need to be made between each TAZ for each time unit (usually hourly). Traffic demands are coded as a matrix consisting of rows and columns. Rows represent journeys leaving zones and columns represent journeys coming to zones. An example of a trip matrix is shown in Table 1, which

Table 1 – An example of a trip matrix in SATURN

Arriving	Zone 1	Zone 2	Zone 3	Total
		Originating		
Zone 1	0	12	10	22
Zone 2	15	0	8	23
Zone 3	13	7	0	20
Total	28	19	18	65

shows for example that seven journeys originating in zone three have zone two as a destination.

The traffic networks in SATURN are coded and based upon information for junctions (e.g. roundabouts and signalled junctions) and individual roads (e.g. free flow speed and road length). The use of the network is assumed in SATURN to be based upon Wardrop's second principle (Institute for Transport Studies, 2003), i.e. "drivers choose routes such that, at equilibrium (i.e. in the long term) for each origin-destination movement, the cost of travel (i.e. average travel time) on all used routes is equal and minimum, and no greater than that on any unused route". The outputs from SATURN indicate the number of vehicles on the road, the vehicle distances travelled, and net speeds and delays, for each individual road.

Both the matrix and network are input into a road choice model in which total flows along links in the network are estimated and the corresponding network costs are calculated. The analysis of the results is possible after the assignment of traffic demand and the programme can be queried for a variety of information (e.g. roads with a specific volume of traffic). The SATURN model has been discussed in further detail by Van Vliet (1998) and Namdeo et al. (2002).

One drawback with SATURN is that its road network usually only contains major roads. It is suitable only for calculating traffic flow on roads, which are coded within network files and it cannot be used for others with traffic data that otherwise would be compatible with SATURN (i.e. minor roads). It is possible that there could be significant CO_2 emissions from minor roads in built up areas and this has been addressed separately in the current study (see Section 3.2).

2.3. *Matlab*

MATLAB is a powerful tool and has been applied in estimating road traffic emissions (Lu et al., 2002). The estimates for given sectors of roads are made by incorporating the information provided by SATURN on traffic density (i.e. number of vehicles per km), length of the road and the average vehicle speed on that road, into MATLAB. In addition, it is necessary to input information on fleet composition using the road (i.e. vehicle and fuel type, and engine size) and the respective emission factors according to speed.

Total emissions (ET_c) can be represented therefore as in Eq. (1) which is embedded into MATLAB. ASCII data (i.e. traffic flow, road speed and length) supplied by SATURN are then imported into MATLAB to estimate emissions initially for a given segment of road and then the entire city's network. The time resolution in the initial SATURN–MATLAB output is hourly, but by extrapolating the data, it is possible to make annual estimates of CO_2 emissions.

$$E_{TC} = \sum_{1}^{N} F_{sv} \times D_{sv} \times C_{sv} \quad (1)$$

where:

- E_{TC} total CO_2 emission (g) for the entire study area for a given vehicle type v.
- N number of street segments (s).
- F_{sv} the traffic flow on a segment of road and type of vehicle.
- D_{sv} the distance travelled on a segment of road by a given type of vehicle.
- C_{sv} the CO_2 emission factor (g km^{-1}) on a segment of road for a given vehicle type and speed).

Each road was described by the co-ordinates of its start and end points and was given an identifier according to whether it was open to one or two way traffic. The model output provided CO_2 emissions in different data formats (ASCII and spreadsheets).

2.4. *ArcGIS*

The appropriate visualisation of results is an important tool for helping decision makers to understand emission issues better and to enable areas that need attention to be easily identified. Traditionally, there have been two methods used to generate data to enable the data visualisation of road traffic emissions. One is based upon the interpolation of measurements on stationary sites by using meteorological and topographical data. This method is useful for certain pollutants, such as NO_x, SO_2, O_3, CO and PM_{10}, which are of concern because of their detrimental effects on health. The other method involves a visualisation of emissions as line sources, with the type of line (e.g. thickness or colour representing) demonstrating increasing pollution levels. In comparison to the first method, this does not require meteorological and topographical data, but suffers from the disadvantage that air concentrations cannot be determined at intermediate points between roads. In the case of CO_2 however, this is not a major disadvantage as it is the emissions that are important rather than the spatially resolved air concentrations.

The technique of visualising emissions is useful in the management and monitoring of air pollution and for CO_2, it allows the contribution of small sources to be easily identified. Consequently, it is sensible to describe emissions on a fine resolution across urban areas (Soegaard and Moller-Jensen, 2003), because road traffic can be such a significant source of pollutants. Such fine resolution enables the provision of CO_2 emission maps according to zones and streets, and these could help inform local authorities for their plans to reduce emissions by encouraging alternative forms of transport or by modifying the traffic infrastructure.

ArcGIS has been used previously in road traffic modelling and mapping (Taylor et al., 2006; Doygun and Kuşat Gurun, 2008) and was adopted as the line visualisation method in the currently reported work. It was configured to utilise the database created by MATLAB containing the co-ordinates of roads and vehicle emissions. These data were imported into ArcGIS and assigned to the appropriate road segments.

3. CO_2 case study

3.1. *Study area*

Norwich is a major city in eastern England and was chosen as the study area. Its location is shown in Fig. 2. The city covers an area of around 4000 ha and has a population of 121,650 (Office for National Statistics, 2003). The total length of the road network in the city is 315 km and it is the only city in England without a motorway within 50 miles. It is also one of the few urban areas in England that still relies primarily on a medieval street layout with a number of narrow street-canyons that are not suited to modern traffic levels. Consequently, many roads in Norwich are heavily congested, particularly during peak hours, which causes pollution hotspots (Chatterton et al., 2000).

The city was divided into zones for analysis and these zones are shown in Fig. 2. In reality, Norwich is still an expanding city and these zones do not cover the entire urban area. Nevertheless, the study area includes the most heavily congested areas that focus around the city centre. The SATURN modelling was undertaken using fleet data relevant for 2003, as supplied by Norfolk County Council (NCC).

3.2. *Application of modelling approach to the study area*

The SATURN model provided estimates of passenger car units at peak times only and so it was necessary to convert this data into daily statistics for all vehicle types (e.g. heavy goods, motorcycles, etc.) and road conditions. The conversion from peak to a daily flow rate was achieved using data from 24-hour traffic counter measurements on selected roads. Furthermore, in order to estimate emissions for vehicles other than cars a matched fleet composition, compatible with the emission factors available was used. In the following sections we explain these in more detail.

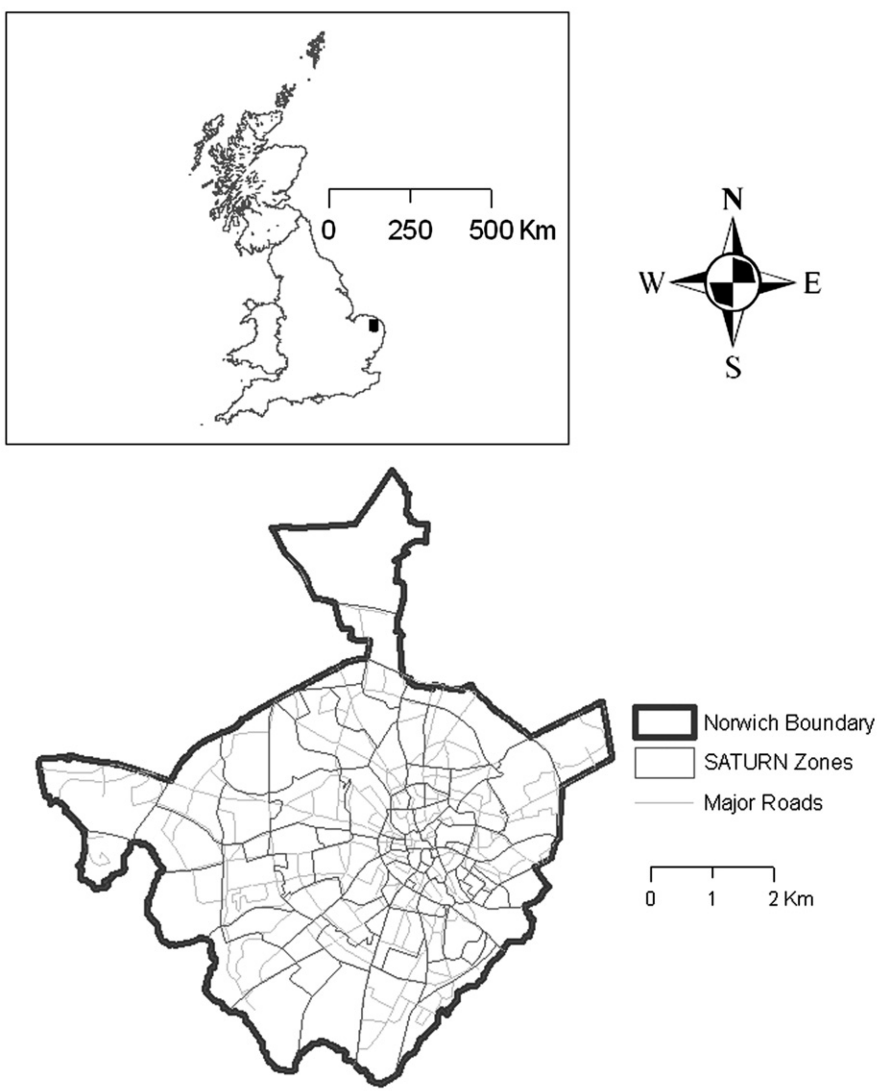

Fig. 2 – Study area.

NCC provided 24-hour traffic flows for weekdays and weekends from a traffic counter located on a road recognised to be representative of average conditions (the Trowse by-pass on the southeast of the city). Counts were available over half-hourly intervals and these were separated into two modes (weekday and weekend). The flow for each 30-minute period was then calculated as a percentage of the AM and PM peak. For example, traffic flow between 10:00–10:30 was considered to be equal to 12/14 of the traffic flow at AM peak plus 2/14 of the traffic flow at PM peak.

SATURN does not produce any weekend flow data. Therefore the weekend flows as a proportion of the weekday flows were calculated using the relationship between weekday and weekend days' flows of the NCC data. This permitted us to calculate weekend flows for the whole city. Based on the method explained, the SATURN data was adjusted to provide traffic flows for every hour for weekdays and weekends for all roads in Norwich.

Ideally, the composition of the traffic fleet should be known for each road within the network, but this information did not exist. It was assumed therefore, that it would have been the same for all roads within the network. It is acknowledged that this is a potential source of error, although there is relatively little through-traffic in Norwich and it was considered that the potential impact of such an assumption would be much less than for many other types of study site.

The overall distribution of vehicle types used was estimated using fleet composition data from both local and national sources. The city's statistics were assumed to be the most accurate, although the vehicle categories were less detailed than those required for matching to the emission factors reported by TRL (see below). For example, the local estimates provided only the number of cars, whereas the emission factor estimates required a split between petrol and diesel engined ones. Therefore, the local traffic composition data (Norfolk County Council, 2001) were complemented with national statistics on sub-categories (National Atmospheric Emissions Inventory, 2003) to produce composition categories consistent with the TRL dataset (Table 2). Buses were excluded from the fleet composition because they had already been coded within SATURN network data and their information was provided to the model on demand.

It was assumed that the traffic speed on the main roads outside the peak periods was the free flow speed (i.e. speeds ignoring the effects of queuing or waiting at traffic signals). Due to the lack of data for minor road speeds, a constant speed of 17.7 km h^{-1} (Lake, 1998) was adopted as typical. It was assumed also that all vehicle types travelled at the same speed.

Usually, there are considered to be three types of vehicle emissions: hot, cold and evaporative (Samaras et al., 1995). Hot emissions are produced after the engine has reached its working temperature and cold emissions are produced during warm up. The third type is evaporative loss and this comes from parts of a car other than exhaust emissions, e.g. the fuel tank, carburettor or fuel injection system (Samaras et al., 1997). The approach adopted does not consider evaporative losses.

Information from the TRL database (Transport Research Laboratory, 2005) was used to estimate hot emissions according to vehicle type. These were categorised according to vehicle type and speed and have been derived from rolling-road tests. Vehicle speed on a road network is determined to some extent by traffic density and this affects vehicle emissions strongly (i.e. emissions per kilometre are highest at very low or very high speeds and lowest at intermediate speeds). Emission coefficients for various categories of vehicle were derived from the TRL dataset and used to determine emission factors according to Eq. (2). An example of the parameters used in estimating emission factors for diesel cars is shown in Table 3. This emissions data is applicable for a minimum speed of 5 km h^{-1} and this figure was used for those roads that had a calculated average speed, estimated by SATURN, equal to or less than this value. There is an upper speed limit of 130 km h^{-1} for emission factors also in the TRL database, although this is significantly in excess of the general speed of traffic in Norwich.

$$E_f = k + av + bv^2 + cv^3 + d/v + e/v^2 + f/v^3 \qquad (2)$$

where:

E_f = CO_2 emission factor (g km^{-1}).
V = the average speed (km h^{-1}).
k, a, b, c, d, e, f are coefficients for each vehicle type.

Cold emission rates are usually accounted for by using an excess emission over the hot emission rate. This is true for emissions other than CO_2 and research by De Vlieger (1997) for example has revealed that cold start hydrocarbons emission levels are 40% higher than hot emission ones. According to Joumard (1999), cold emissions occur on average during the first 5.9 km of a vehicle's journey and most intra-city journeys in the study area would have been for less than this

Table 2 – National, local and matched fleet composition

Scale	National		Local		Revised local estimates compatible with TRL
			Category		
Pedal Cycle	–		2.85%		2.91%
Motorcycle	–		1.57%		1.60%
Petrol car	72.6%		Car	81.05%	70.56%
Diesel car	12.5%				12.15%
Petrol LGV	1.5%		LGV	10.58%	1.53%
Diesel LGV	9.0%				9.26%
HGV	Rigid HGV	2.3%	1.95%		1.99%
	Artic HGV	0.6%			
Bus	1.5%		2.00%		–

Table 3 – An example of the TRL database (coefficient of CO_2 emission factors for diesel cars)

Fuel	Legislation	Engine size	Coefficients							Valid speeds (km/h)
			k	*a*	*b*	*c*	*d*	*e*	*f*	
Diesel	83/351	<2.01	239	−3.33	0.02	0	741	0	0	5 to 130
Diesel	83/351	>2.01	271	−2.60	0.00	0	822	0	0	5 to 130
Diesel	91/441	<2.01	191	−2.66	0.02	0	593	0	0	5 to 130
Diesel	91/441	>2.01	217	−2.08	0.00	0	658	0	0	5 to 130
Diesel	94/12	<2.01	182	−2.53	0.02	0	563	0	0	5 to 130
Diesel	94/12	>2.01	206	−1.98	0.00	0	625	0	0	5 to 130
Diesel	EURO III	<2.01	173	−2.40	0.02	0	535	0	0	5 to 130
Diesel	EURO III	>2.01	196	−1.88	0.00	0	593	0	0	5 to 130
Diesel	EURO IV	<2.01	164	−2.28	0.02	0	508	0	0	5 to 130
Diesel	EURO IV	>2.01	186	−1.78	0.00	0	564	0	0	5 to 130

distance. Vehicles have different cold excess emission factors at different temperatures. The annual mean temperature for the study area in 2003 was 10.67 °C (Climatic Research Unit, 2003) and cold excess emission factors appropriate for the range 10–20 °C were embedded in MATLAB to determine the cold excess emissions for the study area for distances travelled up to 5.9 km. In practice, it was assumed that all journey had a cold excess emissions and these emissions estimated for all journeys.

It was necessary to adopt a specific method for estimating traffic flow rates on minor roads because SATURN does not do this routinely. The technique adopted involved using ArcGIS. In order to include those roads that were not coded within the network's files in SATURN, Ordnance Survey Meridian Data (Edinburgh Data and Information Access, 2004) for the study area was used. The road network data was overlaid over the SATURN zones in the GIS and the length or roads coded in SATURN estimated. It was assumed then that the amounts of traffic flow coming into and leaving each SATURN zone were each equal to the total flows on minor roads within the zones. The argument for this assumption is that once a journey starts, it must follow a minor road before it reaches a segment of main road and joins the SATURN network. As in the case of main roads, the distances travelled on minor roads needed to be estimated. This was carried out by superimposing a 50 m × 50 m grid on the SATURN network and determining the average distance to the nearest major roads from all points within each zone. This assumed that each journey would use the shortest straight-line distance along minor roads until it reached the nearest major road, and that the population is evenly distributed across each zone. An illustration of this approach is shown in Fig. 3. This illustrates that for instance, a grid of 530 points was constructed for Zone 91. The average distance from each point to the nearest major road for this zone was then calculated to be equal to 682 m.

3.3. *Modelling results*

The Norwich City Council dataset covered areas beyond the city's boundary. In other words, trip matrices contained data not only for the city's zones but also for trips starting and finishing outside the study area. From the model, it was estimated therefore that 47% of the morning peak (7:30–9:30) journeys and 58% of the afternoon peak (16:00–18:30) ones originated from outside the study area. It was calculated also that about 5% of all CO_2 emissions would have been cold emissions (in excess of the normal hot emissions). This would mean that, although about 50% of all journeys coming to the city originate from outside the study area, many of these would have been short journeys as some of these zones are close to the city's boundary. As a result, it seems reasonable to assume that cold excess emissions are produced for the duration of all journeys within the study area.

The annual traffic flow in the study area was calculated to be about 350 million vehicle km travelled in 2003, with about 12% of this total on minor roads and 88% on main roads. Petrol cars were the cause of about 69% of the total movements in the city, which was expected as these vehicle types were predominant (71%) in the fleet composition. All cars (petrol and diesel) were the cause of 81% of the movements, followed by light goods vehicles (LGVs) with 11% and pedal cycles with 3%. Other sources included heavy goods vehicles (HGVs), buses and motorcycles with 2%, 1.5% and 1.5%, respectively. The traffic movement hot spots in the area were found to be the inner and outer ring roads around Norwich city centre; the arterial roads leading to and from the inner ring road; and other roads in the city centre. Most movements on the minor roads were found to be to the south west of the outer ring road, west of the inner ring road and north of the outer ring road.

The annual spatial distribution of CO_2 emissions across the city for 2003 is shown in Fig. 4. The most polluted areas were the main arterial roads, the ring roads and the city centre, reflecting the patterns seen for traffic activity. The calculations indicated that 85% of CO_2 emissions were from main roads and only 15% were from minor roads. Cars were the major source, contributing 72.5% of all CO_2 emissions, followed by LGVs (12.5%), HGVs (7.5%), buses (6.5%), and motorcycles (1%).

The total annual CO_2 emissions from traffic within the city (population: 121,650) were calculated to be about 69,100 t in 2003. This means about 568 kg CO_2 would have been emitted for every person resident in the study area. Disaggregating total emissions according to time of day revealed that: 41% were during inter-peaks times (09.30–16:00); 18% were at the PM peak time (16:00–18:30): 17% were during the AM peak (7:30–9:30), 14% were at night-time (24:00–07:30) and 11% were in the evening (18:30–24:00). This is an important observation as transportation planning studies typically focus on peak periods when congestion is highest, whereas significant emissions of CO_2 occur.

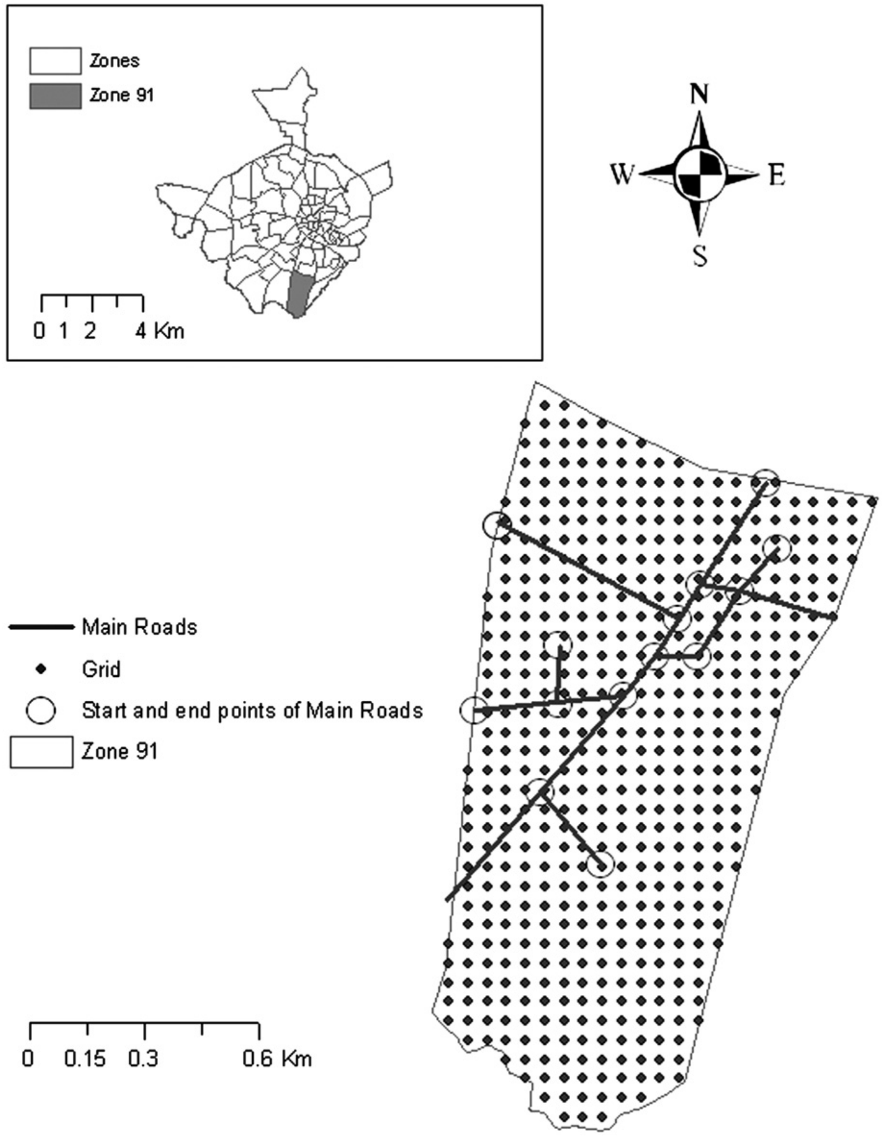

Fig. 3 – An example of calculating average distance travelled on minor roads.

3.4. *Modelling uncertainties*

Although there have been no other estimates for CO_2 emissions for Norwich based on a micro-scale approach, a macro-scale approach has been used to estimate that CO_2 emissions for the city were around 115,000 t in 2004 (Department for Environment Food and Rural Affairs, 2006) which is about 50% more than the estimate from the current study. There are a number of possible reasons for the difference between these estimates. One of the main differences between the two estimates might originate from differences in the study area. As noted earlier, the current study included only areas within the boundary of the city and Norwich has expanded beyond this significantly.

The collection of road traffic data was different in the two approaches also. In the macro-scale approach, the UK Department for Transport estimated traffic volumes based upon road averages across the entire UK (including Norwich). The road traffic estimates were calculated from data collected by some 190 Automatic Traffic Counters (ATC) and 10,000 12-hour manual counts per annum (Department for Transport, 2007b). However, the data (hourly by vehicle type) are very sparse since traffic is counted for only 12 h (7 am–7 pm) on each site. Additionally, the automatic counters do not give 100% accuracy since they have a tendency to malfunction and cannot distinguish well between different vehicle types such as cars and car-based vans, buses and coaches, and goods vehicles having similar axle spacing and chassis height. Compared to manual counts, they operate continuously and can give a complete picture of traffic at the points where they are sited (Department for Transport, 2007a). Whereas in the current study, traffic flows for individual roads were estimated with higher precision based on the SATURN flow modelling. Consequently, it is possible that the figures for Norwich based on national counts might be likely to provide less certain estimates of the traffic volumes in the city. It is possible that systematic differences in the averaging times of the flow data could lead to differences in the calculated emissions (Namdeo et al., 2002). In this respect, annual averages were adopted in the macro-scale approach, whereas the traffic flow was at

Fig. 4 – Annual CO_2 emissions (t/km).

different times of day and week were included in the currently reported work.

Transport Research Laboratory (TRL) emission factors were adopted in the current study, whereas the macro-scale approach study used National Atmospheric Emissions Inventory (NAEI) figures classified into a fewer vehicle types (National Atmospheric Emissions Inventory, 2003). The TRL database uses the new Euro standards and is more up to date than NAEI. Consequently, the better efficiency of new vehicles is taken into account in the TRL figures and these were assumed to be better indicators of traffic emissions.

In summary, there are a number of reasons why the results might differ according to the type of modelling approach adopted. However, all things considered, the macro-scale approach applied to Norwich and the current work are in reasonably good agreement.

Users can validate SATURN with input data within road network file. Once a model has been run, the validity of the data may be examined by regressing the output values against observed traffic counts for selected roads. An uncertainty of less than 10% is usually considered acceptable (Van Vliet, 1998). In the current work, a comparison of traffic flows modelled by SATURN and observed traffic counts for the study period (provided by Norfolk County Council) suggested that there were uncertainties of between 6.5% and 9% for the morning peak periods and between 9% and 12% for the afternoon peak periods. These compare favourably with estimates (between 6.8% and 16.3%) for a 3 km radius road network around the centre of Manchester (UK) using SATURN (Matzoros et al., 1987).

4. Conclusion

In the current approach, CO_2 emissions have been estimated using a micro-scale modelling approach, in which emissions have been estimated on a street-by-street basis. The work was based on a Loose-Coupling approach that incorporated SATURN, MATLAB and ArcGIS. A Loose-Coupling approach has advantages over the alternative macro-scale approach, which relies on overall usage and consumption figures, since it allows the impact of different traffic regimes to be predicted. This is especially true for urban areas. Moreover, it enables the overall area to be split up into zones also, thus enabling local pollution management.

The modelling approach was applied to the city of Norwich for the year 2003. The overall traffic related CO_2 emissions were calculated to be 69,105 t and this is in reasonably good agreement with a macro-scale model applied to the area. The modelling indicated that around 85% of the total CO_2 emissions in Norwich were from main roads in 2003 and only 15% were from minor roads. Cars were the major sources contributing 72.5% of all CO_2 emissions, followed by LGVs (12.5%), HGVs (7.5%), buses (6.5%), and motorcycles (1%). Of the total emissions, about 41% were attributed to the off-peak periods. This is an important observation as a lot of transport planning studies focus on peak periods only.

Another important result is that about half of all journeys were found to have originated from outside of the study area.

While CO_2 emissions in urban areas have been measured and applied in air quality management (Idso, 1998; Idso et al., 2001; Nasrallah et al., 2003), the current work has demonstrated that modelling is an extremely useful tool in assessing emissions in relation to greenhouse gases. This is especially important in the case of traffic-generated emissions, since there might be the opportunity to reduce total emissions by urban restructuring, developing road networks, and changing traffic demands. The study emphasised the versatility of ArcGIS in illustrating urban road traffic CO_2 emissions in a format that might be user-friendly to planners or decision makers.

A Loose-Coupling approach has a disadvantage in that some knowledge and experience of all component models (i.e. SATURM, MATLAM and ArcGIS) is required. Using a Tight-Coupling approach, in which the components are interlinked would make this more user-friendly, although it would have the disadvantage that it would become more difficult to explore the impact of minor model modifications or input data.

The modelling approach is useful for examining future scenarios. Traffic planers and environmentalist can simulate how much road traffic related emissions could be produced using different plans. A following paper is to be presented that addresses the impact of traffic management on carbon dioxide emissions and discusses various scenarios in detail.

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