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Increasing attention has been focused on the health effects of urban transport in recent years. This report highlights the framework in which integrated assessment of the effects of urban transport on health can be carried out. The discussion is based on the results of a research project called HEARTS (health effects and risks of transport systems) conducted as part of the Fifth Framework Programme of the European Union by an international consortium, including leading European research institutions and the WHO European Centre for Environment and Health.

The HEARTS project provides a method for estimating the health effects of air pollution, noise and road accidents and an instrument for integrating health impact assessment in the decision-making on and assessment of transport and land-use policies in urban areas.

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HEALTH EFFECTS AND RISKS OF TRANSPORT SYSTEMS: THE HEARTS PROJECT

WORLD HEALTH ORGANIZATION
EUROPE

Health Effects and Risks of Transport Systems: the HEARTS project

Quality of Life and Management of Living Resources - Environment and Health

Health effects and risks of transport systems: the HEARTS project

Quality of Life and Management of Living Resources - Environment and Health

Abstract

Increasing attention has been focused on the health effects of urban transport in recent years. This report highlights the framework in which integrated assessment of the effects of urban transport on health can be carried out. The discussion is based on the results of a research project called HEARTS (health effects and risks of transport systems) conducted as part of the Fifth Framework Programme of the European Union by an international consortium, including leading European research institutions and the WHO European Centre for Environment and Health. The HEARTS project provides a method for estimating the health effects of air pollution, noise and road accidents and an instrument for integrating health impact assessment in the decision-making on and assessment of transport and land-use policies in urban areas.

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Abbreviations

AVTUNE	AirViro-based Traffic and Urban Noise Evaluator
CO	carbon monoxide
EU	European Union
GIS	geographical information system
HEARTS	Health Effects and Risks of Transport Systems
L_{den}	average levels during daytime, evening and night-time
L_{night}	A-weighted average night-time level over a year for the period from 2300 to 0700 at the façade of a dwelling with the highest L_{den}
NMPB	Nouvelle Méthode de Prevision du Bruit (France's official model for predicting road traffic noise)
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
PM_{10}	particulate matter with aerodynamic diameter smaller than 10 µm
$PM_{2.5}$	particulate matter with aerodynamic diameter smaller than 2.5 µm
$PM_{1.0}$	particulate matter with aerodynamic diameter smaller than 1.0 µm
STEMS	Space Time Exposure Modelling System
TEE	Transport, Energy and Environment

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Executive summary

Promoting healthy and sustainable transport options to prevent the negative effects of transport systems on human health is an important goal of modern policy development. This means ensuring that health issues are considered when transport policies are being formulated and creating the conditions to develop integrated assessments, monitor progress, account fully for social and environmental costs and identify the strategies with the greatest net benefits. Integration initially requires combining scientific knowledge, methods and results into one long list. Further, integration comprises selecting the procedures and practices that contribute most to the overall objective of a healthy and sustainable transport system. Overcoming the shortcomings of fragmented and even inconsistent approaches is also important. More importantly, integration also means promoting a dialogue and developing shared language and tools between various sectors of civil society (such as health, transport and environment) and stakeholders. Nevertheless, analytical tools to pursue an integrated assessment of transport scenarios have been unavailable, inadequate or scantily produced. Characterizing transport-related exposure requires detailed information on the spatial and temporal trends of various risks, people's mobility patterns, the ability to predict exposure in unmonitored settings and considering the policy dimension in terms of the involvement of relevant sectors. This information is developed by and is available from various professions with little experience of collaboration. A main challenge is therefore to bring together within a coherent framework a diversity of inputs to appraise the effects of transport systems on health.

The main purpose of the health effects and risks of transport systems (HEARTS) project was to develop and test integrated health impact assessment methods designed to assess changes in exposure patterns and the related health effects arising from various urban transport policies. The risks considered included air pollution, noise and road crashes. In order to develop an integrated approach, we, the authors of this report, thoroughly reviewed various models relating to transport, especially including models of road traffic, air pollution, noise, crashes, time–activity patterns, exposure and health effects. Based on this review, we selected existing models for incorporation and use in HEARTS and developed new models where necessary. These models operate by assigning exposure to individuals or populations according to the proportion of time they spend in various microenvironments, each of which can be characterized by distributions of pollution concentrations. The various models were linked through a geographical information system (GIS) to provide an integrated assessment toolbox.

Another objective was to test the exposure models and estimate health effects by combining the exposure model with available dose–response curves. To this end, we reviewed relevant epidemiological research and identified the most suitable dose–response functions.

Three case studies were carried out in the cities of Leicester (United Kingdom), Lille (France) and Florence (Italy):

- to help develop the HEARTS methods;
- to field test and validate the various tools; and
- to demonstrate how the HEARTS approach might be used for assessing policy.

In the case studies, integrating health and environment into transport policies required political commitment to intersectoral cooperation and a change in current strategies towards fully considering the social implications of transport policy.

The work undertaken in HEARTS, especially the modelling, was informed by the completion of state-of-the-art reviews of key aspects of methods (Table 1).

Table 1. Summary of the modelling and methods developed

Type of modelling reviewed	Summary of modelling and methods developed	Validation of models
Traffic emission modelling	Traffic models to analyse congestion, trip lengths, fleet composition, the parking process and, through traffic emission models, focusing on the effects of kinematics, cold-start emissions link by link, evaporative emissions and the advantages of considering parking processes	City teams validated the traffic models in part. The emission model the Italian National Agency for New Technologies, Energy and the Environment provided for Florence was validated jointly with the Regional Environmental Protection Agency of Tuscany.
Time–activity patterns under GIS	Custom-designed probabilistic time–activity model to simulate route choice, mode and timing based on incomplete time–activity data (Space Time Exposure Modelling System (STEMS)-Trip)	The STEMS-Trip model could not be formally validated. Trip modelling was tested against detailed trip data for schoolchildren in Leicester, United Kingdom.
Air pollution modelling	Custom-designed air pollution model based on focal sum techniques (STEMS-Air)	STEMS-Air has been validated in Northampton and Leicester (United Kingdom) using carbon monoxide and PM_{10} (particulate matter with aerodynamic diameter smaller than 10 μm) as the marker pollutants. The results show performance comparable to that of proprietary dispersion models.
Noise emission and propagation modelling	Adapted version of the Calculation of Road Traffic Noise (CRTN) model used in the United Kingdom programmed into GIS (STEMS-Noise)	The results from STEMS-Noise were compared with data for sites in Leicester, modelled using the AVTUNE model.
Crash risks	Models for vehicle and pedestrian crashes, based on the Routledge formula, programmed into GIS (STEMS-Crash)	Directly validating the crash models at individual locations is not practicable, given the lack of appropriate reference data on crash events. Comparisons could, however, be made with area-wide data on crash rates.
Pedestrian behaviour	A pedestrian crossing behaviour model, based on reanalysis of Florence and Athens data, was programmed into GIS (STEMS-Walk) The Italian National Agency for New Technologies, Energy and the Environment developed a new model based on Rome measurements in the Via Appia area (subcontract to Rome 3 University)	The results from model validation within the HEARTS city case studies are promising. However, there is some evidence that further improvement is possible, mainly for the further calibration of the parameters.
Time–activity modelling	Time use and activity data in microenvironments were collected from existing databases, including the Harmonised European Time Use Study (HETUS) and EXPOLIS database and from the HEARTS case studies. Data distributions were parametrized and intercorrelations computed for the model to be applied in probabilistic simulations	The model uses primary data, which do not need validation. Model application has been validated earlier using $PM_{2.5}$ data in Helsinki and carbon monoxide data in Milan.

The aim of the case studies was not only to demonstrate and test the available methods but also to help develop and validate the models. The cities chosen for the case studies were Leicester (United Kingdom), Lille (France) and Florence (Italy). Each case study differed in its focus (see Table 2).

In Leicester, the study focused on collecting detailed data on the time–activity patterns of children and personal exposure to air pollution both in-vehicle and while walking, to inform and validate the modelling. Noise was also monitored and modelled in detail, and a policy scenario was analysed relating to a current safe-routes-to-school initiative. In Lille, two scenarios of transport policy were evaluated based on a set of actions recommended in the Plan de Déplacements Urbains, but much of the focus was on pedestrian behaviour and road crash modelling. The Florence case study included monitoring of noise and air pollution and analysis of a planned traffic management policy.

Table 2. Summary of case studies

City	Description of case study	Scale and/or parameters	Scenarios modelled
Leicester	Small-area study of mixed residential area along a major transport corridor in south-western Leicester. The case study focused on collecting primary data on children's time–activity patterns, personal exposure to air pollution in various transport microenvironments and validating and testing air pollution and noise models against monitored data.	Small areas (about 20 km^2). Key parameters: exposure to air pollution (PM) in various transport microenvironments; time–activity patterns and route choice of children; and noise monitoring and modelling measures.	A policy scenario for a walk-to-school initiative was assessed using HEARTS methods. Schoolchildren's exposure to traffic PM in walking to and from school versus riding in cars.
Lille	Data on mobility, networks, traffic, air pollution and road crashes were collected, structured and completed in a data warehouse and GIS. Special simulation tools were developed for routes and places of inhabitants in a part of Lille Métropole, the "new" city of Villenneuve d'Ascq, to assess the health impact of the plan for urban transport specially designed to reduce car use. A method of measuring pedestrians' exposure to crash risk was set up with observation techniques such as follow-up, interview and GIS coding techniques for the route and crossings of walking trips for children, teenagers and adults.	Two types of risk due to transport: crashes and air pollution and two groups in the population: children 5–10 years and employed people 18–60 years old. Activities: commuting (one-way and return trips) associated with a trip by car (plus walking), by pure walking or by metro (plus walking). Because of the capacity of the software, we limited the study area to Villeneuve d'Ascq, which is a "new" city situated on the west of Lille Métropole.	The technical agencies of Lille Métropole elaborated two scenarios of transport policy for 2015: a business-as-usual one and a proactive one based on a set of actions recommended in the Plan de Déplacements Urbains such as: improving public transport: more buses, cleaner buses and faster buses; development of metropolitan and cross-border express trains; planning to encourage bicycles: parking possibilities, cycle paths and tracks; and diffusion of company mobility plans to encourage more rational use of transport for employees in companies and administrations.
Florence	Create an integrated modelling system by loosely coupling the various models within a GIS. Carrying out a campaign to measure exposure to $PM_{2.5}$ and analyse the elements in $PM_{2.5}$ samples.	Whole city area	Commuter exposure to traffic PM in the maximal use of the new planned commuter tram line versus the present.

Table 3 lists the main types of modelling, analysis and data development undertaken in the three case study areas.

In HEARTS, we demonstrated the possibilities and identified the challenges of an integrated approach of assessing the health effects of road transport. We developed and characterized a systematic approach to processing and analysing data and brought together a set of models that constitute a decision-support tool to test various urban policy scenarios. The resulting HEARTS multimodal approach involved the combined use of existing methods (such as noise) and custom-designed new models (such as regarding emissions, road crashes, air pollution, pedestrians and exposure modelling).

Table 3. Summary of general methods (measurement and modelling) used in the HEARTS case studies

Case study	GIS development	Air pollution	Time–activity patterns and trips	Pedestrian crossing	Traffic modelling	Noise	Emission and dispersion	Speed and road crashes
Leicester	√	√	√		√	√		
Lille	√	√	√	√	√			√
Florence	√	√			√	√	√	

The main results and methods developed during the project comprised:

- selection of the most significant health end-points to characterize the health impact of air pollution, noise and road crashes as a function of urban transport policies;
- review of existing data, models and software tools for transport models, time–activity patterns, air pollution and noise;
- improvement of traffic modelling and emission modelling;
- design of a data warehouse and platform within a GIS environment;
- outline of the method for characterizing transport scenarios;
- development of an exposure model that takes into account the mobility patterns of the study population;
- collection of new data on time–activity patterns, personal exposure to air pollution in transport microenvironments, ambient noise and pedestrian behaviour that were used for model development and validation in HEARTS and will provide important databases for future research; and
- development and implementation of a GIS-based system that includes an air pollution model, noise model, pedestrian behaviour model, trip generation model and exposure model.

Overall, the study shows that individuals trying to minimize personal exposure to traffic pollution face different and often conflicting choices and constrictions, not only in the mode of transport but also in relation to where they live and work. The consequences of these choices and constrictions for the individual do not always match those for the community. For example, people moving to live in the suburbs to obtain better air quality contribute to urban sprawl and addition demand for transport. Optimizing both individual and common benefits will require new approaches to urban planning together with investment to reduce the emissions of private cars, public transport and to clean the indoor air in buses, metro stations and metro cars.

For example, case studies showed the following.

- The time–activity patterns of children 5–11 years old are complex. Most children in the Leicester study area walk to school (only about 20% went by car), and most children go to local schools, with average journey times (walking or by car or bus) of about 10–15 minutes. Out-of-school activities, however, were extensive, especially for a minority of children who were involved in complex trip chains during the day. Modelling shows that travel behaviour greatly affects children's exposure to air pollution and is likely to be important in determining health risks.

- Our study provided evidence of significant differences between exposure to air pollution while in-vehicle and walking. In the Leicester case study, kerbside concentrations of PM tend to be greater than those in-vehicle and the durations of exposure longer for people walking than those travelling by car or public transport, leading to about a 4- to 10-fold increase in exposure for pedestrians compared with car passengers or drivers. This has important implications for policies aimed at encouraging walking and highlights the need to design safe low-pollution walking routes for pedestrians.

- A scenario modelling a no-driving-to-school policy shows that effects on exposure to air pollution vary depending on the lifestyle of individuals. For most children, exposure would increase if they changed from travelling by car to walking; for those who continue to use a car (or continue to walk), however, the reduction in local air pollution levels provides a slight alleviation of exposure. The disadvantages in terms of air pollution exposure to those shifting their behaviour are likely to be offset by other advantages – including more exercise and opportunities for socialization. This highlights the need for an integrated approach to the risk assessment of such policies.

- Various techniques can be used to estimate the road crash risks for pedestrians, and this is an important step in integrating the modelling of exposure to road crashes with exposure to noise and air pollution.

- About 9% of people's time is spent in traffic during weekdays in Florence. This result is consistent with other studies in European cities and seems to indicate a nearly constant percentage of time that people use during their daily routines to travel, which has relevant policy implications.

- According to a comparison between the situation in 2003 and a scenario tested for 2010, PM10 can decrease, with positive health effects such as a reduction of 129 adult deaths per year and a reduction of 1400 years of life lost per year.

- In Florence, a relevant percentage of the population is exposed to high noise levels during both the whole day and at night. According to the scenarios tested, 2003 versus 2010, the expected reductions are 10% of annoyed people, 12% of highly annoyed people, 10% of sleep-disturbed people and 11% of highly sleep-disturbed people.

Critical evaluation of HEARTS' accomplishments has identified questions and open issues that future research projects can address. Several open issues on integration were successfully addressed, but the full development of an integrated method requires continuing and further strengthening the collaboration among different partners and testing several modelling solutions. The HEARTS approach represents a step forward in the development of an integrated approach to assess the health implications of urban transport policy (for more information and details, see the WHO Regional Office for Europe web site (http://www.euro.who.int/hearts)).

1. Introduction

Transport is an essential component of modern life and brings with it the potential to improve and erode public health. Road traffic is a major cause of adverse health effects – ranking with smoking and diet as one of the most important determinants of health in Europe. The European Commission (2006) evaluated the transport system in the European Union (EU) as "currently not sustainable, and in many respects moving away from sustainability rather than towards it". Traffic-related air pollution, noise, crashes and social effects combine to generate a wide range of negative health consequences, including increased mortality, cardiovascular, respiratory and stress-related diseases, cancer and physical injury. These affect not only transport users but also the population at large, with particular impact on vulnerable groups such as children and elderly people, cyclists and pedestrians. However, European countries do not have a uniform set of experiences, methods and applications, and most of the progress in transport tends to be concentrated in a few countries, such as the Nordic countries, France, the Netherlands and the United Kingdom.

The main purpose of the health effects and risks of transport systems (HEARTS) project was to develop and test an integrated impact assessment method to evaluate changes in exposure patterns and related health effects caused by various urban transport policies. The risks under consideration include air pollution, noise and road crashes. There is a complex relationship between the levels of environmental pollution, social deprivation, sociobehavioural factors, respiratory ill health, risky behaviour such as smoking and people's perceptions about pollution (Hunter et al., 2003). HEARTS did not consider psychosocial effects, lack of physical activity and other risks associated with transport scenarios, primarily because further basic research is needed to confirm these effects and the causative mechanisms involved. We, the authors of this report, focused the analysis on vehicular transport, not considering emissions from air, rail and water transport that are also partly responsible for noise emission, acid deposition and other air pollution as well as climate change.

To inform the study, we first thoroughly reviewed various models relating to transport. In particular, we reviewed models concerning traffic, air pollution, noise, crashes, time–activity patterns, exposure and health effects. Based on this review, relevant models and methods were selected and brought together and new models developed where necessary. The various methods and models were then linked via a geographical information system (GIS). Three case studies were carried out in Leicester (United Kingdom), Lille (France) and Florence (Italy) to help develop the models, field-test the methods and demonstrate the use of the HEARTS approach. The first issues to be discussed are related to the scientific background of the project and how a health-centred research agenda can be developed for urban and regional planning that transcends traditional academic and institutional boundaries.

1.1 Scientific background

Since 2000, the need for a new approach integrating the direct and the indirect effects assessed during health impact assessment has been recognized. The HEARTS project was developed as a response to this challenge in order to improve the tools for assessing effects on the environment and health.

A WHO meeting in 1986 recommended that the health component of environmental impact assessment include not only disease-related effects but also all effects that might change the well-being of humans (WHO Regional Office for Europe, 1987). But this recommendation is not reflected in environmental impact assessment practice, and health effects are often overlooked. An empirical study of 42 environmental impact statements from the United States found that more than half contained no mention of health effects; the statements consistently overlooked health effects or superficially addressed them (Steinemann, 2000). Thus, flexible methods are needed for describing health effects. In the development of health impact assessment, two broad approaches are usually acknowledged: the biomedical approach and the social determinants of health approach (Morgan, 2003). WHO initially promoted the first approach in the 1980s and defined it as environmental health impact assessment (WHO Regional Office for Europe, 1987). Environmental health impact assessment is based on the biomedical model of health, illustrated in direct effects such as mortality and morbidity. The second approach of health impact assessment evolved from public health considerations and is based on the interrelationships between the population and the environment, including socioeconomic determinants of health and institutional factors. This approach allows the indirect effects of projects and policies on health to be estimated.

Health impact assessment provides a structured framework to map the full range of health effects of any proposal and action, whether these are negative or positive (WHO Regional Office for Europe, 2002): “Health impact assessment is a combination of procedures, methods and tools by which a policy, programme or project may be judged as to its potential effects on the health of a population, and the distribution of those effects within the population” (WHO European Centre for Health Policy, 1999:4). Integrated assessment, incorporating health impact assessment, allows policy development to ensure that health effects are not overlooked. The integration of the modelling of various risks with scenario testing is a recent development in road transport planning. Modelling has also been linked to GIS to evaluate the environmental effects of air pollution from road traffic in urban areas (Affum et al., 2003).

Extended modelling of the exposure of population groups to air pollution has developed a “geography of risk” (Jerrett & Finkelstein, 2005), including susceptible population groups, clustering and the possible confounding and modifying influences of socioeconomic aspects. For example, studies indicate that people with lower educational attainment have greater negative effects associated with air pollution than people with higher education (Krewski et al., 2000). The susceptibility of individuals, groups and populations is related to both time and scale. Agent-based modelling and time geography entered into the latest integration developments, opening new directions not only for research but also for applications (Longley & Batty, 2003). Assessment of exposure to urban pollution must balance "nighttime geography" (where people reside) with the "daytime geography" of pollution: "To understand and quantify exposure effectively, therefore, models need to recognize the ever-changing intersection between two dynamic geographies – that of pollution and that of people" (Briggs, 2005:1252). The study of the exposure patterns and the evidence of negative health effects associated with several transport-related factors are then essential in developing an integrated strategy.

"Health impacts are the overall effects, direct or indirect, of a policy, strategy, programme or project on the health of a population" (WHO European Centre for Health Policy, 1999:4). Considerable evidence shows that a wide range of health risks is associated with specific types of exposure to road traffic (Krzyzanowski et al., 2005). Much concern in recent years has focused on the link between traffic-related air pollution (especially fine particulate matter (PM) and respiratory and cardiovascular illness, but evidence is also growing about the health effects of other air pollutants (such as ozone (O_3), carbon monoxide (CO) and nitrogen dioxide (NO_2)) that are directly or indirectly associated with transport (Brunekreef & Holgate, 2002). In addition, some studies have shown an association between respiratory disease and living near busy roads or roads with many heavy vehicles (Brunekreef et al., 1997). Evidence also shows that road traffic noise has health effects, ranging from annoyance to sleep disturbance and stress-related mental and physical effects (such as increase in blood pressure) associated with traffic-related noise, and perhaps air pollution (Babisch, 2005; Berglund et al., 1999; van Kempen et al., 2005). Road traffic injuries are among the major causes of loss of life and disability in Europe, especially among younger people, leading to major societal costs, with most road traffic injuries taking place in urban areas.

The health effects of transport affect the population at large and not only transport users. Many of the negative effects are borne by vulnerable groups such as children and elderly people, those with cardiovascular and pulmonary diseases and cyclists and pedestrians (Dora & Phillips, 2000; Transport, Health and Environment Pan-European Programme, 2004). Pedestrians and motorcyclists suffer the most severe injuries and report more continuing health problems (Mayou & Bryant, 2003). For example, in Barcelona, pedestrians and two-wheel motor-vehicle occupants, besides accounting for two thirds of motor-vehicle injury cases, are the user groups with a greater risk of a more severe injury (Cirera et al., 2001): "Focusing on these two subgroups, rather than applying broadly unspecific injury prevention policies, should contribute to an important reduction in motor vehicle crash rates, as well as in the severity of injuries" (Cirera et al., 2001:206). However, this should be seen not only in the context of vulnerable road users; addressing these groups implies making the system safe for everybody.

Integrated approaches to risk assessment are clearly needed to assess these various effects on human populations and the consequences of various transport policies. The main aspects of an integration process are related to collecting and manipulating complex empirical information. This is complex because data are linked to an array of variables, designed with different purposes and techniques and dependent on space and time. For this reason, statistical manipulation of data implies sophisticated methods and not just the use of one statistical technique. Integration means a tool and a research direction based on different specific moments, including theoretical elaboration, political discussion, data collection and statistical analysis. A detailed description of these aspects referred to a concrete experience of case studies gave us the opportunity to discuss the possible applications. In the wider context of impact assessment, the integrated approach involves different practices and "a move towards integrated assessment could be an opportunity to reassess existing practices" (Mindell & Joffe, 2003:111) such as environmental impact assessment, strategic environmental assessment and social impact assessment. In accordance with the principles of recent developments of policy and legislation on environment and health in Europe, policies in several sectors should endeavour to reduce the health risks associated with transport while also meeting other policy goals.[1] The importance of this is heightened by the continued growth in transport demand and road traffic, which means that road transport is likely to remain a major policy concern for the foreseeable future (Peden et al., 2004). According to the Global Burden of Disease study, road crashes were ranked number nine in the list of disability-adjusted life-years in 1990 but are projected to rank third in disability-adjusted life-years by 2020 (Murray & Lopez, 1996).

Transport poses a large burden in terms of health effects and has deep implications for sustainability (Dora & Philips, 2000). Transport activities should be equitable in a broad sense between generations and across social groups and countries. Transport activities should allow the needs of the present generation to be met without compromising the ability of future generations to meet their own needs. At the same time, the transport network should not be socially discriminatory and should ensure spatial equity that does not generate inequality in accessibility at any scale but a distribution of transport resources benefiting the population regardless of their residential, work and leisure location. A sustainable transport system should limit emissions and contamination to the environment's capacity to receive them, minimize consumption of nonrenewable resources, limit consumption of renewable resources, reuse and recycle its components, minimize the use of land and the production of noise, consider transboundary pollution effects and not result in death and severe injury.

1.2 Objectives of the project

The HEARTS project was aimed at better characterizing the health implications of road traffic and urban transport in Europe by developing and demonstrating an integrated approach to and methods for risk assessment.[2] Applying this approach would then help to reduce adverse consequences of transport on health in Europe by:

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1 Article 152 of the European Union Amsterdam Treaty, ratified in 1998, states that "A high level of human health protection shall be ensured in the definition and implementation of all Community policies and activities".

2 "Generally speaking a sustainable transport system must contribute to economic and social welfare without depleting natural resources, destroying the environment or harming human health" (European Commission Expert Group on Transport and Environment, 2000).

- more accurately specifying the health effects of urban transport;
- improving the ability to carry out integrated risk assessment to assess and compare urban transport schemes and policies;
- deepening understanding of the geographical and social distribution of the health risks of transport within urban areas and developing related land-use policies specific to local conditions and to population groups across the EU;
- better characterizing the subgroups most at risk for multiple health effects and better targeting public health and transport-related policy interventions to mitigate these risks;
- facilitating dialogue between different sectors of urban administration, policy-makers and stakeholders and explicit trade-offs in urban transport and land-use planning decisions.

The development and application of an integrated approach was pursued through the following actions:

- discussing and reviewing risk assessment methods, dose–response relationships and evidence of exposure and effects and measures of risk assessment outcomes;
- identifying relevant transport-related health end-points to be considered in integrated health impact analysis;
- defining case studies in terms of policy scenarios and data requirements;
- reviewing existing models and software tools regarding road traffic;
- integrated modelling of the exposure to and risks of air pollution, noise and road crashes;
- identifying spatial and temporal scales suitable for integrating risk analysis; and
- planning a survey and monitoring campaign in city case studies.

1.3 Phases of the project

The HEARTS project was divided into five overlapping and interdependent phases:

- phase 1: reviewing, comparing and selecting concepts, models and policies; specifying data requirements; and selecting city case studies;

- phase 2: acquiring, developing, testing and validating models; and collecting data at test sites.

- phase 3: linking models and developing transport scenarios;

- phase 4: developing the case studies; and

- phase 5: synthesis, statistical analysis and interpretation.

The project produced 26 deliverables. This publication summarizes all the phases of the project.

1.4 List of partners and key responsibilities

HEARTS was a three-year, multiple-partner project. Table 1 describes the consortium and the responsibilities of each partner.

Table 1. HEARTS partners and key responsibilities

Partner name	Key responsibilities
WHO European Centre for Environment and Health, WHO Regional Office for Europe	Coordination Health effects models (relevant outcomes, dose response functions) Synthesis and interpretation
Imperial College, London, United Kingdom	Air pollution models Exposure modelling Model development and linkage (overall integration in a GIS environment) United Kingdom case study
National Public Health Institute, Helsinki, Finland	Population exposure (to air and noise pollution in indoor, outdoor and transport microenvironments) Time–activity models
Italian National Agency for New Technologies, Energy and the Environment, Rome, Italy	Noise models Transport and emissions models
French National Institute for Transport and Safety Research, Arcueil, France	Road crash models France case study
Institute of Studies for the Integration of Systems, Rome, Italy	Transport policies and scenarios Italy case study
Université de Versailles Saint-Quentin en Yvelines, France	Development of a data warehouse
Subcontractors	
National Technical University of Athens, Greece	Pedestrian behaviour
National Institute of Public Health and the Environment, Bilthoven, Netherlands	Noise and health reviews
Berry Environmental Ltd, Shepperton, United Kingdom	Noise and health reviews
Institute for Transport Studies, Leeds, United Kingdom	Noise models

2. Material and methods

In evaluating the health implications of urban transport policies, the traditional focus on the impact of a single risk factor has some limitations. Strategies and policies developed to address one risk might increase other risks. Tools for integrated risk assessment are therefore needed to provide appropriate information to policy-makers and stakeholders and to inform the development of road transport policies that ensure that health is fully taken into account.

2.1 Reviews

The work undertaken in HEARTS, in particular the modelling, was strongly informed by the completion of state-of-the-art reviews of key areas of research, including air pollution, noise pollution, traffic and pedestrian movements and road crashes. These reviews were completed early in the project but, reflecting the dynamic nature of this field of research, developments continued to occur throughout the lifetime of the project, so reviews were updated as necessary.

Table 2 summarizes the results of this review.

Table 2. Summary of the results of state-of-the-art reviews used to inform HEARTS methods

Issue	Information reviewed	Summary and conclusions
Traffic models	Over 15 widely used traffic models were reviewed	Models normally used can have difficulties in modelling congested links
Emission models	Over 32 emission models of various types were reviewed	The Transport, Energy and Environment (TEE) model of the Italian National Agency for New Technologies, Energy and the Environment was selected for further development: focus on parking processes and linked cold start and evaporative emissions. New software was positively applied and assessed in a Florence case study
Air pollution	Review of extensive literature on air pollution models and of results from other EU and national projects; bench-testing of selected models	Most cities have access to their own dispersion models and are reluctant to use models imposed from outside; exposure modelling thus needs to use outputs from locally selected models; simple screening model is needed for users who do not have access to their own models
Noise pollution	Scientific and technical literature, project reports, EU directives and guidelines, technical specifications by software package suppliers	Standards, methods and software packages to calculate the main noise indicators (L_{den}, L_{night}) selected as end-points to estimate population exposure to noise and relevant health effects
Time–activity models	Scientific publications, international and national time-use surveys (Harmonised European Time Use Study (HETUS), Multinational Time Use Study (MTUS) and National Human Activity Pattern Study (NHAPS), EXPOLIS database)	Time use and activities in microenvironments were parametrized and intercorrelations computed for a model to be applied in probabilistic simulations
Road crashes	Crash risk models (Transport Research Laboratory (TRL)) Pedestrian movement models, pedestrian behaviour models and pedestrian crossing decision models	The existing modelling techniques (gap acceptance theory, pedestrian level-of-service and discrete choice models) are not adequate for the detailed description of pedestrian crossing behaviour along a trip, as required in HEARTS
Health effects	Scientific literature, WHO guidelines and reports	PM and O_3 were the pollutants of interest in models

2.2 Road traffic and emissions

Information on road traffic and its associated emissions underpins the HEARTS methods. It is essential as a basis both for assessing risks and for identifying potential loci for intervention. Reliable data and models on road traffic and emissions are thus a prerequisite for integrated risk assessment using the HEARTS approach.

Clear criteria were initially developed to help identify and select appropriate methods and models. Framing these were a set of general criteria valid for both transport and emission models:

- adequacy for the types of application to be modelled: the capacity for adequately handling the transport scenarios and predicting the consequences (such as traffic redistribution, congestion reduction, higher traffic fluidity and lower emissions and noise) associated with the city case studies carried out in HEARTS and anticipated future applications; and

- adequacy with respect to the prerequisites of the HEARTS methods: the capability in general terms to reliably predict the variables involved in the HEARTS methods with the proper spatial and temporal resolutions.

More particularly, the following specific methodological criteria were defined for the transport models to be selected:

- full spatial coverage of the area of impact (sufficient description of the transport network, consideration of all area types such as residential and central business districts and parks);

- capability of modelling different modes of transport (car, bus, motorcycles, walking, cycling and rail vehicles such as urban trains, trams and underground) and behaviour related to modal choice;

- ability to handle detailed information on trips and network (spatial and temporal resolution of origin–destination matrices and description of secondary streets if these are considered relevant for the impact on people);

- the possibility of including an adequate description of fleet composition by link type (at least in terms of macro categories, such as passenger cars, motorcycles and buses);

- adequate microrepresentation of cold trips – providing either the fraction of cold vehicles in each link or the distance travelled from the origin that can then be used in an emission model for calculating the local percentage of cold vehicles; and

- providing information on the speed variability along each link of the modelled network, either in relatively simple terms (waiting time, queue length and primary and secondary stops) or more accurately (speed second by second as managed by traffic simulators).

Similarly, the following specific methodological criteria were identified for emission models:

- capability of predicting emissions in terms of appropriate sensitivity to the parameters likely to be affected by the measures considered (such as fleet composition, vehicle kinematics and trip length);

- capability of providing results related both to a single link in a single hour and to a complete domain of the network in a flexible time interval;

- capability of considering all the vehicle categories comprising the European fleet, up to the most recent vehicles (such as the Euro 4 category for cars);

- adequate micro-scale representation of cold-start effects, based on the availability from traffic models of either the percentage of cold vehicles in each link or the provision of the distance travelled from the origin of the trip; and

- realistic modelling of the effects of the speed variability along each link of the modelled network.

2.2.1 Traffic models

Traffic models are normally split into a) static models (such as EMME/2); semidynamic models (such as VISUPOLIS or SATURN); land-use and transport models (such as TRANUS) and microsimulators (such as HUTSIM, NETSIM or PARAMICS). Each category is best fitted for different studies. Emission models estimate emissions from vehicles, and air pollution models calculate pollutant concentrations by simulating the dispersion and transformation processes taking place in the air. The choice of the computer simulation systems to be used in transport studies is governed by the objectives of the analysis as well as the available resources. A common classification method for computer simulation systems is based on the detail level with which the incorporated models suite intends to simulate the components of the transport system. According to this, computer simulation systems can be conveniently classified into four categories that reconcile the differences between alternative modelling concepts and theories, as well as between different levels of investigation in traffic and transport studies. Starting at the most detailed (micro) level, there are:

- operational micro-simulation models that consider the characteristics of each individual vehicle and its interactions with other vehicles in the traffic stream;

- tactical network models that are suitable for analysing dynamic traffic effects, which are critical in network simulation during medium to congested flow conditions;

- strategic multimodal transport models that are best suited to the urban-scale analysis of travel demand and transport network performance; and

- models of the interaction between land-use and transport that synthesize the dynamic interaction between transport provision and land-use activities.

Tactical network modelling packages (also called congested assignment models) generally have a wider geographical scale of application than micro-simulation models. These can be used for representing a variety of situations from congested urban networks to regional inter-urban areas. In particular, they are designed to model the varying traffic demand and congestion that occurs during the day and to represent the peaks of congestion as well as off-peak conditions. They are ideally suited to traffic management schemes and systems. Thanks to their dynamic ability, these models can simulate unexpected events such as incidents that reduce network capacity and the effects of driver information systems. Some computer simulation systems can also handle more specific requirements such as modelling special vehicle lanes for buses or banning turning movements in certain situations. These models consider traffic as an aggregate fluid flow and divide the day into time slices, which are used to model the build-up and decline of traffic. Vehicles are assigned to their minimum cost routes, taking account of the traffic interactions and delays caused by other vehicles in the network. Two distinct submodels are usually incorporated in the classical computer simulation systems based on the fixed demand approach: the route choice model and the dynamic network loading. The route choice model estimates driver route choice based on the generalized costs that includes time- and distance-related costs. The dynamic network loading represents the interactions between vehicles, both on link and junctions, and calculates resulting traffic flows and network performance statistics. These two submodels are used iteratively until satisfactory levels of stability and convergence are achieved.

Dynamic network assignment models overcome the limitations of static assignment models by capturing the dynamics of the formation and dissipation of congestion associated with peak traffic periods. This enables the evaluation of a wide array of congestion relief measures, which could include both supply-side and demand-oriented measures.

Classical tactical network model packages exclude trip generation, distribution and modal split elements and are therefore suitable for evaluating schemes or policies that will only cause local rerouting of traffic. Nevertheless, recent extensions to the classical route choice models framework focus on the explicit modelling of departure time choice that allows the continuous splitting of a static origin–destination matrix over the time of the day based on the traffic situation.

The advantages of tactical network models are also that they produce output statistics that provide useful details on the speed-cycle for emissions and fuel consumption analysis, although aggregated on traffic flows and not available for each vehicle. Applying tactical network models to analysing air quality is suitable and advisable.[3]

The review highlighted the variety of tools available. Within the three cities running case studies, classical models have been used, including a typical static model such as EMME/2 and a typical micro-simulator such as PARAMICS. The differences among the various models allow areas of application to be identified where each type can be used with good confidence. The choice of the model depends on the type of policy to be studied. In this perspective, we can conclude that the choices made in the three cities were appropriate, even though this does not mean that the used models were perfect and without inherent approximations. Certainly a static model such as EMME/2 can give limited information on congestion and road crash–related variables, but the quality of the results achieved with this model also depends on the experience of the user. None of these models deals with exposure. Traffic models give traffic variables as output (such as flows, speed, queue length and speed profiles in the case of micro-simulators). If we consider emission models (or a direct effects model such as TEE 2005 by the Italian National Agency for New Technologies, Energy and the Environment) then it is possible to get information on pollutant emissions, noise emissions and road crash occurrence. Reaching exposure estimates also requires population behaviour models, pollutant and noise dispersion models and exposure models. Normally these models are independent and not linked. In a few cases (such as in the ISHTAR Project[4] under the Fifth Framework Programme), such models have been integrated in a suite. The Italian National Agency for New Technologies, Energy and the Environment proposed the use of the TEE 2005 version developed by the Agency itself in the framework of HEARTS Project in the Florence case study. This version is a significant upgrade of the 2004 version, produced for the ISHTAR Project, and focuses on modelling parking processes that have a major role in quantifying cold-start emissions, a major contributor to total emissions in urban centres.

The TEE 2005 software was applied and validated in the Florence case study. Traffic input came from EMME/2 model calculations, made available to the Regional Environmental Protection Agency of Tuscany by Florence partners. The emission results allowed better prediction of CO and PM concentrations. TEE 2005 was used with a 24-hour-per-day approach by applying the innovative kinematics correction model and parking model. The section on case studies provides details.

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3 Further information on the functionality and features of the software packages for micro-simulation is available at the following web sites: http://www.contram.com (CONTRAM), http://www.dynamictrafficassignment.org (DYNAMIT and DYNASMART), http://www.wsatkins.com (SATURN) and http://www.adpc.be (METROPOLIS). Other related references: University of Florida – Transportation Research Center – McTrans: http://www-mctrans.ce.ufl.edu and PTV AG: http://www.ptv.de.

4 The European Commission funded ISHTAR within the Fifth Framework Programme (EVK4-CT-2000-00034).

2.3 Air pollution

Air pollution modelling was reviewed and several models tested to help select appropriate models for use within the HEARTS approach and to inform further model development. Air pollution models vary greatly in complexity from simple screening models to more advanced models that are capable of simulating micro-scale dispersion of air pollutants (such as within a street canyon or at road junctions). Screening models are typically used to make a quick and general assessment of air pollution, often preliminarily to using more sophisticated models. For example, they are often applied in air quality management studies to identify pollution hotspots and areas where there is potential for exceeding EU limit values. Screening models tend to be based on a simple function that describes the magnitude of the emissions source and the distance between the air pollution source and the receptor, or target. Examples of screening models are Calculation of Air Pollution from Road Traffic (CAR) from the Netherlands and the one implemented in the United Kingdom government guidance *Design manual for roads and bridges* (Highways Agency et al., 1997).

Many dispersion models have been developed for modelling emissions from a range of source types (point, line and area), and these loosely fall into two groups: intermediate and advanced models. Intermediate dispersion models are capable of providing estimates over both space and time while having relatively simple parameterization and capabilities. These dispersion models apply Gaussian and Eulerian or other mathematical models of distribution and use some weather data to achieve results over time intervals (such as hourly). The main inputs are weekly or daily average traffic flow and speeds and hourly weather data.

Advanced models can accommodate relatively large numbers of sources and provide concentrations at high spatial and temporal (hourly) resolution for a number of grid or point receptors. They can use detailed information on traffic emissions and weather varying by the time of day and week. A distinguishing feature of advanced models is that they incorporate the effects that boundary layer conditions have on dispersion. Examples of advanced models are California Line Source Dispersion Model (CALINE4), AERMOD, AIRVIRO and Atmospheric Dispersion Modelling System (ADMS)-Urban.

However, health impact assessment does not fully exploit the capabilities of these models. The evidence on the health effects of air pollution, in fact, is based on large population groups characterized by the average pollutant concentrations, measured over time and space, often at low resolution. In some cases, the occurrence of adverse health effects is also studied in relation to distance from roads. Although sophisticated air pollution dispersion models can contribute to improving these approximations, the detailed information they provide cannot always be translated into equally accurate results on health effects.

2.4 Noise pollution

2.4.1 Methods and computation methods

Similar to any other modelling situation, the most important elements in selecting a traffic-related noise model are the validity and accuracy of results, the calculation time and the availability of suitable commercial software packages for its implementation.

The validity and accuracy of the predictions of a noise emission model depends mainly on:

- the validity and accuracy of the input data (site modelling and traffic data);
- the accuracy of the computation method (noise emission source and noise propagation models); and
- the quality of the software used for implementing the computation method, including the effect of optimization techniques on the calculation.

Most traffic noise models use semi-empirical methods, based on a combination of well-established theories on noise propagation with substantial experimental data from different origins (emission databases). This approach has the disadvantage of being based on data extrapolation, which can lead to great uncertainty. However, limitation in the accuracy of the noise prediction models does not outweigh the importance of a high level of validity of the results, this being the crucial factor in choosing a computation method.

Reproducibility, which means different users obtaining comparable results starting from the same input data and using the same standardized computation methods, is also an important criterion. Reproducibility is mainly ensured by adopting suitable and standardized computation procedures and, for this purpose, many EU countries (such as Austria, France, Germany, the Netherlands, the United Kingdom and Nordic countries) apply their own national standardized method for calculating road traffic noise emission and propagation. Table 3 lists the European noise models adopted as national computation methods.

All these official calculation methods have been defined based on extensive experimental and theoretical research. However, they all need to be improved in accuracy and harmonized at the European level. This has been the major aim of many research programmes and projects, such as the EU-funded Harmonoise, Rotranomo and Imagine (http://www.imagine-project.org) projects (Berry, 2001; Steele, 2001; Wölfel Meßsysteme-Software GmbH&Co et al., 2003).

Table 3. Noise models adopted as standard computation methods in selected European countries

Country	Model name
Austria	RVS 3.02 Lärmschutz (RVS 3.02)
France	NMPB (draft standard Pr S 31-133, incorporating *Guide de Bruit*)
Germany and Luxembourg	Richtlinien für den Lärmschutz an Straßen (RLS-90)
Netherlands	Reken- en Meetvoorschrift Verkeerslawaai II (RMV II)
Joint Nordic	Road Traffic Noise – the Nordic Prediction Method (NMR-96)
Switzerland	STL 86
United Kingdom and Ireland	Calculation of Road Traffic Noise (CRTN)

In urban areas, noise source models need to be improved to include additional factors, such as noise due to traffic congestion and to traffic lights (idling engine noise), which can greatly affect the accuracy of the overall prediction model. However, this can hardly enhance the accuracy of the overall prediction model. It is therefore necessary to have a better and more detailed description of urban traffic as a noise source by taking into account the kinematic behaviour (acceleration, deceleration and idling) of vehicles in the urban driving cycle and the effects of traffic signals. Further, the databases now available (such as the *Guide du Bruit* issued in 1980) are becoming out of date and need to be updated and extended by incorporating more vehicle categories. A research programme for updating the *Guide du Bruit* 1980 is already underway at the Transport and Environment Laboratory of the French National Institute for Transport and Safety Research, and some interesting results have been already published.

To overcome some of these remaining modelling problems, a new approach was tested within the Florence case study, which remedies the standard computational methods with a statistical model. This enables the results of the traditional calculation methods, applied to the main street network, to be adjusted to take account both of the traffic flowing along the secondary streets and specific local noise attenuation factors.

2.4.2 Noise software packages

Most of the commercial software packages are suitable for performing the required calculations and for producing the strategic noise maps required by the EU Environmental Noise Directive (European Commission, 2002).

Accuracy and calculation speed are inversely linked (the higher the accuracy required, the longer the calculation will take for a given number of receiver points), but each software package uses specific techniques and offers different user options for optimizing calculations. Therefore, the time required to calculate the resulting noise maps and data tables for a specific project and a defined area depends on the kind and quality of the software used.

Starting from an overview of a large group of software packages widely used in Europe, which are able to deal with almost all the specified European standard calculation methods, six software packages (IMMI, SoundPlan, Computer-Aided Noise Abatement (Cadna), Noisemap 2000, Lima and MITHRA) were short-listed, from which the following four were selected as the preferred models for use within the HEARTS approach:

- CadnaA-Mithra (DataKustik)
- IMMI (Wölfel)
- Lima (Brüel & Kjær)
- SoundPLAN (Soundplan).

These were chosen because they are fully GIS compatible and are able to perform the calculations according to many different computation methods and standards, including those recommended in the interim method (Nouvelle Méthode de Prevision du Bruit (NMPB)-Route 96 and French standard XPS 31–133). They also have been recently revised or updated to fulfil all the requirements related to environmental noise mapping according to the EU Environmental Noise Directive (European Commission, 2002).

2.5 Road crashes

2.5.1 Principles

Models of the total number of injuries, of the number of road crashes involving pedestrians and of the number of vehicle-only crashes were developed as early as the 1980s by TRL in the United Kingdom and implemented in the Software for Accident Frequency Estimation for Networks (SafeNET) tool. Since then, a wide range of models has been devised that differ in their underlying assumptions, functionality and scope. Some models aim at integrating speed as a risk factor. Crash severity is measured as the mean number of fatal, serious and minor casualties per crash. Various relationships have been proposed between the impact speed and the probability of being killed as a pedestrian if hit by a vehicle or between the decrease of speed in a collision and the probability of being killed as a car occupant. A critical analysis of these models concluded that the crash risk formulas estimated from samples of links or junctions are not really suitable for estimating the individual risk of involvement in an injury crash for any kind of road user (Summersgill & Layfield, 1996; Taylor et al., 1996). This is mainly because the forms of the relationship between the individual risk measured as the crash rate per kilometre for a car occupant and the three traffic variables (volume, concentration and speed) obtained from them are not realistic.

Against this background, HEARTS carried out specific research to develop a risk indicator that was:

- suitable for pedestrian and car occupants;
- linked to the speed and concentration of the flow of vehicles, by lane;

- applicable both to links and junctions; and
- based on the principle of exposure to risk consistent with the concept used in environmental epidemiology, such as the exposure to air pollutants.

We defined the exposure to crash during the crossing or the passing of a street by analogy with the exposure to air pollution when walking outside. In environmental epidemiology, exposure is usually defined as an event that occurs when there is a contact at the boundary between a human and the environment with a contaminant of a specific concentration for an interval of time. In a road crash, there is direct (physical) contact between a road user and a vehicle with dissipation of mechanical energy, which is the agent of the damage. In the street, there is virtual contact between a road user and an "atmosphere" generated by the traffic. The quality of this "atmosphere" depends on the presence of contaminants in the traffic, which are the moving vehicles described by a volume flow and a speed flow. The difficulty is in defining an appropriate "concentration" suited to the situation of crossing or passing. The time of exposure of a car driver depends on the speed of the car in the flow of vehicles. The time of exposure of a pedestrian is defined by the time spent by the pedestrian to cross the street of a certain width with a walking speed. The walking speed depends on several factors, such as the age of the person and the motive for the trip. Time spent in traffic has always been a recommended indicator of what the road safety specialists call a measure of the exposure to the risk. Based on this, we propose to define a measure of "concentration" for a pedestrian that gives the proportion of space not available for a free and safe crossing. This is defined as the space occupied by a virtual flow of vehicles with a length equal to the distance traversed by the vehicle during the time spent by the pedestrian crossing the street. This same approach has also been extended to take into account multiple flows on a link and at junctions (with and without traffic lights). The same kind of indicator has also been adapted as a measure of risk for car occupants. In this case, this measurement is divided into the risk of vehicle-only collisions between two or more vehicles travelling in the same direction and the risk of collision between two or more vehicles travelling in opposite directions. At junctions, the "concentration" is based on crossing and merging flows, regulated or not by traffic lights, in the same combination.

The set of concentrations, times spent and speeds thus derived provides the elements for estimating a combined exposure to the risk for all trips made by car or by walking by a population in an urban network considering that health effects are relevant over a wide area and time. When there is no motorized vehicle on the street, such as in Venice, the concentration is 0 and no crash is possible. When the traffic is totally congested, there is also no possibility of a crash. The crash frequency reaches its maximum between these two extreme situations, and the severity of the collision decreases with the concentration. The risk is high at low concentration, which usually means high speed, and low at high concentration, which means low speed.

2.5.2 Pedestrian crossing behaviour

Previous research on pedestrian movement in the urban environment is extensive and ranges from modelling pedestrian behaviour and vehicle-pedestrian interactions to crash analysis and evaluation of safety measures. However, few attempts at modelling pedestrians' crossing behaviour at the trip level have been made.

Several theories and approaches have been proposed for pedestrian modelling. Most see crossing behaviour as largely governed by the gap-acceptance theory, which states that each pedestrian has a critical gap to cross the street (Hamed, 2001; Manuszac et al., 2005). Another interesting approach for estimating crossing preferences is pedestrian level-of-service models (Baltes & Chu, 2002; Phillips et al., 2001; Sarkar, 1995). In addition, discrete choice models offer a promising approach for modelling pedestrian crossing behaviour by correlating crossing decisions to a utility function (Evans & Norman, 1998; Hine & Russel, 1993).

Several attempts at modelling pedestrians' crossing behaviour have previously progressed far enough to produce interesting results. However, an overall approach on pedestrian crossing decisions (where pedestrians are more likely to cross) and the relative determinants has not yet been presented. In particular:

- most studies analyse crossing decisions at a particular location, whereas the behaviour of pedestrians along an entire trip has not been explored in detail;
- most studies focus on particular determinants (road, traffic and individual parameters) and neglect or consider only partially other important parameters;
- most studies do not consider crossing at uncontrolled locations (such as mid-block crossing and jaywalking), which is common; and
- most studies are not designed to link the observed crossing behaviour to pedestrian risk exposure.

In the framework of HEARTS, therefore, analysis was undertaken to investigate pedestrian crossing behaviour in a more integrated way: along an entire trip. For this purpose, existing methods were exploited and adapted and new models developed. In particular, a hierarchical method was developed and tested, based on the following steps:

- estimation of the total number of crossings along a trip, in relation to origin and destination parameters;
- estimation of crossing probabilities at different locations along each road segment (link) in relation to road geometry, traffic conditions, trip parameters and individual pedestrian characteristics;
- estimation of crossing probabilities along each trip segment in relation to the distance from origin and destination; and

- calculation of the weighted final crossing probabilities for each location along the trip.

Based on this, a complex model for estimating the type, number and location of crossings along a trip was developed. The resulting algorithm allows the probabilities for different pedestrian crossing choices along a trip to be calculated through a limited yet adequate number of variables. Validation of the model in the case study cities gave promising results. In particular, the first step of the model, concerning the selection of the total number of crossings, was validated based on real data from a pedestrian survey in Lille, France. For step 2 of the model, the transformation of the nested logit model proved to be adequate to describe the distribution of crossing probabilities along a road link (junction or mid-block). Validation was based on two data sets:

- closed-circuit video recordings of crossing decisions of 1870 pedestrians in Florence, Italy, on a road link between non-signalized junctions; and

- a field survey in Athens, Greece, recording the crossing decisions of 1793 pedestrians on a road link between signalized junctions.

The results showed nonsignificant differences between model predictions and observed behaviour. Nevertheless, the performance of the model is improved for links with signalized junctions. Finally, the non-uniform probability distribution of the third step of the pedestrian behaviour model was compared with real data from the Lille pedestrian survey. It was demonstrated that the basic assumptions of the model are accurate (higher probability of crossing at the beginning or the end of the trip).

2.6 Population exposure

Three main modelling approaches were identified for characterizing and quantifying people's exposure to transport-related risk factors: non-geographical or microenvironmental models, non-dynamic geographical models and dynamic geographical models. Examples of all three were identified and assessed.

Microenvironmental models operate by assigning exposure to individuals or populations according to the proportion of their time spent in various microenvironments (such as residence, workplace, outdoors or in traffic), each of which can be characterized by distributions of pollution concentrations derived from representative (mostly outdoor) monitoring studies, monitoring sites or dispersion models. Concentrations in indoor environments are typically estimated using infiltration modelling (Hänninen et al. 2004, 2005). The advantages of this approach are that it can readily be applied to large populations (perhaps more than several thousand people) based on aggregate time–activity data, and estimates can be validated against data from a population exposure survey. The main disadvantage of microenvironmental modelling, perhaps, is that it provides no individual- or location-specific information on exposure. This is because such models integrate exposure over a defined period (such as 24 hours) during which people are mobile, so that their overall exposure cannot be related to specific locations.

Non-dynamic geographical models take account of spatial variation in the distribution of both air pollution and population but take little or no account of the effects of temporal variation. Exposure is thus assessed essentially by intersecting static maps of pollution and population (with adjustments if appropriate for microenvironment). Time-varying patterns of pollution and population distribution may, however, be accommodated through an hourly sequence of such maps. Populations or individuals on each map are discrete, so that exposure profiles for specific groups of individuals cannot be constructed directly and validating the model is practically almost impossible. This approach again has the advantage of being applicable to large populations based on aggregated time–activity data.

Dynamic geographical models are designed to provide detailed, individual or near-individual assessment of exposure over both time and space. Ott (1984) established long ago the principles on which these models do this. They thus require detailed space–time–activity data as well as information on time-varying patterns of pollution. Typically they operate by following individuals as they move through the changing pollution field and thereby accumulate exposure profiles. Their advantage is that they provide information on exposure at a much higher resolution that reflects individual behaviour patterns. Their disadvantage is that they place high demands on data and processing resources and are difficult to validate and extend to large representative populations.

Based on the review of exposure models, HEARTS decided to use two types of exposure models. Dynamic geographical models were used for detailed assessment of transport-related exposure to air pollution and noise at the local scale, and population exposure models using a probabilistic simulation framework (microenvironmental models) were used for broader-scale population-level exposure assessment or studies of long-term effects.

2.7 Health effects

The selection of health end-points and related indicators due to air pollution, noise and road crashes is a fundamental step in developing an integrated risk assessment for traffic-related health effects.

This selection is largely based on the availability and strength of evidence on the health effects of exposure associated with transport. Building on the established methods developed in risk assessment, methods for more comprehensive health impact assessment exercises have been developed in recent years, notably in ambient air quality (WHO European Centre for Environment and Health, 2000). For pairs of associations between risk factors and health outcomes supported by convincing evidence and quantitative estimates of the association, dose–response functions are combined with data on the prevalence of the exposure to calculate the proportion of the outcome in question due to the risk factor in question. When data are available on the frequency of the outcome observed in the population, such proportions can be translated into absolute numbers of attributable cases, often regarded as "effects" (Martuzzi et al., 2003).

In this context, the degree of evidence varies. Although there is a well-consolidated body of studies on air pollution, development of exposure-response curves based on noise effects is more recent, and the most reliable data are limited to annoyance and sleep disturbance effects (European Commission Working Group on Health and Socioeconomic Aspects, 2004). There is also evidence that environmental noise elevates blood pressure (Stansfeld & Matheson, 2003) and the risk of myocardial infarction (Babisch, 2006). Similarly, interest has been increasing recently in epidemiological modelling of the health effects of crashes.

An important point is that, although evidence on the health effects of various types of transport-related exposure is abundant, not all relevant effects can be quantified yet. Some air pollutants, for example, are known to be noxious, but current information on concentration–response function in interaction with other risk factors is lacking. Thus, although health effects cannot be quantified, estimating the levels of exposure contributes to evaluating a given transport policy. In other words, any proposed policy can be evaluated in terms of its health implications, by estimating the direct health effects but also with estimates of the consequences of the levels of exposure.

2.7.1 Air pollution

A list of pollutants relevant in terms of their association with effects on health was discussed and recommendations about the most important and relevant ones made. The air pollutants of interest are:

- PM with an aerodynamic diameter smaller than 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$);
- CO;
- nitrogen oxides (NO_x);
- NO_2;
- O_3; and
- benzene.

In line with the growing body of literature on the subject, PM and O_3 were selected for inclusion in the models. The reason for the distinction between PM_{10} and $PM_{2.5}$ is that fine PM penetrates deeper into the lungs, creating the potential for more harm to human health. Other pollutants mentioned above also have adverse health effects but are often correlated with PM in urban settings, since road traffic is one of the main direct sources. Thus, estimating the separate impact for different pollutants would result in double-counting the impact. PM and O_3, in contrast, are not correlated and can thus be expected to produce separate and additive effects. They were selected because they capture the most relevant health effects of traffic-related air pollution (Krzyzanowski et al., 2005). It is not conclusively established which pollutants are most responsible, but PM and O_3 have the strongest associations. Air pollution is causally associated with increases in the risk of death and chronic disease, hospital admission and exacerbation of illnesses in Europe or North America (Schwartz, 2004). For the exacerbation of asthma, traffic pollution, particularly from diesel engines, plays an important role (Krzyzanowski et al., 2005).

The health risk models available for these different air pollutants are not suitable for application in every microenvironment. Considering the scientific evidence available to date (Hurley et al., 2005; Künzli et al., 1999; Martuzzi et al., 2002; Pope et al., 2002), a list of health effects of air pollution from road traffic was proposed (Box 1).

Box 1. Health end-points for PM and other exposure

Mortality (aged ≥30 years, excluding accidental causes) – long term
Hospital admissions for cardiovascular disease causes
Hospital admissions for respiratory disease
Acute bronchitis (aged <15 years)
Asthma exacerbation (aged <15 years)
Asthma exacerbation (aged ≥15 years)
Restricted activity days (aged 15–64 years)
Occurrence of respiratory symptoms
Lung cancer

2.7.2 Noise

The noise effects considered are based on epidemiological reviews and EU directives. Health end-points include:

- annoyance (exposure–effect curves available are based on outdoor noise levels only);
- disturbance of sleep; and
- cardiovascular diseases such as hypertension and ischaemic heart disease.

Recommended indicators of exposure are:

- day-evening-night level (L_{den}); plus night level (L_{night}) and other physical descriptors for other possible requirements;
- hourly average; and
- outdoor levels.

It is recommended here to use L_{den} and L_{night} as the main noise indices since these are the indices on which available risk coefficients are based.

Further decisions include:

- noise from aircraft, airports and railways was not addressed;
- annoyance and sleep disturbance cannot yet be easily translated into aggregated indicators, such as disability-adjusted life years or years of life lost, due to methodological difficulties with defining and applying appropriate severity weights; and
- transport microenvironments, such as in-car or in-train, can be important for noise exposure, but characterizing these effects is difficult; the available information was therefore reviewed and integrated into the project as much as possible.

Considering change situations is also very important: increases or decreases in noise compared with the long-term steady state. Key points in this context are that:

- the annoyance dose–response curves are derived from, or based on, steady-state situations; and
- models of change effects, currently being researched, could be included in future development (Brown & Kamp, 2005).

2.7.3 Road traffic injuries

Models for predicting road crashes and their health impact were reviewed in detail.

The ECOEHIS project (Development of Environment and Health Indicators for European Union Countries) defined 11 indicators that are considered to be the best candidates for valid monitoring of the chain of cause and effect for road crashes (WHO European Centre for Environment and Health, 2004). Two indicators were directly related to exposure to the road risk factors. One, the time spent on the road according to road user, was chosen to take into account the exposure of vulnerable categories such as pedestrians and cyclists (and to consider children and older people); the second was the distance travelled. The crash rate and the indicators of the health effects of road crashes, the injury rate and the mortality rate, are indicators present in almost all the health systems and were therefore chosen to be part of the core set. Additional health effect indicators, important in terms of the enormous toll paid by the youngest people, were the years of life lost and the disability-adjusted life years attributable to crashes. Other important indicators were related to behavioural aspects. The use of safety devices (such as seat-belts), for example, strongly determines the outcome of a crash for car occupants. For example, the percentages of motorcyclists using helmets and car drivers wearing seat-belts are commonly used indicators related to the behavioural aspects of these groups of road users and are strongly associated with the outcomes of crashes.

The percentage of cars exceeding speed limits and mortality due to drink-driving are primary and secondary risk factors, acting both to increase the probability of the occurrence of a crash and to exacerbate its consequences.

Statistical data on road traffic injuries, which are essential to prevention programmes, are produced by different institutions and are usually available from police files or hospital admission data. This implies some difficulty, including coding problems and missing data, especially on crash circumstances and causative agents (the site of the crash and the activity of the victim). Differences in the availability and quality of the information can affect interpretation and lead to serious underestimation of injury; mortality does not seem to be underestimated.

Speed remains the main risk factor in modelling collisions between vehicles and road users and the frequency or the severity of health effects (Peden et al., 2004; Racioppi et al., 2004).

One indicator of health outcome was therefore proposed:

- the number of people dying and injured – injury and death rates.

Further, another indicator, useful for scenario modelling purposes, was investigated:

- the probability of being killed or injured during the trip.

Exposure is defined as the time spent or distance (in km) driven on the road network. The time spent on the road is the only real indicator of exposure. This provides information that is relevant to vulnerable road users, such as pedestrians, as well as vehicle drivers, and can thus be used to describe exposure to the road, also for children and older people. A limitation that has to be kept in mind in developing models of road traffic injuries lies in the issues related to the completeness and quality of data related to the health outcomes and characteristics (such as blood alcohol concentration) of the road users involved. Several countries (such as the Netherlands) are attempting to make improvements by linking road police databases with records in health care facilities that provide treatment to people involved in road crashes (Racioppi et al., 2004).

2.8 Case studies

Three case studies were developed during the project. The cities chosen for the case studies were Lille (France), Florence (Italy) and Leicester (United Kingdom). Each case study differed in its focus (Table 4). In addition to the HEARTS partner agencies, local institutes and organizations were involved to support the completion of the case studies.

The case studies had three purposes:

- to help inform the design and development of methods and models;
- to test and validate the models under real-world conditions; and
- to demonstrate the use of the HEARTS approach to evaluate the potential health effects of locally relevant transport issues.

In each case, cities focused on specific aspects and issues, depending on their data situation and on local policy concerns.

In Leicester, the study focused on collecting detailed data on the time–activity patterns of children and personal exposure to air pollution both within vehicles and while walking, to inform and validate the modelling. A custom-designed survey of time–activity patterns was undertaken in 10 schools in the area and repeated personal monitoring carried out on two routes. Noise was also monitored and modelled in detail. Data on traffic flow were obtained using a vehicle allocation model (TRIPS), and this was used, together with the Space Time Exposure Modelling System (STEMS) developed during HEARTS, to simulate exposure under a safe-routes-to-school initiative.[5] TRIPS was used to generate traffic flows and speeds on roads within the study area. The model was tested and validated using the data collected in the study area. The study area represented an expansion of an area previously used by the local authority to develop detailed traffic models and traffic management scenarios.

In Lille, much of the focus was on crash modelling. Target subgroups investigated include: children 5–10 years old and employed people 18–60 years old. In Lille, a new method was tested to measure the exposure to crash risk for pedestrians with observation techniques such as follow-up and interview and GIS coding techniques for the route and crossings of the walking trip for children, teenagers and adults.

In Florence, traffic emissions, noise measurements and exposure were modelled. In particular, a campaign to measure exposure to $PM_{2.5}$ and the elements in $PM_{2.5}$ samples were analysed to run a statistical model for exposure. Two scenarios were tested comparing the situation for traffic and emission modelling from 2003 to 2010.

2.8.1 Case study methods

Table 5 summarizes the general approach and methods of each case study.

Full GIS were built for the three case studies. STEMS2 (see section 3.2), specifically designed for HEARTS, and AVTUNE (see section 3.4) were applied in Leicester. Emissions in Lille were estimated using COPERT III. COPERT III is the official macroscopic emission model of the EU.

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5 Safe Routes to Schools is a national initiative in the United Kingdom managed at the local level by the relevant local authority. The aim is to deliver a network of safer and more sustainable transport links to all schools in Leicester by working closely with parents, students, teachers and local residents.

Table 4. Summary of case studies

City	Description of case study	Lead agency	Partner agencies	Scale and/or parameters	Scenarios modelled
Leicester	Small-area study of mixed residential area along a major transport corridor in south-western Leicester. The case study focused on collecting primary data on children's time–activity patterns, personal exposure to air pollution in various transport microenvironments and validating and testing air pollution and noise models against monitored data.	Imperial College, London	University of Leeds and the Leicester City Council	Small areas (about 20 km^2). Key parameters: exposure to air pollution (PM) in various transport microenvironments; time–activity patterns and route choice of children; and noise monitoring and modelling measures.	A policy scenario for a walk-to-school initiative was assessed using HEARTS methods. Schoolchildren's exposure to traffic PM in walking to and from school versus riding in cars.
Lille	Data on mobility, networks, traffic, air pollution and road crashes were collected, structured and completed in a data warehouse and GIS. Special simulation tools were developed for routes and places of inhabitants in a part of Lille Métropole, the "new" city of Villenneuve d'Ascq, to assess the health impact of the plan for urban transport specially designed to reduce car use. A method of measuring pedestrians' exposure to crash risk was set up with observation techniques such as follow-up, interview and GIS coding techniques for the route and crossings of walking trips for children, teenagers and adults.	French National Institute for Transport and Safety Research	Lille Métropole Communauté Urbaine Centre d'Etudes Techniques de l'Equipement Direction Départementale de l'Equipement Association pour la mise en œuvre du Réseau d'Etude, de Mesure et d'Alerte pour la prévention de la pollution atmosphérique dans l'Arrondissement de Lille Observatoire Régional de la Santé Association pour la Prévention de la Pollution Atmosphérique Observatoire National de l'Aménagement Durable Accessible	Two types of risk due to transport: crashes and air pollution and two groups in the population: children 5–10 years and employed people 18–60 years old. Activities: commuting (one-way and return trips) associated with a trip by car (plus walking), by pure walking or by metro (plus walking). Because of the capacity of the software, we limited the study area to Villeneuve d'Ascq, which is a "new" city situated on the west of Lille Métropole.	The technical agencies of Lille Métropole elaborated two scenarios of transport policy for 2015: a business-as-usual one and a proactive one based on a set of actions recommended in the Plan de Déplacements Urbains (Centre d'Etudes Techniques de l'Equipement, 1996) such as: improving public transport: more buses, cleaner buses and faster buses; development of metropolitan and cross-border express trains; planning to encourage bicycles: parking possibilities, cycle paths and tracks; and diffusion of company mobility plans to encourage more rational use of transport for employees in companies and administrations.
Florence	Create an integrated modelling system by loosely coupling the various models within a GIS. Carrying out a campaign to measure exposure to $PM_{2.5}$ and analyse the elements in $PM_{2.5}$ samples.	Institute of Studies for the Integration of Systems	Regional Environmental Protection Agency of Tuscany Centre for the Study and Prevention of Cancer University of Florence	Whole city area	Commuter exposure to traffic PM in the maximal use of the new planned commuter tram line versus the present.

Fitted for applications at the national level, it is often extrapolated at very local level with subsequent heavy approximations. The model is based on a large number of experiments. Vehicle kinematics is considered only in terms of average speed. Cold-start emissions and evaporative emissions are covered with a macroscopically aggregated approach.

Table 5. Summary of modelling approaches used in the HEARTS case studies

Case study	GIS development	Air pollution	Time activity and trips	Pedestrian crossing	Traffic modelling	Noise	Emission and dispersion	Speed and road crashes
Leicester	Full GIS built for the case study area STEMS development and validation	Primary data collection (personal monitoring), modelling (using STEMS-Air) and model validation	Primary data collection (time–activity survey), modelling (using STEMS-Trip) and a reality check of the model			Primary data collection (monitoring) and modelling using the AirViro-based Traffic and Urban Noise Evaluator (AVTUNE) model (Goodman, 2005)	Emissions modelled using *Design manual for roads and bridges* (Highways Agency et al., 1997) defaults	
Lille	Full GIS built for the case study area	Emissions are estimated using COmputer Programme to calculate Emissions from Road Transport (COPERT) III methods for 8 pollutants, 24 hours and 3 scenarios (1998, 2015 business as usual, 2015 proactive)	Markov chain models were estimated over 24 hours of activities with choice models of modes of transport for children and active adults	Pedestrians followed and data inserted into the GIS	The Direction Départementale de l'Equipement ran EMME/2 based on origin-destination matrices on three scenarios: 1998, 2015 business as usual and 2015 proactive[6]			Speed measurements are available on 500 sites and road crash files with localization also
Florence	GIS datasets (modelled and measured data: emission of noise and air pollutants, population)	Survey and monitoring campaigns in three parts: background questionnaire time–location–activity diary measurement of exposure to noise and of to $PM_{2.5}$	Time–activity survey		EMME/2 simulation from a previous project of the Municipality of Florence	A deterministic traffic noise model developed according to the EU Environmental Noise Directive (European Commission, 2002) and STEMS-Noise	TEE 2005	

TEE 2005 software (see section 3.1), specifically designed for HEARTS, includes various COPERT III content but with a significant effort to create differentiation for varying local conditions (such as considering different congestion levels for the same average speed in different link types). EMME/2 was the model available for traffic modelling in Lille and Florence. EMME/2 is a classic static model developed in Canada by INRO Consultants and used by hundreds of organizations worldwide. It is multimodal in the sense that it distinguishes between private and public transport. The model can have limitations in modelling of congestion.

Case studies shared common goals and, within the limitations of local data, modelling capability and policy concerns, common methods. Within each case,

[6] Traffic modelling outputs include many details. The results produced in the Lille case study include: hourly traffic data (volumes and speeds) by link. Traffic estimates (total number of vehicles and average speed per link) were available on an hourly base, for each scenario, but for the traffic network only. A protocol was able to estimate traffic on secondary links (street network) from estimates available for primary links (traffic network). Information on the turning movements was only accessible through traffic counts made by observers on the main traffic network.

however, differences occurred in the detailed methods. Table 6 summarizes the methods and models used.

Table 6. Summary of methodological approaches and data collection methods for HEARTS case studies

Overall method	Data collection and/or modelling method	Population group	Time period
Lille			
Air pollution	Maps of ambient air concentration pollutions (NO_x, CO, $PM_{2.5}$ and PM_{10})	General	1998 2015 (business as usual) 2015 (proactive)
	Estimates for STEMS air pollution model	General	2015
Time–activity patterns and trips	Simulation of individual activity and mobility patterns using ArcGIS	Children, active adults	1998
Traffic modelling	Three scenarios (see time period) using EMME/2	General	1998 2015 (business as usual) 2015 (proactive)
Speed and road crashes	Pedestrian crash exposure data collected by observation techniques such as follow-up and interviews and by GIS coding techniques	Students and employees in a university quarter Employed people of three other quarters in the municipality Children at two schools	2005
	Speed measurements collected from the Lille Métropole network	General	1998–2003
	Collection of geographically coded injury crash data	General	2000–2004
	Access to detailed information of individuals involved in crashes	Individuals in crashes in Villenenuve d'Ascq	2004
Leicester			
GIS development	GIS developed for study area and a city GIS at 1:50 000 scale on the road network and resident population	Not applicable	Not applicable
Air pollution	Personal air pollution monitoring in transport microenvironments. Instruments and pollutants were: Osiris optical particle counter for total suspended PM, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$; P-TRAK® Ultrafine Particle Counter; BGI-MIE-pDR-1000 $PM_{2.5}$ nephelometer and filter sampler	General	2004–2005
	Fixed-site air pollution monitoring	General	2004–2005
	Rural fixed-site air pollution monitoring	General	2004–2005
	Co-location of the different monitoring devices	General	2004
	Modelling using STEMS-Air	Schoolchildren	2005
Time–activity patterns and trips	A custom-designed time–activity study implemented (based on EXPOLIS experience), including: A travel diary A map of the study area to record each journey route	Primary, infant and junior schools (children aged 4–11 years)	Autumn 2004
Traffic modelling	Use of TRIPS to reflect the 2004 situation	General population	2004 traffic situation
Noise	Noise measurements (in the network of the study area) and monitoring from several sites.	Schoolchildren and general population	November 2004
	Noise pollution modelling with AVTUNE and STEMS-Noise	General population	2005
	Data from noise monitoring compared with AVTUNE and STEMS-Noise modelling	General population	November 2004
Florence			
GIS development	Development of a GIS to record and manage the noise and emission and dispersion modelling	Whole population in observed area	Not applicable
Air pollution	Use of computer-assisted telephone interviewing to collect information on mobility among 641 resident subjects using a questionnaire Forty interviewees participated in the monitoring campaigns	Random sample Self-selected	2004 2004
	Air pollution monitoring for: $PM_{2.5}$ personal monitoring among targets (n = 40) $PM_{2.5}$ in microenvironments (n = 64) $PM_{2.5}$ and PM_{10} in ambient air quality site $PM_{2.5}$ in traffic environments	Participants in a air pollution monitoring campaign Participants in a air pollution monitoring campaign General General	2004
Noise	Noise measurements performed according to ISO 140-5 (noise level obtained as an average mean of outside and inside measurements, 2 metres from the window).	General	2003–2010
	A deterministic traffic noise model developed according to the EU Environmental Noise Directive (European Commission, 2002)	General	2003–2010
Emission and dispersion	Emission and consumption calculation using the software TEE provided by the Italian National Agency for New Technologies, Energy and the Environment	General	2003–2010

3. Results

The HEARTS project produced important advances in several areas, including the following development of methods:

- improvement of a traffic emission model, TEE;
- advances in modelling of road crashes and pedestrian behaviour;
- refinement of microenvironment exposure assessment; and
- development of a GIS-based system (STEMS), which includes an air pollution model, noise model, pedestrian behaviour model, trip generation model and exposure model.

Methodological developments were mostly oriented towards improving the traffic-related risk assessment. The application of the methods in the case studies not only tested these methods but also provided a means of developing and validating new or updated models and to improve their capability for integration (so that, for example, outputs from one model could become the inputs to another model). Important developments included refining the exposure measurements of a population, in terms of the amount of time, movement or travel within a selected area. A further element of this work was to investigate the availability, quality and utility of the information needed for risk assessment and to develop improved methods for data collection, organization and linkage.

3.1 Traffic emissions

The new version of the TEE model was developed in the framework of the HEARTS project (Negrenti et al., 2005). The preceding version was developed in the ISHTAR Project under the Fifth Framework Programme and is called TEE 2004. Improvements focused on better analysing direct transport-related effects via air pollutant emissions, noise emissions and road crash occurrence. Specific efforts were dedicated to modelling the effects of vehicle kinematics on hot emissions (where the software calculates link emissions by adopting functions based on average speed), instantaneous emissions or the innovative kinematics correction functions model, and the modelling of parking processes, which are relevant for both cold-start and evaporative emissions. According to Krasenbrink et al. (2005:26):

> Most cold-start over-emission of pollutants, which depends on fuel enrichment, occurs mainly in the earliest fractions of the trip. Estimation of the over-emission of engine cold start at a fleet level is a function of the pollutant considered, ambient temperature, vehicle technology, mean speed and average trip distance. The effect of cold starts is concentrated mainly in urban areas, where most passenger cars are started and where many trips are shorter than 6 km. As a consequence, the aftertreatment system does not work under optimum conditions most of the time; this leads to relatively high emissions

per distance driven, compared with long-distance driving (even at high speed) on roads outside of urban areas and on highways.

Around 90% of the petrol emissions that arrive in the atmosphere during real-life driving are produced during the cold-start phase and the following minute (Krasenbrink et al., 2005). Cold-start trips are often neglected in urban transport analysis. This is very dangerous, since urban trips are normally 5–7 km and vehicles remain cold (engine and catalyser) for the first 3–4 km, during which they can emit 10 times more CO and volatile organic compounds. This is why HEARTS emphasized cold-start emissions. The effort has given rise to the latest version of the TEE software, called TEE 2005 that specializes in considering cold-start trips. Several options are offered to the users for calculating cold-start emissions, including a sophisticated analysis of parking areas. The Rome Public Transport Agency calculates cold-start emissions in Rome using the Healthier Environment through Abatement of Vehicle Emission and Noise (HEAVEN) system, which has incorporated TEE software. Further, the city of Genoa has taken a recent version of TEE (2004 package) and can now calculate with reasonable uncertainty cold-start emissions on a link-by-link basis.

These modelling efforts help to reduce uncertainty in estimating the emissions and concentrations of pollutants at the link level. Achieving higher accuracy in estimating the spatial and temporal distribution of pollutant emissions is essential for credibly estimating population exposure to air pollution, since exposure depends on the detailed (time- and place-specific) intersection between people and the transport-related emissions and concentrations. Similarly, the results obtained in modelling micro-scale vehicle kinematics offer the potential for estimating noise levels and road crash occurrence at the link level with an unprecedented accuracy.

3.1.1 Kinematics modelling for transit flows

One of the promising alternatives to the classically macroscopic average speed emissions approach is to adequately describe the kinematics based on easily available input data. This involves linking average speed, a congestion indicator such as the lane flow density, link length and the fraction of green time at the intersection at the end of the link. This approach assumes that the effect of speed variability can be expressed by means of a kinematics correction function. The corrected emission E is obtained as the product of the average speed emission e and the kinematics correction factor KCF.

3.1.2 The modelling of parking

The model of the time spent in searching for parking is based on analysing the probability of the number of attempts a driver must carry out before finding a useful place to park. The parking model shows a relationship between the occupation rate, the searching time and the vehicle density. Searching time increases very slowly up to an occupation rate of 95% then increases quickly to a maximum value achieved when the parking capacity is full.

The Florence case study within the HEARTS project applied the TEE 2005 model. Emphasis was placed on modelling parking flows from and to both the on-road parking places and off-road parking lots. Modelling traffic-related emissions can refine the assessment of the burden of air pollution concentration originated by a set of different sources: traffic in this case.

More generally, the new software tool can be used as a decision-support system for designing and assessing policies and measures for reducing the exposure of population to traffic-generated air pollution or more in general to the direct effects of transport systems.

3.2 GIS-based exposure modelling: the STEMS model

3.2.1 Rationale and overview

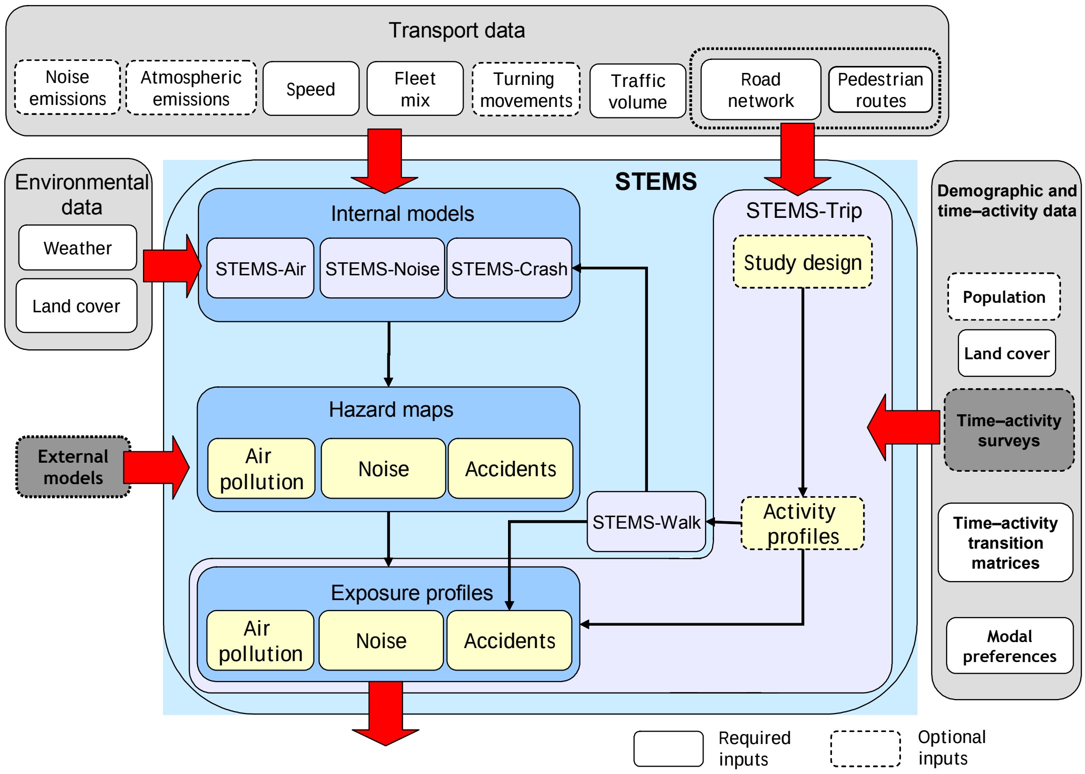
This section reports on the development of model integration, with particular focus on the STEMS models. The assessment system was built on, and greatly extends, a GIS-based method, STEMS, previously developed as part of a project funded by the Engineering and Physical Sciences Research Council on the health effects of traffic-related air pollution in Northamptonshire, England (Gulliver & Briggs, 2005). In its original form, STEMS was concerned only with air pollution and used externally provided data on time–activity patterns and air pollutant concentrations to simulate exposure profiles for sample individuals. Within HEARTS, this simple base model has been greatly extended and enhanced by incorporating internal models of:

- air pollution concentrations;
- traffic-related noise;
- road crash risks (to both vehicle users and pedestrians);
- trip selection and time and activity patterns; and
- pedestrian crossing behaviour.

The system has also been greatly refined by developing a graphical user interface, which provides menus and drop-down windows to enable the models to be run interactively.

Fig. 1 shows the overall system structure. The main principle of STEMS-2 is that any individual's risk experience depends on what Hagerstrand (1970) called their time-line: the sequence of activities they undertake and the places in which they perform them, as a continuous series or narrative. STEMS-2 uses information on individual time-lines (or imputes time-lines when necessary) to model the exposure of the individual to air pollution, noise and road crash risks from road traffic. Both the temporal and spatial resolution of the modelling can be altered according to the availability of data or user need; the default is a one-hour increment and 100-metre spatial resolution. The important feature of this approach is that exposure is modelled as a continuous process, operating in time and space and not as a set of discrete events. This means that people's entire exposure experience is considered, allowing interactions between behaviour and exposure to be taken into account and the cumulative effects of different types of exposure to different hazards, in different microenvironments at different times of the day (or life) to be assessed. STEMS-2 thus provides a means of integrated risk assessment.

Fig. 1. The STEMS-2 structure



As indicated above (and as shown in Fig. 1), STEMS-2 comprises five main modules or components. The underlying framework that links the system is STEMS-Trip. This models time–activity patterns and trip behaviour based on either detailed, individual-level time–activity data (if they exist) or by imputation based on aggregate statistics on time–activity patterns (hourly transition matrices and modal preferences). This module also provides the graphical user interface to design any individual study or assessment and constructs exposure profiles by dynamically intersecting the time-line of each individual with the underlying and changing hazard "surfaces": continuous spatial estimates of risk. These hazard surfaces can be provided as ready-made inputs, derived from external models, or can be generated using the internal models: STEMS-Air, STEMS-Noise, STEMS-Crash and STEMS-Walk. STEMS-Air provides an internal model of ambient air pollution concentrations for every grid cell in the study area. STEMS-Noise models ambient noise levels, when more powerful models are not available. This comprises an adapted version of the CRTN model, which has been widely used in the United Kingdom. STEMS-Crash models the risks of vehicle crashes, estimating the individual risk of involvement in an injury crash for two kinds of road users: pedestrian and car drivers. We define the exposure to the crash during the crossing or passing of a street by analogy with the exposure to air pollution when walking outside. The difficulty is in defining an appropriate "concentration" suited to the situation of crossing or passing. The time a car driver is exposed depends on the speed of the car in the flow of vehicles. The time a pedestrian is exposed is defined by the time spent by the pedestrian to cross the street of a certain width with a certain walking speed. Time spent in traffic has always been a recommended indicator of what road safety specialists call a measure of the exposure to the risk. The exposure assessment algorithm is based on identifying the flows crossed by the pedestrian on his or her trip on a street, because each moment of exposure to the risk for a pedestrian comprises the crossing of a one-lane traffic flow qualified by a "concentration" indicator C during a duration t equal to the time of crossing. Using this principle, model development in HEARTS took into consideration two main sets of situation: a) mid-block or junction without red lights or roundabouts; and b) a junction with red lights or mid-block with red lights. The model of road crashes is based on the long-established Routledge formula (Routledge et al., 1974). STEMS-Walk provides an additional module that simulates pedestrian crossing behaviour (and thus crash risks) along the selected routes. As part of the HEARTS study, the internal models, except for STEMS-Crash, were validated against models and data available in the case studies.

STEMS-2 is thus designed to be run either using data derived externally (such as from custom-designed surveys or external models) or using the internal models. The minimum input requirements comprise detailed, geographical information on the road network and land cover and time-varying data on traffic characteristics (volume and flow profile by road link and hour of the day), along with statistical information on time and activity (hourly transition matrices and model preferences). For each of the model elements (crashes, air and noise), trips can be generated from data derived externally (such as from custom-designed surveys or external models) or using STEMS-Trip, which models destinations, activities, transport mode and journey times using a probabilistic model. Other data requirements (such as fleet mix, vehicle speed, air pollutant and noise emissions and details of time–activity patterns, pedestrian behaviour and road characteristics) can be provided if available, but will otherwise be automatically imputed within the system.[7]

3.3 A probabilistic approach to simulating microenvironmental exposure

As described in section 2.5, the integrated modelling system of HEARTS was defined and conducted at two levels: the city-wide long-term level using the proportions of time spent in different microenvironments and the detailed level using individualized space–time–activity patterns. Monte Carlo simulation was used in both modelling approaches. Hänninen et al. (2005) have analysed the probabilistic simulation techniques and associated errors in detail.

7 The whole system is programmed as a closely coupled (that is, within one commercially available piece of software rather than many) set of modules using Avenue scripts in ArcGIS.

The distributions of time fractions used in different microenvironments can be based on literature or other available information (such as EXPOLIS time–activity data) and were validated in the city case study of Florence. Space–time–activity patterns need both to survey mobility in the city of interest and to estimate the time spent in other than traffic-related microenvironments.

3.4 Case studies

Case studies were undertaken to help to inform the development of the HEARTS approach, test and validate specific models and methods and demonstrate potential applications for policy analysis. This section describes the three case studies in Leicester, Lille and Florence.

3.4.1 Leicester

The Leicester case study targeted informing and validating models in three main areas – time–activity patterns, air pollution and noise – as well as demonstrating the application of the HEARTS approach to assess a walk-to-school policy. Key activities included:

- construction of a GIS for the study area, containing the data needed to apply the HEARTS approach;
- conducting a detailed survey of time–activity patterns of schoolchildren living and going to school in the study area;
- conducting an air pollution monitoring campaign to assess personal exposure while walking and in a car complemented by monitoring at fixed roadside and two mobile sites at schools;
- calibrating and testing the STEMS-Air model using data monitored both in Leicester and the surrounding rural area;
- conducting custom-designed monitoring and modelling of noise; and
- applying the HEARTS models to assess the potential effects of a walk-to-school initiative on the travel-time exposure of children to air pollution.

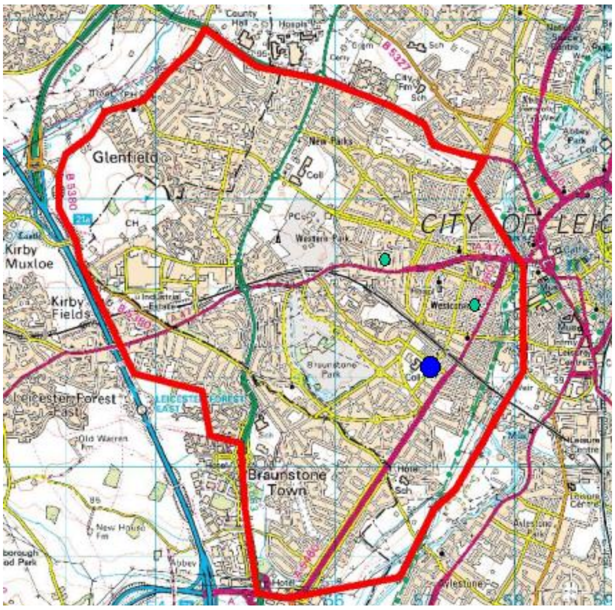
3.4.1.1 Case study area

Leicester City has 290 000 residents. It is part of a wider urban conurbation of 400 000 people and lies in the county of Leicestershire with a population of 600 000.

The transport network is controlled through an integrated system of real-time observation and intervention (Urban Traffic Management and Control (UTMC) including the Split Cycle Offset Optimisation Technique (SCOOT) system and traffic monitoring). Data from an intensive system of environmental and traffic monitoring is archived in the Instrumented City Facility.

The HEARTS case study focused on an area in south-western Leicester (Fig. 2). The area offers a diversity of environments, including major road arteries running into the city centre (including Narborough Road (A5460), Hinckley Road (A47), Groby Road (A50) and Ring Road (A563)), densely populated areas of inner-city housing and small shopping centres, lower-density residential estates and areas of open urban land. The SCOOT system covers key roads, thereby offering detailed data on road traffic behaviour. It contains 10 schools, which provided a sufficiently large study group for analysing time–activity patterns, and includes two air pollution monitoring sites that could be used for calibrating and validating the model. The extended study area covers about one quarter (10 km^2) of the City of Leicester.

Fig. 2. The Leicester case study area (red boundary)

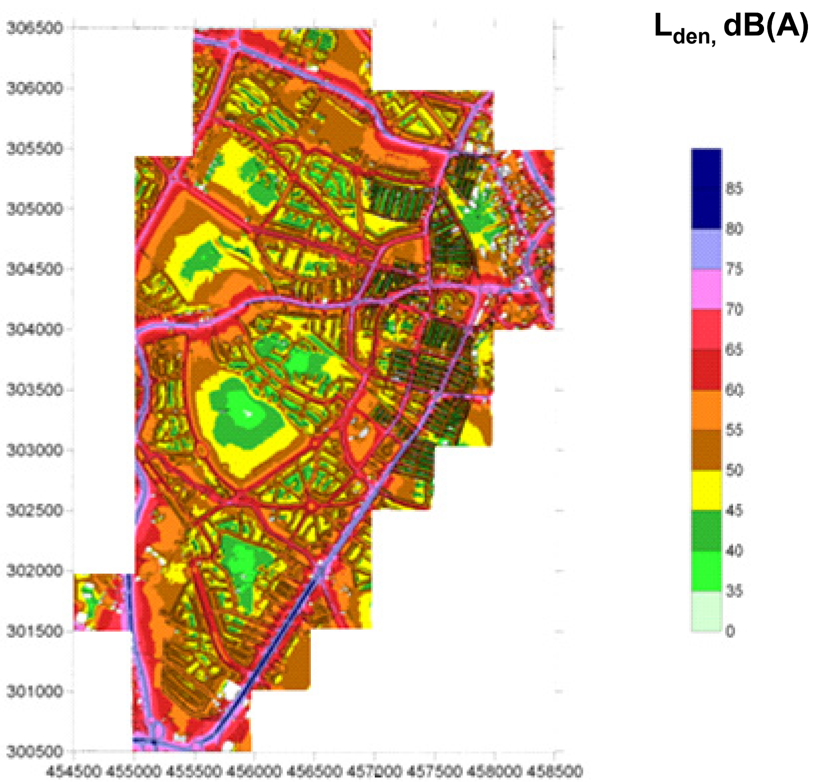


The fixed-site tapered-element oscillating microbalance air pollution monitor is shown as a blue circle, and the two mobile air pollution van locations are shown as green circles.

3.4.1.2 Noise modelling

The AVTUNE model (Goodman, 2005) uses GIS-based road traffic information to calculate noise emissions, coupled with acoustic ray-tracing for sound propagation. For HEARTS, the model was set up to provide noise levels on a 10-m grid throughout the study area, using 24-hour traffic data supplied by Leicester City Council. Emissions were calculated as octave-band sound power levels using a method derived from the French standard (XPS 31-133 – Bruit des infrastructures de transports terrestres) and propagated using ISO 9613-1 (ISO 9613-1:1993) and 9613-2 (ISO 9613-2:1996), based on annual-average weather and climate conditions and favourable downwind propagation. A total of 24 hourly noise maps of L_{Aeq} levels from traffic were produced. These were then combined to produce L_{day}, $L_{evening}$, L_{night} and L_{den} maps. Fig. 3 shows a portion of the complete L_{den} map a portion of the complete L_{den} map.

Fig. 3. L_{den} map produced by AVTUNE



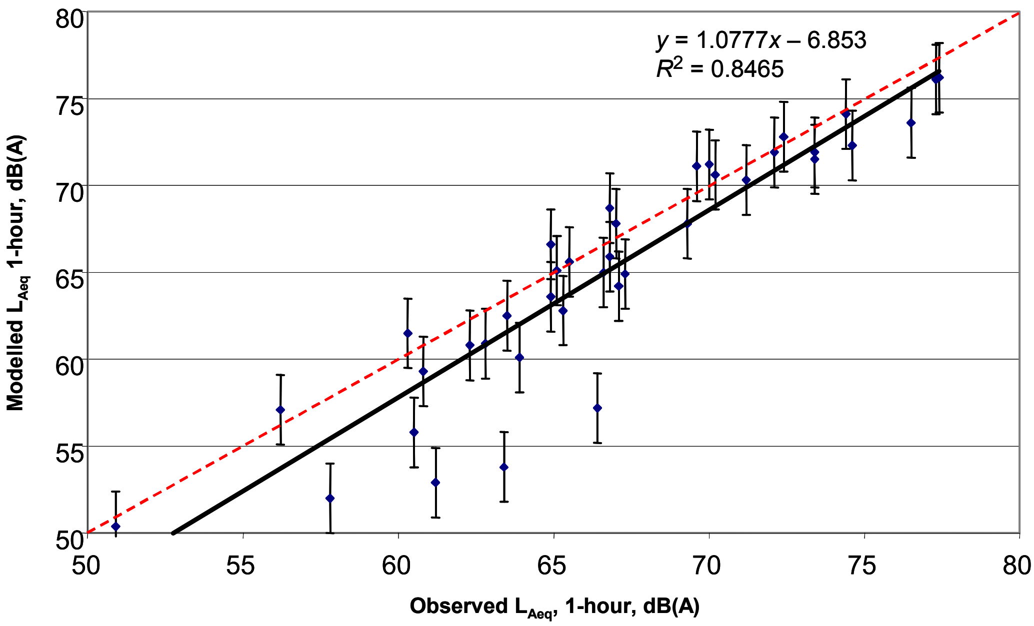
Two noise monitoring campaigns were undertaken; one (short-term monitoring) to establish typical daytime noise levels at various locations across the study area, and another (long-term monitoring) to establish the diurnal variation of noise at selected locations.

The former provided 20 short-term noise and traffic (flow, speed and composition) measurements. These were then combined with a further 18 daytime measurements from a previous project (Harris et al., 2003) to produce a dataset spanning the study area. Two 24-hour L_{Aeq} measurements were undertaken at a school and a residential location as part of the diurnal variation study. These measurements were analysed alongside two pre-existing measurements from Harris et al. (2003).

The results of the monitoring were used to test and validate the estimates from both AVTUNE and STEMS-Noise. The results from AVTUNE were also compared with those from STEMS-Noise at a sample of 254 locations. Fig. 4 compares the AVTUNE-modelled versus monitored data for the short-term sites. For the long-term monitoring sites, AVTUNE tracked the observed noise levels well over time (with R^2 typically in the range of 0.80 to 0.95) but with a varying degree of under-prediction.

The AVTUNE-predicted levels were also compared with STEMS-Noise. The two models provide similar overall mean values, with small fractional biases.

Fig. 4. AVTUNE-modelled daytime noise levels versus observed levels



Correlations across the modelled sites are poor, however, partly because of differences in the traffic data used for the two models and the lack of speed or detailed composition data for use in STEMS-Noise. STEMS-Noise needs to be developed and tested further before more rigorous comparisons are possible.

3.4.1.3 Time–activity survey

Data on the time–activity patterns of schoolchildren were sought in this case study both to inform the development of the STEMS-Trip model and as input to the demonstration analysis of the walk-to-school policy. Children were targeted in this instance for a number of reasons, because:

- child safety, and the walk-to-school policy specifically, are important national and local policy issues;
- children are also a major priority in environmental health;
- children's time–activity patterns are relatively routine and provide a useful test-bed for model development; and
- children are more easily surveyed than adults, and high response rates can be achieved (especially if the surveys are done via the school).

The aim of the survey was to obtain detailed individual-level data on journey behaviour (including routes, modes and time) and intervening activities for a representative sample of children in the study area. Such data are rare and this would thus represent an important data set in its own right. Several of the project partners have been involved in previous studies collecting and using time–activity data (such as the Northampton Air Pollution Study) utilizing similar methods. Data on individual-level time–activity patterns, however, remain rare. A paper on the validation of the STEMS-Trip model is due for publication in the near future. Within the HEARTS project, it was also used to help to develop transition matrices and modal preferences for use in STEMS-Trip and to test the performance of the model against real-world data. For these reasons, care was needed both in designing the survey tools and in ensuring high levels of participation and response.

A custom-designed diary pack was developed for the children taking part in the survey comprising:

- a detailed map of the school and surrounding area, showing all roads and key features (the school, shops etc.);
- an illustrated diary;
- an illustrated example and guide of how to complete their diaries; and
- a Safer Routes to School and Breathe Easy questionnaire, the main focus of which is to minimize road dangers, to encourage walking, cycling and bus use and to reduce car dependence.

The survey targeted primary, infant and junior schools (aged 4–11 years) in the Leicester study area during autumn 2004. A total of 10 schools and more than 1000 children were recruited.

Children used the travel diary to record the details of each journey they made on the survey day, including the starting and ending time of each journey, the origin and destination activity type (such as home-to-school, home-to-leisure etc.) and the mode of transport. The map was used to trace each journey route; the children were asked to show each journey in a different colour and to note the colour used for this journey on the diary. To introduce the survey, each school was provided with a presentation either in assembly or in individual classrooms. The older children (aged 8–11 years) completed the survey from recall in class within normal lesson time and took a second travel diary pack home to complete as homework (thus potentially giving a 48-hour time–activity record), whereas the younger children (aged 4–7 years) took the survey home with an accompanying letter to their parents and were instructed to complete the survey with the help of an adult (covering a 24-hour period).

In total, time–activity diaries were provided to 1062 children in the ten survey schools, of which 762 diaries were returned (72% response rate). Following screening to remove unusable or internally inconsistent results, a total of 617 usable diaries were obtained (81% of the diaries returned). The results were used to construct hourly transition matrices for children, showing the probabilities of transitions between each pair of activities throughout the day for inclusion in the STEMS-Trip model. The data were also used to derive modal preferences based on journey length and travel time. In addition, the data provide valuable statistical data on time–activity patterns across the day that can be used for modelling children's exposure in future studies. The results thus add important information to a sparse body of existing time–activity data for children in Europe.

3.4.1.4 Personal exposure to air pollution

Choice of transport mode clearly affects people's exposure to traffic-related air pollution and might be expected to have significant implications for overall exposure and health effects. If integrated assessments of the health risks of transport systems are to be meaningful, therefore, they need to allow for these effects. To date, however, very little is known about how the choice of travel mode affects people's exposure to air pollution. The few studies that have been carried out have varied in design (such as in choice of pollutant and transport modes studied), and most have been conducted in the United States. As part of the Leicester case study, a custom-designed campaign was therefore carried out to collect new information on travel-time exposure.

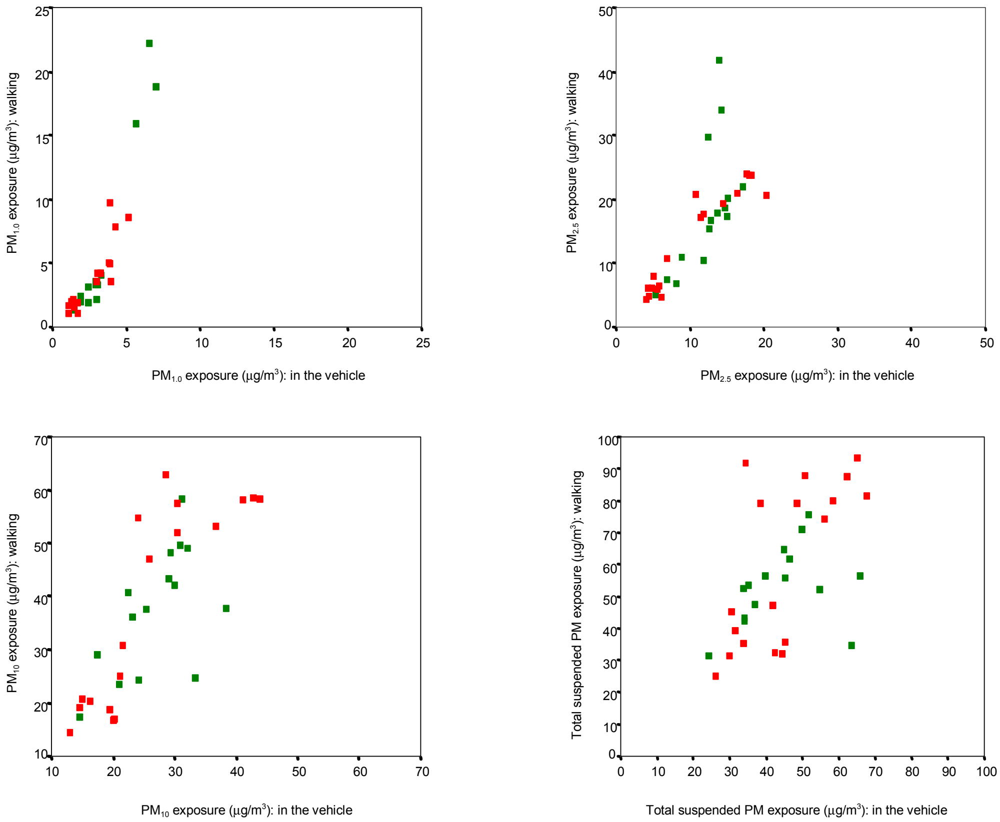
The survey focused on two modes of transport: car or walking. These were selected primarily because they represent the most important modes of travel for most people in urban areas (and especially for children) but also because they are relatively easy to study (monitoring public transport requires the cooperation of the transport providers). Concentration data for these two modes of transport were collected using continuous personal exposure monitoring equipment in March 2005. Fine PM was monitored, since these represent the main cause of health concern, and five fractions were analysed: total suspended PM, PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ (all using an optical scattering instantaneous respirable dust indication system) and ultrafine PM (using a P-TRAK® Ultrafine Particle Counter). Probabilistic exposure simulation was used to estimate the tailpipe PM exposure distributions of schoolchildren for the two scenarios. Limited analysis was also undertaken of CO_2.

Two circular routes were monitored, selected to comprise a range of different exposure microenvironments (busy streets, junctions and quiet residential areas) and to be close to a continuous monitoring site. Monitors were set to record at 15-second intervals, and pairs of researchers followed the routes simultaneously, one in a car and one on foot. The car repeated the route at least twice on each occasion and the pedestrian once. The routes took about 35–40 minutes to walk. The car used was a petrol-fuelled Fiat Doblo and was operated with the windows shut, the air-conditioning off and the ventilation system open and with a low fan setting. The monitors in the car were set up on the passenger seat, close to, but not directly in the line of, the inlet vents. At the start of each set of measurements, clocks in the instruments were synchronized and a series of time-markers was also recorded on each route to aid spatial matching of the data. In total, 33 sets of measurements were taken over a period of 13 days: seven on route 1 and six on route 2. A further five measurements were lost because of equipment failure.

Fig. 5 summarizes the results of the survey. Several features are evident. The first is that the relationships between in-vehicle and walking exposure vary depending on the particle size. For finer fractions ($PM_{1.0}$ and $PM_{2.5}$), the relationships tend to be linear and quite strong; for coarser fractions, the relationships are weaker, with much greater scatter. These differences probably reflect the combined effects of ventilation and local sources. Finer fractions are likely to be more easily drawn into vehicles, with the result that concentrations in the car probably vary more or less in accordance with those outside. Coarser particles, recycled from the street and dust from vehicle furnishings (plus, perhaps, the personal cloud from the vehicle occupant) are likely to lead to more variation in concentrations of PM_{10} and total suspended PM.

The second characteristic of these results is that average exposure during walking exceeded that experienced in the vehicle. The differences are more marked for finer particle fractions rather than coarser. Fig. 5 shows boxplots of the ratios across all sets of measurements. In Leicester, the average ratio is about 1.25 for all particle fractions, with very little variation between either measurements or the two routes. Within each set of data, therefore, the variation is temporal. The results suggest that this component of variation is small – though notably three measurements on route 2 are seen to have somewhat raised levels of exposure while walking. The two routes were also close together, so showed little variation in the ratios. The implication from the Leicester survey is that the relationship between walking and in-vehicle exposure is temporally rather invariate but locationally dependent.

Fig. 5. Relationships between exposure to various fractions of PM in the vehicle and while walking for two routes in Leicester



A further implication of these results needs to be emphasized. In most cases, walking takes considerably longer than travelling by car – typically at least two- or three-fold. The total burden of exposure when walking is thus considerably increased relative to that when travelling in a vehicle. Since the time saved by driving is likely to be spent in relatively clean environments indoors, the differences are not compensated for by increased exposure at the origin or destination (unless people are exposed to tobacco smoke). This does not suggest that walking is inherently less healthy; other important benefits clearly accrue in terms of exercise and socialization. It does, however, highlight the need to provide improved walking environments in towns if the health effects of walking are to be optimized.

3.4.1.5 Policy analysis: walk-to-school

Opportunities to apply the HEARTS approach in Leicester were sought, both as a means of providing further testing of the methods and to demonstrate their utility in addressing specific policy questions. One policy issue is of particular interest in this context and is especially amenable to analysis using the HEARTS methods. This concerns providing safe traffic routes to school as a means of encouraging more children to walk to school and of improving the health and safety of those who do. In the United Kingdom, a programme has been established that provides funding to schools that establish safe routes.[8]

During the survey of time–activity patterns in Leicester schools, this was found to be an important priority for most of the participating schools. For this reason, a simulated study was developed to demonstrate the use of the HEARTS approach in addressing this issue in relation to a single school. In the future, as more complete data on traffic flows become available, more detailed analysis will be carried out for all participating schools in the study area.

The school selected for analysis was Braunstone School. This was a small to medium-sized school with a well-defined catchment area (as indicated by the distribution of home locations of pupils), covering a mixed area that included part of the busy Narborough Road. The scenario assessed was that, by implementing the safe routes to school policy across the city, children attending this school would elect to walk to school rather than travel by car. The study investigated the potential effects of such a change on exposure to air pollution using the STEMS-Trip and STEMS-Air models.

The shift from being driven to walking to school can be expected to have an important effect on traffic volumes at peak periods and thus on air pollutant concentrations. In the United Kingdom, as much as 40% of the road traffic in the morning peak hour (between 8:00 and 9:00) is estimated to be involved in some way in the school run. Leicester may be assumed to be broadly typical in this respect. As a basis for a simple demonstration study, therefore, the following assumptions were made.

- A city-wide initiative would encourage about 50% of those currently going to school by car to shift to walking or cycling.
- As a result of this shift, about 20% of the morning peak hour traffic (8:00–9:00) and the afternoon return from school period (15:00–16:00) would be removed from local roads.

[8] The main aims of the "Safe Routes" programme are to minimize road dangers, to encourage walking, cycling and bus use and to reduce car dependence.

- Locally derived emissions and concentrations during the peak hour would fall proportionally, but the contribution from long-range sources would not change.

- Children attending Braunstone School would continue to follow the same routes to school but would change their mode of travel from car to walking (cycling was not considered).

Based on these assumptions, STEMS-Trip and STEMS-Air were run for two scenario conditions: a baseline, comprising current air pollution conditions, and the intervention, which included a uniform 20% reduction in locally derived concentrations for the two travel-to-school periods. To simulate effects both individually and collectively, modelling was done for each of the 40 children for which time–activity data were available, for both walking and car travel under each condition. This enabled the potential change in exposure for any individual to be assessed under three possible circumstances: car travel in both the base case and intervention, walking in both base case and intervention, or a shift from car in the base case to walking in the intervention. Each child could thus be treated as an adopter or non-adopter of the walk-to-school option. Travel times were modelled in STEMS-Trip using current travel speeds (no change in speed was assumed because the study area has strict speed limits). Routes were defined both based on the time–activity data provided by the children themselves and by simulation based on the home and school location using the route-finding algorithms in STEMS-Trip. The latter approach enabled changes in route, as a consequence of change in travel mode, to be considered. The results were expressed as average travel-time exposure to $PM_{2.5}$ for each child under each condition for the specified journey (to or from school). $PM_{2.5}$ was chosen as the target pollutant both because this is of greatest concern in terms of potential health effects and because it is proportionally more local in origin than coarser particle fractions.

Table 7 presents the results on the effects of the modelled policy scenario. A value in Table 7 close to 1 means no difference when changing mode of travel; a higher value means an increase in exposure. Differences in exposure depend on the modal choices made by individuals before and after the policy was implemented. For those who maintain the same mode of travel (whether by car or walking), the changes are small (0.96 and 0.94 in Table 7) and arise solely because of the small reduction in the local contribution to pollution levels as a result of removing a proportion of cars from the local roads (assumed in this case to be 20% as a proxy for assuming that parents do not drive their children to school). For those who shift from the car to walking, as a result of the policy, there are three competing effects. Ambient concentrations fall slightly; changing from car to walking increases the average exposure (because of the higher kerbside concentrations relative to those in-vehicle); but most importantly, from our estimates, journey times increase by about 5–8 times, with the result that the duration of exposure is greatly increased. While average exposure for this last group thus rises by only about 30%, the total burden of exposure during the journey to and from school increases more than 4- to 10-fold. The increased journey time is typically at the expense of time spent indoors, either at home or at school, and in both of these environments pollution levels would be expected to be low (subject to no exposure to environmental tobacco smoke).

Compensating for these changes are the benefits of walking, such as increased exercise and opportunity for socialization.

Table 7. Effects of policy scenarios in Leicester: ratios of exposure from scenario to the base case, by mode of transport

	Total afternoon exposure			Total morning exposure			Average afternoon exposure			Average morning exposure		
Base case	Car	Walk	Car	Car	Walk	Car	Car	Walk	Car	Car	Walk	Car
Scenario	Car	Walk	Walk	Car	Walk	Walk	Car	Walk	Walk	Car	Walk	Walk
Mean	0.96	0.94	11.16	0.96	0.94	11.22	0.96	0.94	1.31	0.96	0.94	1.32
Standard deviation	0.008	0.011	1.546	0.008	0.012	1.564	0.008	0.011	0.026	0.008	0.012	0.027
Maximum	0.98	0.96	16.98	0.98	0.96	17.11	0.98	0.96	1.37	0.98	0.96	1.38
Mean	0.95	0.92	9.11	0.94	0.91	9.13	0.95	0.92	1.27	0.94	0.91	1.27

This example thus demonstrates both the potential to use the STEMS method for analysing policy and some of the surprising results that may then be discovered. Those developing policy need to consider these unexpected effects. They are not always immediately intuitive, and therein lies the benefits of a more sophisticated approach to risk and policy assessment, such as that developed in HEARTS.

3.4.2 Lille

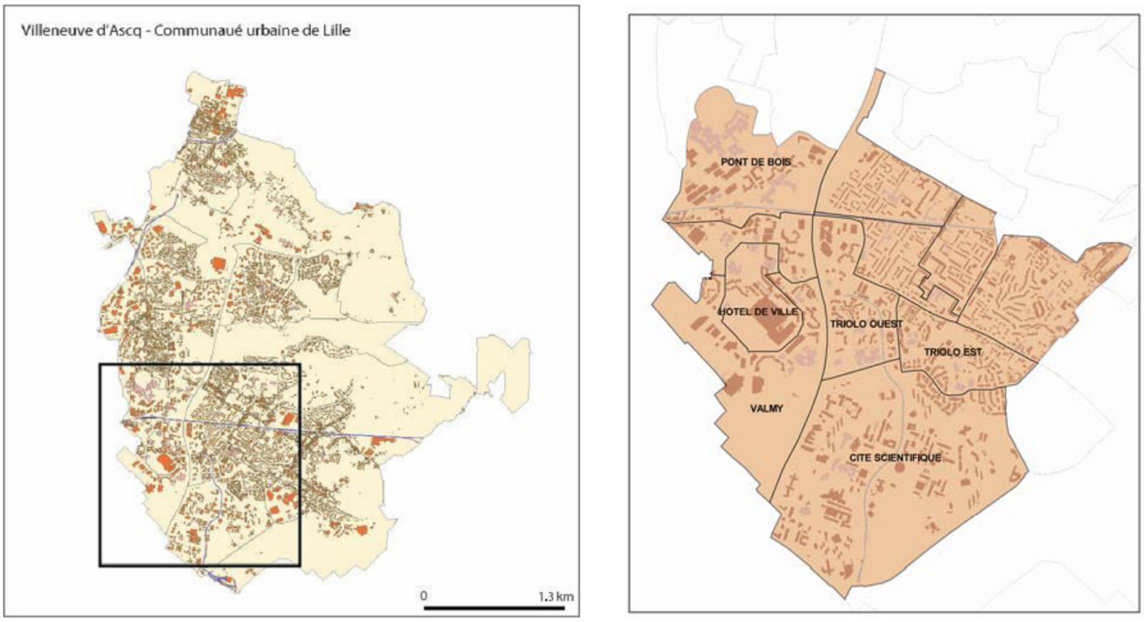
3.4.2.1 Case study area

Lille Métropole is a three-pole urban area: Lille-Roubaix-Tourcoing covers 612 km^2 with 85 city councils and a population of 1 091 000 in 2004. Motorways and a rail network link the Métropole with Paris, Belgium and northern and eastern France. There are two metro lines and one tramway line plus a dense bus network. The transport policies are taken at the level of Lille Métropole, and the scenarios in 2015 following the Plan de Déplacements Urbains are developed for the metropolitan area. For the case study, we examined the impact of theses scenarios on Villeneuve d'Ascq, a "new" city dating from the 1970s in the western part of the area (Fig. 6). The focus was on the southern part of Villeneuve d'Ascq, which is the most populated and active part of the city, including the Cité Scientifique (Fig. 6).

3.4.2.2 Data warehouse

The city of Lille has a great advantage for study and policy assessment, which is the availability of a household mobility survey. Since 1965, four surveys have assessed the daily activity and mobility of the population. The last one was realized in 1998 and another is planned in 2006. Moreover, the survey procedure follows a national standard defined by the Centre for the Study of Urban Planning, Transport and Public Facilities. It describes 5100 households, 13 000 individuals older than five years of age and a total of 52 000 trips on working days. Lille agglomeration covers 126 councils and contains 1 177 000 inhabitants. Data from the surveys were reorganized, cleaned, complemented and accessed using a reversed engineering process (Wang et al., 2001), which resulted in a complex structure.

Fig. 6. Map of Villeneuve d'Ascq and its southern part



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3.4.2.3 Modelling and scenarios

We considered two types of risk due to transport – crashes and air pollution – and three groups in the population: children 5–10 years old, students 18–24 years old and employed people 18–60 years old. We considered a simplified activity pattern with commuting associated with a trip by car (plus walking) or by pure walking.

The aim was to assess the health impact of two scenarios of transport policy for 2015: a business-as-usual one and a proactive one based on a set of actions recommended in the Plan de Déplacements Urbains (Centre d'Etudes Techniques de l'Equipement, 1996) consisting of:

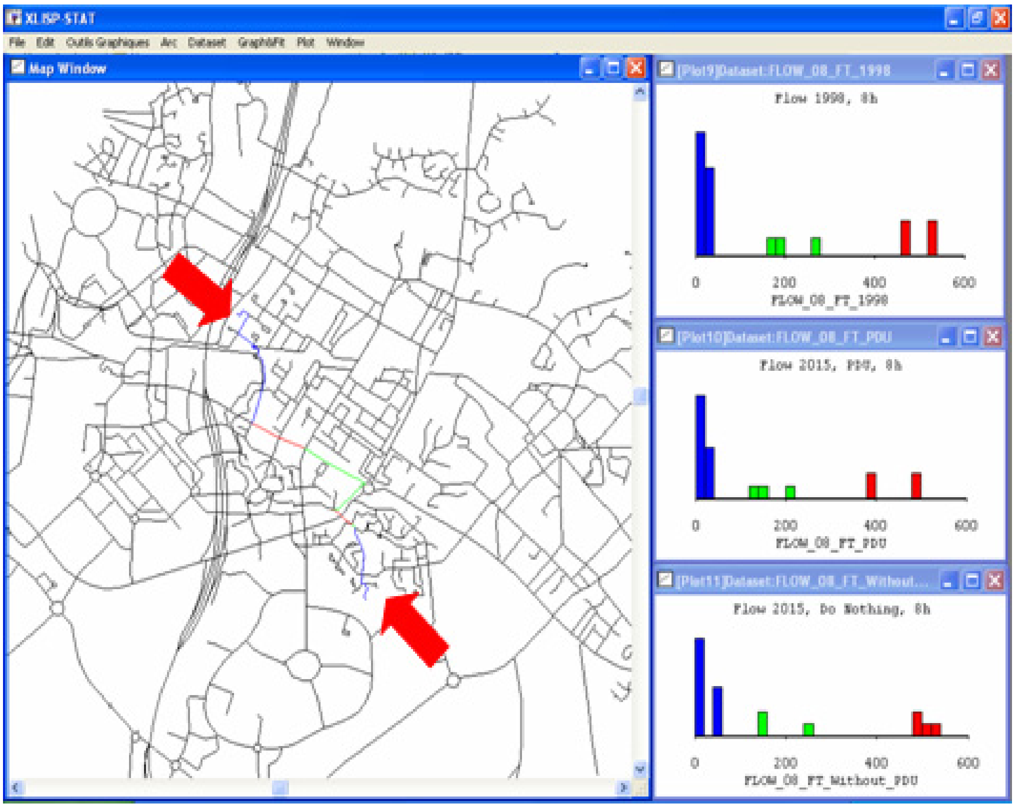
- improving public transport: more buses, cleaner buses and faster buses;
- developing metropolitan and cross-border express trains;

- planning to encourage cycling: parking possibilities and cycle paths and tracks; and

- diffusing company mobility plans to encourage more rational use of transport for employees in companies and administrations.

The model developed for simulating the crossing behaviour of an individual and his or her exposure to risk of crashes exploits traffic flow as a key variable. For this reason a simulation was run;[9] the elaboration and visualization of the various traffic flows in the three scenarios (the current situation, the situation in 2015 with a proactive policy, and the business-as-usual situation in 2015) seemed to be similar, as shown by the three statistical graphs (Fig. 7).

Fig. 7. Traffic flows encountered along a path at 8:00 for the three scenarios



The three scenarios seem to entail limited changes in traffic flow and therefore in the associated risks. However, field surveys, GIS methods and simulation techniques provided important results.

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9 In Fig. 7, the network selected in green shows the various streets and junctions an individual may follow (and cross) following the shortest path between a selected origin and destination in a given time and for a given mode (for example, 10 minutes of walking). This subnetwork is known as a potential path space in the vocabulary of time geography and as a minimum spanning tree in mathematical graph theory.

3.4.2.4 Modelling time–activity patterns and traffic intensity using Markov chains

Iterative methods based on Markov chain simulation techniques were used to estimate the risks of road pedestrian crashes. The basic idea of this modelling approach is to create a hypothetical population (for example, children) with specific mobility patterns. To achieve this goal, a probabilistic procedure was adopted, allowing the hypothetical individuals to be generated step by step. At each node of a decision tree, a random choice is made, using probabilities obtained from the initial mobility survey. For any given subject, we choose at random a type of pattern (home-school-home or home-school-home-school-home) by using their proportion in the observed data as probabilities. The durations of the various trip segments are generated at random using transition matrices and considering modes of transport. This procedure is generic and can be adapted to any specific subgroups as long as some baseline data are available. The outputs thus generated are simulated activity patterns for a typical population group (children here) with departure times, transport duration and mode and arrival times. The next step is to allocate these individuals in space: a home place and a school have to be assigned to each child as well as a route corresponding to their mode of transport and trip duration. Again, a school is assigned randomly, with probabilities determined by the survey data; then, given the school, the home location as well as the trip duration and mode are derived.

Next, the complete traffic patterns were needed. Traffic models are usually run on simplified networks usually primary streets only (30% of the network), and no estimates are available for the rest of the actual network. We developed a procedure to impute traffic flows and average speed on secondary links, using data available for primary links only. The traffic volume (number of vehicles per hour) of each secondary link was first approximated as a function of the traffic volumes of adjacent links. Then, following an iterative process, new values are computed until equilibrium is reached. For each secondary link, a mean speed is then computed based on the traffic volume of the link and the estimates from regression models for each hour of the day and in each scenario.

Thus, with traffic estimates available for the whole network, including secondary streets, and complete patterns of daily mobility, the pedestrian crossing model defined by the National Technical University of Athens could be applied to estimate, for each link, the probability of a given pedestrian crossing at a junction or at mid-block. Fig. 8. Lille: identification of crossings and the density of trips from the survey around the metro station Hôtel de Ville
shows the various streets and junctions an individual may follow and cross, choosing the shortest path between a given origin and destination.

3.4.2.5 Validation

Observed data were used for estimating the validity of the predictions by measuring the exposure to crash risk during walking trips: the number of crossings made and the conditions of these crossings related to protection (such as red lights and crosswalks) and the traffic characteristics (speed and flow).

First, information was collected about the commuting trips (origin, destination, length, duration and motivation) made by the three groups: children 6–10 years old from school to home and 11–16 years old from school to home and active adults from home to work. Second, the behaviour of pedestrians was analysed, especially concerning choices of places and timing of crossings for age groups and on the influence of urban environment and local traffic conditions.

Information was collected for adults and teenagers as follows:

- by questionnaire interviews at the exits of metro stations, workplaces or schools;
- by visual observation by a fixed observer at the exit of metro stations, workplaces or schools within a 300-metre radius with an information grid related to the demographic characteristics (such as age and sex) and observed behaviour (time of the crossing and number of intersections crossed); the grid also takes into account the configuration of the environment (such as weather conditions and the density of the traffic); and
- by further analysis of the pedestrian path described by the grid on aerial photography for a five-minute follow-up time; the route followed by an individual is drawn on an aerial photography and digitized in GIS.

This information made it possible to describe the behaviour and the conditions of the trip (solely pedestrian movement, walking before and after a car trip and walking before and after a public transport trip). Data also specified the reason for transport, the distances covered (real and perceived), time duration and the environmental context.

One primary school (Ecole Verhaeren), one secondary school (Triolo high school) and three subway stations (Hôtel de Ville, Triolo and four cantons) were selected for the exercise. shows, as an example, the identification of crossings in the GIS and the density of trips from the survey around the metro station Hôtel de Ville.

In total, 255 crossings in 77 trips (an average of 3.3 crossings per trip) were observed. The distribution, shown in Fig. 9, is rather skewed and suggests a mixed distribution.

Fig. 10 shows the distribution of crossing decisions at junctions and mid-block locations (protected and non-protected) versus the available options. Most pedestrians selected protected crossing locations. The high proportion of mid-block crossings can be attributed to the limited number of signalized junctions in the study area (the protected options are mainly crosswalks), leading pedestrians to cross indifferently at junctions or mid-block locations. In this case study, the results suggest that the strategy of crossing is influenced more by the urban structure of the city and the network configuration than the individual characteristics of the pedestrians.

Fig. 8. Lille: identification of crossings and the density of trips from the survey around the metro station Hôtel de Ville

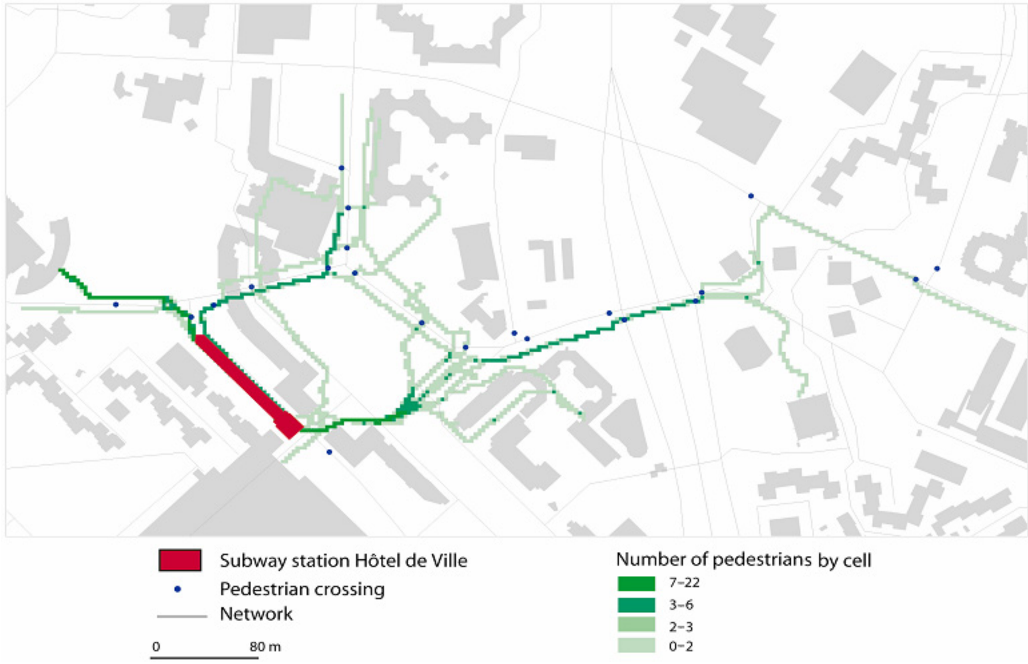


Fig. 9. Number of total crossings per trip according to the survey

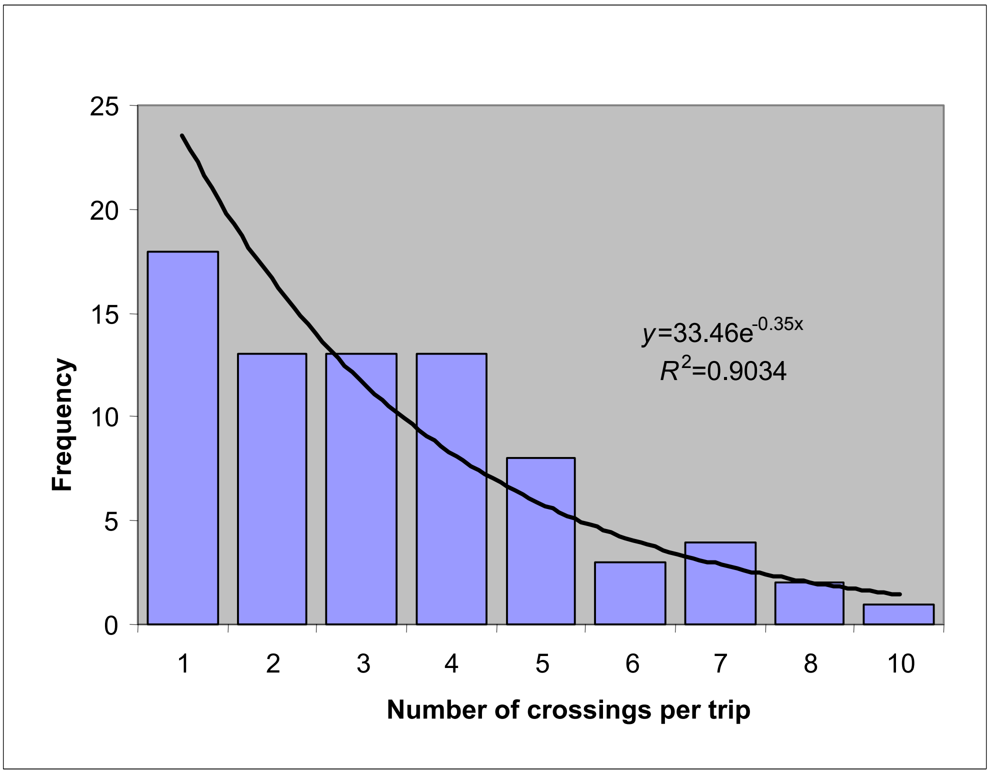
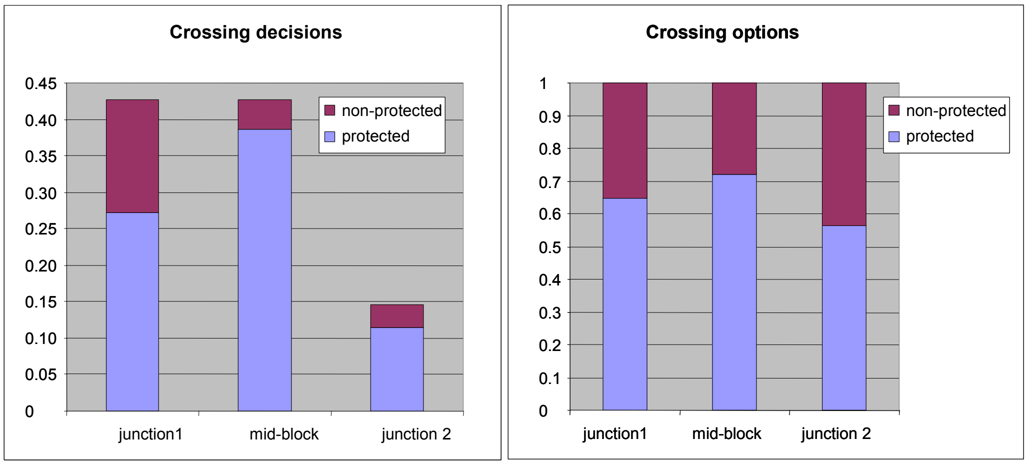


Fig. 10. Number of crossing decisions and proportion of protection among the crossing options according to the place of crossing



3.4.2.6 Comments

In the Lille case study, it proved difficult to gather and structure information for health impact assessment involving the comparison of the three transport scenarios described above because of the need to use different sources and format of data. Much of the work was devoted to adapting and completing the data to fit the prerequisite of the risk models. The proposed method to measure exposure to crashes among pedestrians, however, is an important methodological step, as the implications of transport policies in terms of road crashes may result in mortality and injuries posing a burden of disease comparable or possibly greater than other types of traffic-related exposure such as air pollution and noise.[10]

In the case study, some innovative methods were developed and applied, including:

- the data warehouse of mobility and activity of the resident population from the 1998 mobility survey data;
- the simulation tool for generating the origin and destination of trips within zones for specific groups such as children and active adults;
- the development of integrated GIS layers of networks (road, pedestrian, metro and bus) with the maps of traffic flows and speeds;

[10] The crash risk model, which is equivalent to the dose–response function related to air pollution or noise, supposes that the risk in term of frequency is proportional to the concentration indicator or to a power (less than 1) of the concentration and that the risk of crash severity is proportional to the fourth power of the speed. From these formulas and assuming data can be obtained about the measurements of exposure for concentration and speed, we could proceed to the estimation of attributable risk. What is actually missing in the modelling is the retroaction effect due to a very dangerous microenvironment, such as a high-speed street, on pedestrian behaviour and mobility. Pedestrians tend to avoid such places to cross, even if this reduces their mobility and trips.

- the development of tools for estimating the traffic variables on the secondary network; and

- setting up a method to measure the exposure to crash risk for pedestrians with observation techniques such as follow-up, interview and GIS coding techniques for the route and crossings of the walking trip for children, teenagers and adults.

3.4.3 Florence

The HEARTS integration approach in the context of the Florence case study involved the use of existing methods (such as noise and air pollution dispersion modelling) in particular models within a GIS.

Building on the available methods, the Florence case study undertook the following main activities.

- GIS datasets (modelled and measured data: noise and air pollutants emission data, etc.) were produced and used to apply and test STEMS-2.

- Air pollution exposure was measured considering: time–activity patterns, measurement of personal, home indoor and home outdoor $PM_{2.5}$ concentrations and $PM_{2.5}$ concentrations in traffic; in particular, a campaign was conducted for measuring exposure to $PM_{2.5}$ and the elements present in $PM_{2.5}$ samples were analysed.

- Two scenarios were tested comparing the situation regarding traffic and emission modelling for 2003 and 2010.

3.4.3.1 Case study area

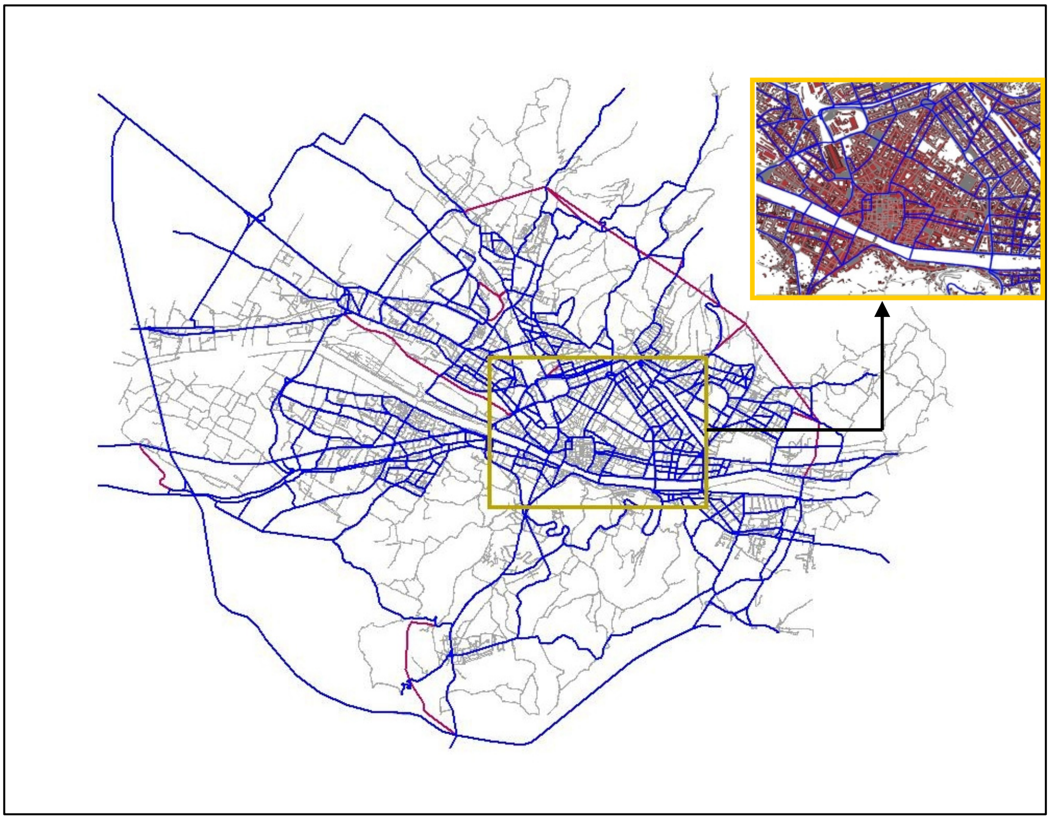
The traffic network covering the whole area of the Municipality of Florence consists of about 1000 links; it develops from about 330 km (scenario year 2003) up to 350 km (scenario year 2010) of existing or planned roads. Georeferenced data cover the entire main network and several secondary streets. The applications described below cover 40–50% of all the streets in the area.

3.4.3.2 Scenarios

In Florence, the Municipality has designed a new transport plan including: three new tram lines, planned parking at the outside terminus of tram lines, use of railways for urban transport, rearranging the urban bus network, a new connection road with the Prato and Campi Bisenzio area, a new connection road with the A1 exit of Firenze-Certosa, a new ring-road in the north of the town and increased traffic capacity of highway A1 with the construction of a new lane. The aim of the Florence case study was to test the 2010 scenario with the current situation: the 2003 scenario.

Fig. 11 shows the traffic network in Florence for both scenarios.

Fig. 11. Florence: traffic network used in the case study (2010) compared with the current map of roads



The new links for the scenario year 2010 are shown in red. (The square enlarged shows an example of the superimposition with the Florence town map.)

The next paragraphs summarize the main results on traffic, air pollution emissions and exposure, noise emissions and exposure and health effects.

3.4.3.3 Traffic

The two reference scenarios (2003 and 2010) were investigated, estimating the effects of changing both the fleet composition and the city development plan.

The results of traffic modelling show a decrease in transport volume between 2003 and 2010 of 14.6% by private cars and 1.6% by public transport (Table 8).

Table 8. Florence, results of the transport model

Scenario	Total [cars times link length] (car-km)	Total [urban buses times link length] (bus-km)
Year 2003	396 435	4 359
Year 2010	338 409	4 290
Variation		
Change (%)	–14.6%	–1.6%

It was possible to estimate the effects on emission levels of changing both the fleet composition and the general city development plan in 2010.

Starting from the geographically coded results of a traffic model, a chain of different models have been implemented and partly validated:

- a noise pollution model
- an emission model for traffic air pollutants
- air dispersion and exposure models.

3.4.3.4 Air pollution emissions

The main purpose of the emission model is to evaluate the amount of the most critical air pollutants emitted by the traffic network and to compare the effects of different scenarios. Briefly, the total emissions variation between 2003 and 2010 is a reduction of about 60% for CO, about 50% for NO_x and about 40% for PM_{10}.

Table 9 shows the effects yielded from technology: that is, the effects produced by changing the fleet composition compared with the reference scenario (the traffic scenario in 2003). In fact, the scenario in 2003, compared with scenario 2, shows a CO emission reduction of about 43% (for NO_x about 37% and for PM_{10} about 21%). Further, the comparison of scenarios 1 and 4 shows the effects in the emissions due to the change of traffic conditions (CO about 29%, NO_x about 16% and PM_{10} about 21%).

Table 9. Florence: variation in pollutant emissions between scenarios

Variation between scenarios: daily total emission (%)	CO	NO_x	PM_{10}
(scenario 1 – scenario 2)/scenario 1	43	37	21
(scenario 1 – scenario 4)/scenario 1	29	16	21
(scenario 1 – scenario 3)/scenario 1	59	48	38
(scenario 4 – scenario 3)/scenario 4	42	38	21

Explanation of scenarios

Emission scenario	Traffic scenario	Vehicular fleet
1	2003	2003
2	2003	2010
3	2010	2010
4	2010	2003

3.4.3.5 Air pollution exposure

Valid time–activity patterns were collected for 641 randomly chosen adult residents of Florence. Table 10 shows some results of the microenvironment and personal measurement campaign.

Table 10. Florence: fraction of time used in different modes of transport by all the subjects contacted

Occupational status	*n*	Car	Bus	Moped	Walking	Cycling
Employed	347	0.54	0.22	0.17	0.03	0.04
Unemployed	7	0.42	0.00	0.36	0.07	0.16
Looking for their first job	5	0.42	0.28	0.21	0.01	0.07
Homemaker	53	0.37	0.18	0.00	0.28	0.17
Student	51	0.24	0.33	0.33	0.04	0.06
Retired	178	0.45	0.22	0.04	0.24	0.05

Further, black smoke was measured and the elements present in $PM_{2.5}$ were analysed for four days in four buses of the public service company and four taxis and $PM_{2.5}$, black smoke and $PM_{2.5}$ were measured and the elements present analysed for 34 houses of resident subjects for one day. The elemental composition of the samples was determined using ion-beam analysis.

The results of the Florence case study regarding air pollution and time–activity patterns, $PM_{2.5}$ concentrations in traffic and measurement of personal, home indoor and home outdoor $PM_{2.5}$ concentrations, can be summarized as follows.

- About 9% of people's time is spent in traffic during weekdays.
- About 14% of the average daily $PM_{2.5}$ exposure derives from in-traffic exposure.
- The $PM_{2.5}$ concentrations in vehicles were 8–43 µg/m³ higher than in an urban park and 2–43 µg/m³ higher than in a high-density traffic street.
- The $PM_{2.5}$ concentrations were about 10 µg/m³ higher in buses than in taxis. This result might be related to different weather conditions during sampling days. In any case, sulfur and potassium concentrations were higher in bus-sampled filters than in taxis, and this needs to be analysed in depth.
- As expected, most of daytime is spent indoors where the mean $PM_{2.5}$ concentration is 21 µg/m³ (standard deviation ±15).
- Of the $PM_{2.5}$ indoor concentrations, indoor sources generate an estimated 39%.

This results confirm previous research results, such as the EXPOLIS study, which showed that 10% of the daily time spent in the outdoor microenvironment contributed to approximately 25% of the personal exposure to pollution of nonsmoking adults (Boudet et al., 1998).

These results have important policy consequences given that using public transport minimizes urban ambient air pollution and population exposure and that using a personal car minimizes personal in-traffic exposure to $PM_{2.5}$. Thus, new efforts and investment are needed for reducing the emissions of private and public transport as well as reducing the traffic congestion and consequent pollution. Regarding public transport, special attention must be paid to cleaning the indoor air in buses, enlarging the bus feet with vehicles with low emissions, introducing more priority bus routes and reducing bus caravanning and unnecessary idling time at the bus stop.

3.4.3.6 Noise emissions and exposure

The main objective of the noise exposure modelling was to assess the evolution of the number of people affected by traffic noise in the whole urban area when comparing the 2003 to the 2010 transport scenario. The selected indicators and method were those proposed for noise mapping by the EU Environmental Noise Directive (European Commission, 2002).

The main achievements and findings of the noise emission analysis are the following.

- After thorough investigation of emission outputs, noise emissions in the Florence area were calculated after determining "regional" correction emission factors.[11]
- The results of noise modelling show a large proportion of the population highly exposed to noise in the 2003 scenario.
- The effects of noise on health were estimated to be 19% of the adult population highly annoyed and 10% highly sleep disturbed.

Noise emission factors of the standard NMPB model required large corrections to be adapted to the specific traffic characteristics of Florence. Otherwise the NMPB model overestimates noise levels from 2 to 5 dB(A). The time needed for large-scale elaboration of accurate noise modelling still exceeds that needed for practical application. Simplified modelling tools, such as those adopted in Leicester case study, can represent a reliable solution for urban planning exercises.

Fig. 12 shows how the buildings and the receivers could be represented with different colours depending on the noise level.

These data, using the GIS, were combined with demographic data to design the Florence noise hazard maps. The exposure indicator to support estimates of health effects was calculated in accordance with the EU Environmental Noise Directive (European Commission, 2002), which includes a definition of the "noise-exposed population". Due to the low resolution of such maps, several

[11] NMPB, the interim recommended method in accordance with the EU Environmental Noise Directive (European Commission, 2002), was used and correction factors appeared as relevant. It has been estimated that adopting the new emission factors produces an overall correction of the noise emissions of streets in Florence ranging from –2 dB(A) to –5 dB(A), depending on the traffic mix on different types of streets.

buildings are aggregated in the same block. Hence, assuming that the highest noise level receptor is representative of the most exposed façade of each dwelling is incorrect and may result in substantial overestimation of the exposure index. So receptors were divided in two groups, "front" and "rear", based on their noise level, compared with the mean level of each block. Finally, the population residing in each block was divided equally between all "front" receptors.

This approach generates roughly 120 000 different receptors for which to compute noise levels for each of the two different scenarios under investigation. One implication is that calculating an estimate of the noise exposure indicator for the whole urban area requires more than one month of computing time at a latest-generation work station (currently available latest technology).

A pilot survey was carried out on the types of insulation from traffic noise in a sample of 16 residential buildings. This survey is one of the rare examples in Italy of collection of that kind of data. The results in the figure below demonstrate a large range of measured attenuations. Each point in the graph represents the value of a measured facade noise isolation index (Dw). This index expresses the difference, in decibels, between the noise level outside the windows and that inside the room, with the windows closed, on the building side facing the street.[12]

Fig. 12. A specific noise map of Florence

Blue: L_{night} <55 dB(A); cyan: L_{night} = 55–60 dB(A); green: L_{night} = 60–65 dB(A); orange: L_{night} 65–70 dB(A); red: L_{night} ≥70 dB(A).

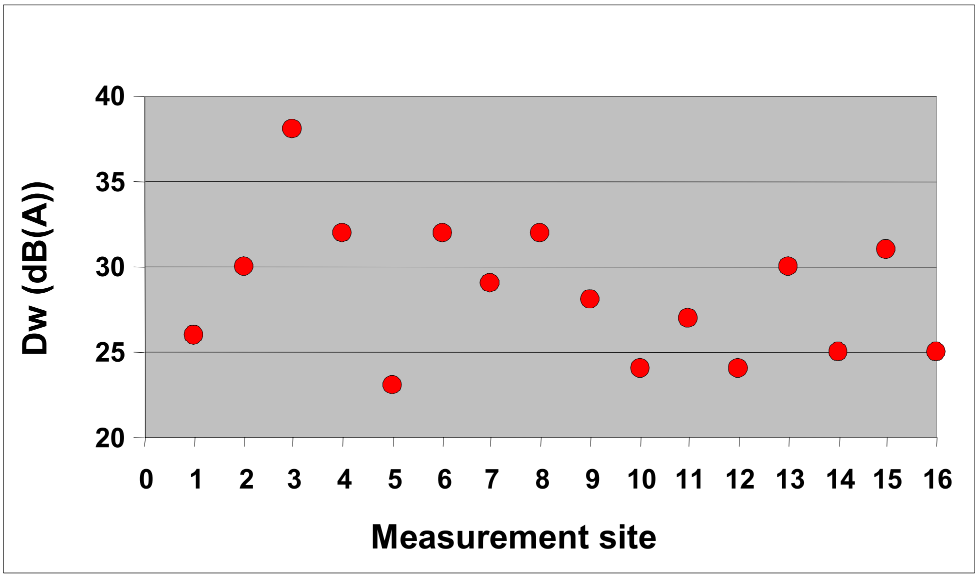
Façades very frequently offer poor insulation from outdoor noise compared with the minimum requirements adopted in several northern European countries.

[12] Italian laws establish, for new buildings, a minimum value of such parameter of 40 dB(A).

These results suggest that architectural characteristics may play an important role in differentiating the effects of noise pollution from one country to another. So far, dose–effect curves have not accounted for these effects. However, the time needed for such large-scale elaborations of accurate noise modelling is still prohibitive, so simplified modelling tools such as those adopted in the Leicester case study provide feasible solutions for urban planning exercises.

The main result of the acoustic modelling is the evaluation of the fraction of the affected population calculated by means of the model (primary network emission only). In such a way, the model can consider about 60% of the whole population[13] (Fig. 13).

Fig. 13. Florence: results of measurement of façade noise insulation



The situation in the 2003 scenario shows a large proportion of the population affected by high levels of noise both during the day and at night (Fig. 14 and 15). In terms of L_{night}, 60% of the population exceeds the night limit values (about 53 dB(A)) established by the Municipality of Florence noise zoning regulation.

A comparison of noise levels in the 2010 versus 2003 scenario (Fig. 16) shows a marked reduction in L_{night} levels.

3.4.3.7 Air pollution: health effects

Health effects due to air pollution were calculated using the average PM_{10} levels measured by the monitoring stations in 2003 of 42 µg/m³ (Regional Environmental Protection Agency of Tuscany, 2004); this value was compared with the 2010 scenario, when a 38% reduction in emission of PM_{10} is expected (Table 11). The results of the health effects of air pollution must be considered cautiously, although they are conservative. In fact, we assumed a linear

[13] In Fig. 14 and 15, the evaluation is based on the population on the main network of the whole town (total population investigated about 218 000).

“rollback model”: that is, direct proportionality between emissions and concentrations over a long period, one year in our case.

Fig. 14. Florence: percentage of people in different exposure classes for L_{night} indicator

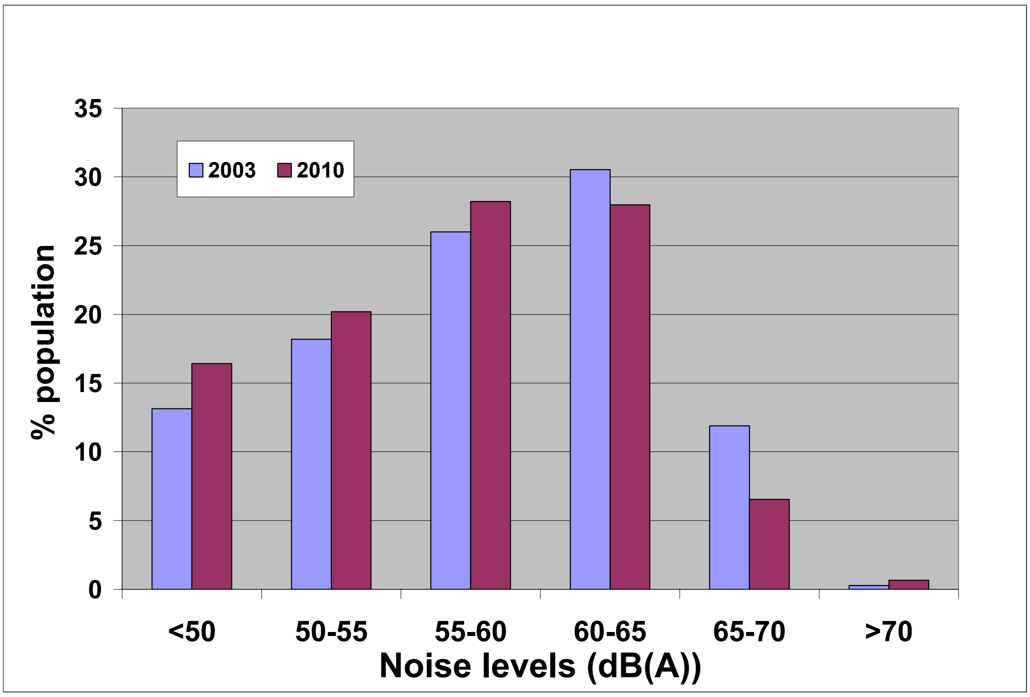


Fig. 15. Percentage of people in different exposure classes for L_{den} indicator, assessed for the population on the main network of the whole town

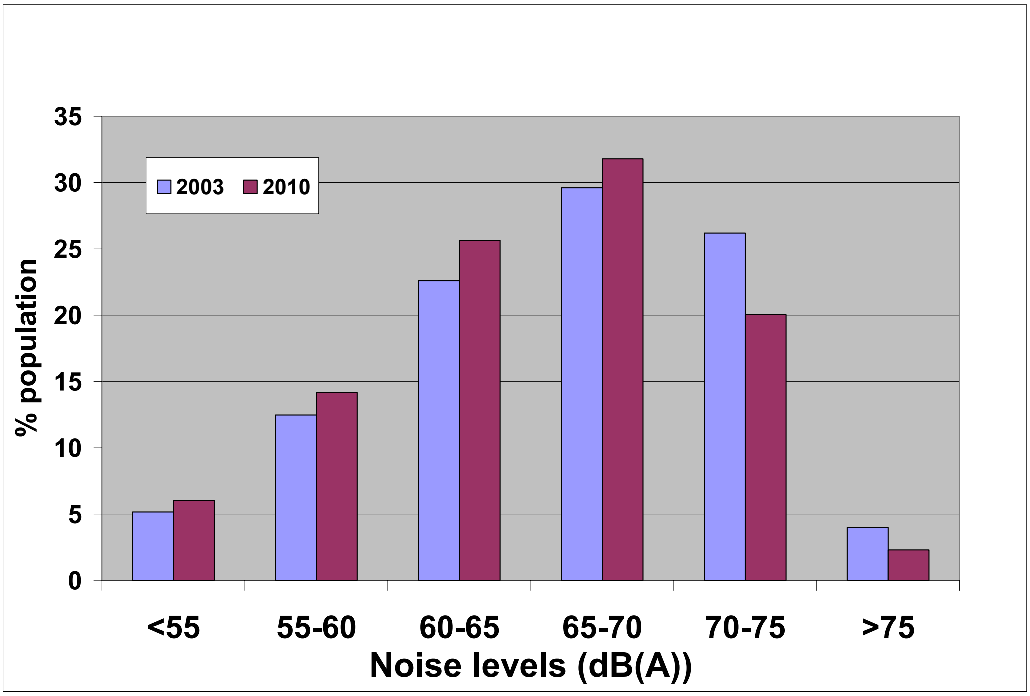
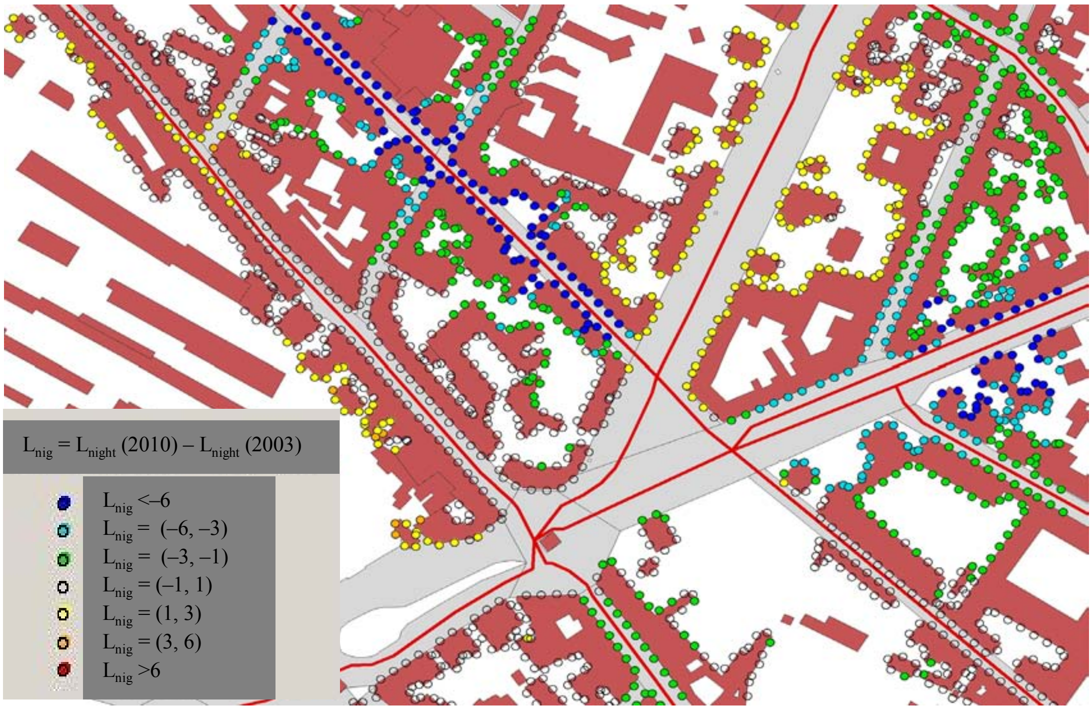


Fig. 16. L_{night} differences in receptors (coloured dots) between the 2010 and 2003 scenarios



Further, in HEARTS we solely modelled the proportion of emissions from road traffic, assuming that the 38% reduction in PM_{10} emission in 2010 would result in a 19% reduction in PM_{10} concentration, with traffic being responsible for only 50% of the total PM_{10} in the air (the average value expected is about 34 μg/m³).

Table 11. Florence, 2003–2010: modelled effects on air pollution

Effects	**Difference 2010–2003: annual decrease in health effects compared with 2003 (95% CI)**
Mortality (aged ≥30 years, excluding accidental causes) – long term	129 (45–219)
Acute bronchitis (aged <15 years)	596 (340–755)
Restricted-activity days (aged 15–64 years)	5869 (5153–6591)
Years of life lost	1400 (496–2386)

We assumed stable death rates and used the official population data for 2003 for the 2010 scenario.[14] The total population exposed in 2003 was 352 940 and the total population older than 30 years was 266 921; the total population aged 15–64 years was 223 442.

In terms of mortality, our simulation shows a reduction of 129 deaths, 596 acute bronchitis (aged <15 years), 5869 restricted-activity days (aged 15–64 years) and 1400 years of life lost per year when comparing the 2003 situation with the 2010 scenario.

14 Regarding relative risks, see Box 1 for the calculation of the years of life lost (Mathers et al., 2001).

3.4.3.9 Noise: health effects

The Florence case study also examined the effects of road traffic noise on the population. The health effects were calculated based on the noise levels estimated for the situation in 2003 compared with the 2010 scenario. Annoyance and sleep disturbance were the health effects assessed.

In assessing urban noise effects, the number of people exposed and the level of noise to which they are exposed must be considered together with the fact that the dose–response relationships were only available for the adult population at the time of the study (Stansfeld et al., 2005). For this reason, the assessment of the health effects included a population of 195 826 of 218 800 in 2003 and 186 706 of 208 610 in 2010. In 2003, in terms of annoyance it was calculated that about 38% of the adult population, 74 275 people, are annoyed and 19%, 37 146 people, highly annoyed (Table 12). In 2003, 21% of adults were sleep disturbed and 10% highly sleep disturbed – 40 385 and 19 685 people respectively (Table 12).

Table 12. Florence, 2003–2010: modelled effects of noise on health

Effects	2003	2010	Reduction 2010 versus 2003
Annoyed	74 275	66 847	–7 428 (–10%)
Highly annoyed	37 146	32 530	–4 616 (–12%)
Sleep disturbed	40 385	36 401	–3 984 (–10%)
Highly sleep disturbed	19 685	17 492	–2 193 (–11%)

Note. Total adult population exposed: 195 826 in 2003 and 186 706 in 2010

The change in noise health effects from the 2003 to 2010 scenario is significant in terms of number (Table 12). The reduction of exposure is accompanied by a likely reduction of negative health effects. The scenarios tested expect a reduction of 10% of annoyed people (7428 people), 12% of highly annoyed people (4616 people), 10% of sleep disturbed people (3984 people) and 11% of highly sleep disturbed people (2193 people).

These results complete the chain of modelling going through traffic flows, emission and dispersion modelling, exposure assessment and eventually health effects for the Florence case study.

4. Discussion

4.1 The HEARTS approach

The overall objective of HEARTS was to develop and apply an integrated method for assessing health risk to assess the multiple health effects of road traffic as a basis for informing policy and improving public health. Its motivation was the need for more integrated methods for health risk assessment that consider the full range of exposure and health effects and can be applied early in the policy or planning process. These tools should also make explicit the trade-offs between certain policy options. One of the achievements of HEARTS was the development of a loosely coupled modelling system, enabling integrated assessment of the exposure to air pollution, noise and road crashes and the associated health risks in relation to road traffic. The question during the process has been whether, in addition to this, calculating an overall estimate of the combined exposure and total health loss is useful and possible.

The consortium identified and characterized a complex set of steps and selection of models that, when integrated together, will constitute a decision-support tool for testing different urban policy scenarios. The relevant health outcomes and specific types of exposure that determine the most significant effects were identified through extensive review of the substantial evidence on the effects of ambient air pollution, noise and road crashes. To accommodate each complex structure of information, the STEMS software was refined and developed to include new models for air pollution, noise and road crash risks and was also greatly enhanced by the development of a time–activity model and graphical user interface.

As part of this process, a range of new models was developed and others adopted and adapted. The TEE emissions model was extensively improved to take into account the fact that STEMS needed to be modified and a new algorithm for the risk of crashes need to be inserted. Two additional issues were explored: the first refers to the analysis of the characteristics of pedestrian crossings in relation to infrastructure; the second one deals with speed variation along the links and near junctions. The results of the investigations described above are expected to allow the degree of exposure to be calculated accurately and realistically for different traffic conditions and types of pedestrian behaviour.

4.2 City case studies

The HEARTS approach was tested in three case studies.

In Leicester, the key results were as follows.

- The time–activity patterns of children are complex. Most children in the study area walked to school (only about 20% went by car), and most children went to local schools, with average journey times (walking or by car or bus) of about 10–15 minutes. Out-of-school activities, however, were extensive, especially for a minority of children who were involved in complex trip chains during the day. Modelling shows that travel behaviour greatly affects children's exposure to air pollution and is likely to be important in determining health risks.

- There is evidence of significant differences in exposure to air pollution between people in vehicles and people walking. Kerbside concentrations of fine PM tend to be greater than those in vehicles, and durations of exposure are longer for people walking than those travelling by car, leading to about a four- to ten-fold increase in exposure for pedestrians compared with car occupants. This has important implications for policies aimed at encouraging walking and highlights the need to design low-pollution walking routes for pedestrians.

- A scenario in which the walk-to-school policy was modelled shows that the effects on exposure to air pollution vary depending on the lifestyle of the individuals concerned. For most children, exposure would increase if they changed from travelling by car to walking; for those who continue to use a car (or continue to walk), however, the reduction in local air pollution levels provides a slight alleviation of exposure. The disadvantages in terms of air pollution exposure to those shifting their behaviour is likely to be offset by other advantages – including more exercise and opportunities for socialization.

In Lille, in Villeneuve d'Ascq, three kinds of survey techniques were used targeting adults and teenagers (interviews with questionnaire, visual observation and follow-up by an observer). In the case of follow-up by an observer, for example, the real routes used by pedestrians were recorded and entered into the GIS. Most pedestrians selected protected crossing locations.

In Florence, the results of traffic modelling showed a decrease in transport volume between the two modelled scenarios, 2003 and 2010, of 15% for private cars and 1.6% for public transport. The effects on emission levels of both changing the fleet composition and the general city development plan were estimated for 2010. For example, the total effect on emissions variation between the scenario year 2003 and the scenario year 2010 is a reduction of about 40% for traffic emissions of PM. Air pollution exposure was measured considering: time–activity patterns, measurement of personal, home indoor and home outdoor $PM_{2.5}$ concentrations and $PM_{2.5}$ concentrations in traffic. The outcomes can be summarized as follows.

- About 9% of people's time is used in traffic during weekdays.
- About 14% of the average daily $PM_{2.5}$ exposure takes place from in-traffic exposure.
- The $PM_{2.5}$ concentrations in vehicles were 8–43 μg/m³ higher than in an urban park and 2–43 μg/m³ higher than in a high-density traffic street.
- The higher $PM_{2.5}$ concentrations observed in buses than in taxis need to be evaluated in depth.
- Of the $PM_{2.5}$ indoor concentrations, outdoor sources generate an estimated 61%.
- According to a comparison between the situation in 2003 and a scenario tested for 2010, PM_{10} can decrease and have positive health effects such as an annual reduction of 129 deaths in adult mortality and an annual reduction of 1400 years of life lost.
- A relevant percentage of the population is exposed to high noise levels both during the whole day and at night. According to the scenarios tested, 2003 versus 2010, the expected reductions are 10% of annoyed people, 12% of highly annoyed people, 10% of sleep disturbed people and 11% of highly sleep disturbed people.

These results have important political consequences, given that:

- urban ambient air pollution and population exposure are minimized by using public transport; and
- using a personal car minimizes personal in-traffic exposure to $PM_{2.5}$.

New efforts and investment are needed for reducing the emissions of private and public transport as well as reducing traffic congestion and consequent pollution. Regarding public transport, special attention must be paid to reducing the emissions of public transport as well as cleaning the indoor air in buses.

In Florence, other important results originating from the noise modelling showed a large proportion of population exposed to high noise levels with resultant health effects. In terms of noise exposure, the situation seems to be comparable to other cities in Italy (Italian Agency for the Protection of the Environment and for Technical Services, 2005). The quantification of the effects of noise on health in terms of annoyance and sleep disturbance illustrated that, in 2003, 19% of the adult population was highly annoyed and 10% highly sleep disturbed; in this case, comparable data for all of Italy are lacking.

4.3 Structure and functionality of the HEARTS decision-support system

In summary, the HEARTS approach is based on a series of actions aimed at interconnecting risk assessment methods, dose–response and exposure evidence, measures of risk assessment outcome and space–time–activity patterns. Reviewing and developing the methods and subsequently applying and testing them in case studies indicated the need to go through some general steps:

- defining the purpose of the study in terms of policy scenarios;
- collecting data from internal (available in the city) and external (available from outside sources) models;
- selecting risks of interest such as air pollution, noise and road crashes;
- selecting health end-points such as adult mortality;
- collecting health statistics such as mortality incidence, life expectancy, hospital admissions for cardiovascular disease causes and hospital admissions for respiratory disease;
- defining space–time–activity data: location-specific or applying the results from other projects;
- configuring data management on space–time–activity data to organize the original data files gathered from different agencies, to structure the information contained in these files and to transform and integrate the data for their use under the GIS and/or other software;
- starting the process of analysis (spatial approach and/or probabilistic approach);
- coordinating GIS elaborations (such as simulating individual activity and mobility patterns and runs);
- providing a common approach for exposure for all risks, extending to road crashes the exposure approach developed for air and noise pollution based on modelling concentrations and space and time spent in contact with the risk factor; and
- making available significant outputs.

These are not strictly sequential steps but logical actions and topics that have to be addressed, based on the HEARTS reviews, selection of models and classification of scenarios. The HEARTS system forms a modular structure that allows any of the internal models to be used independently or bypassed and exchanged with data from external models.

The case studies demonstrated the possibility of integrated studies using existing data and/or producing new data. This flexibility is important, because in the realistic application of any integrated system in European cities, the pre-existing completeness and quality of data, availability of modelling tools, local expertise and previous experience may be expected to vary. Indeed, this variability is among the main challenges of any integrated approach. It is currently unlikely that a complex analytical system involving multiple models can be made readily available for urban administrations interested in characterizing the health implications of their transport policies. An approach such as HEARTS seems to be practicable, in most cases, by putting in place dedicated expertise not routinely available in the non-specialist domain.

The challenges that inspired the research include the different levels of integration relative to:

- information about the activity and mobility of the population;
- information about traffic (flows, emissions, speeds, etc.);
- availability and use of dose–effect relationships;
- aggregation of exposure and risk on time–space scales; and
- estimation of a disease burden encompassing different effects (such as by using years of life lost).

Moreover, we faced two issues: difficult communication among institutional bodies and the lack of a scenario culture.

Difficult communication between different planning departments of local authorities and public bodies can represent a major obstacle when applying multimodal efforts. The findings from case studies implementation have shown that the problems of communication should be addressed from the bottom up, mainly regarding issues such as the design of common format for data collection, the decision about the type of information to be collected and the people and tools to be employed. However, HEARTS acted as a catalyst for multi-authority work.

The adoption of a scenario-based culture implies that the local administration is willing to invest resources for providing integrated health assessment. This implies a commitment:

- to using transport models that can integrate the effects arising from the partial assessment of noise, emissions level and road crash risks; and
- to raising public awareness of the interwoven and trade-off effects of transport policies that not only curb emissions of pollutants but can also curb noise emissions and reduce crash and injury risks.

Politicians may be apprehensive about the unpredictable results originating from an integrated planning exercise.

4.4 Policy implications

Integrated assessment of exposure and health risks from transport policies and plans is clearly essential if the effects of policies are to be fully and properly assessed and compared and the health effects of policies factored into discussions about their costs and benefits. HEARTS did not consider the economic effects of transport, although the costs by effect and mode of transport can be used to design pricing policies based on real social costs. It is well known that the costs associated with different transport policies do vary. For example, the health and social costs of transport-related air pollution in the Madrid Region were estimated to be €357 million per year (Monzon & Guerrero, 2004). Air pollution, noise and road crashes in urban areas have a relevant impact on the quality of urban life, cause significant costs and are normally placed at the core of urban sustainability policies. Quite often measures aiming at improving safety tend to increase pollution and vice versa. The planning solution is the integration of approaches for environment and safety protection. The realization of tools allowing the future decision-makers to search for the optimal strategy is a step in this direction. HEARTS aimed at defining how these tools should operate and what the requirements are.

The models and methods developed in HEARTS have much to offer: they provide a means to analyse and assess collective effects from air pollution, noise and road crashes within a coherent and consistent framework. They also enable what-if scenarios to be developed, examining, for example, the implications of changes in policies and plans. Further, they represent a first step in the direction of more articulated policy on the mobility of vulnerable groups. Children, for example, have a right to safe play and safe walking. Patterns of physical activity are established during youth, and the long-term health benefits of fitness have been recognized. As Posner et al. (2002:234) stated, "An effective pedestrian injury prevention program must focus on the reduction of traffic exposure in several aspects of children's outdoor activities, balancing the goal of improving safety with that of preserving mobility".

As Morrison et al. (2003) pointed out: "The population health would be improved by implementing transport policies based on high quality research evidence and by withdrawing those where there is good evidence that any benefits are outweighed by harms". Several of the products and findings are relevant to policy as well as science. The comparison of air pollution exposure models, for example, has demonstrated the differences between different approaches to exposure assessment and provides useful guidance for local authorities undertaking air quality assessment in accordance with the EU Air Quality Directive. Further developing the methods used here will provide these authorities with improved tools for assessing air quality and health risk. Examples of problems of data availability, data consistency and modelling were also highlighted that are directly relevant to the EU's Global Monitoring for Environment and Security initiative.

Generally, the noise produced by motor vehicles is not sufficient to induce direct hearing damage to people exposed in normal environmental situations. However, considerable evidence indicates that such noise levels cause annoyance, stress and sleep disturbance. It has also been shown that noise is a contributing factor in cardiovascular disease (Babisch, 2005). Indirectly, noise may be a contributing factor in mental and physical problems (such as stress-related health effects). The *Green paper on the future noise policy* (European Commission, 1996) illustrates well the socioeconomic relevance and the policy implications of this problem. This paper, together with the remarks collected on it, formed the basis for the 1998 Conference on the EU's Future Noise Policy in Copenhagen, where the work of preparing the EU Environmental Noise Directive (European Commission, 2002) was started. This was also the starting-point for the work of up to ten different working groups headed by a Steering Group. On 18 July 2002, at the end of four years of work and debates, the directive was published: strategic noise mapping and interim computation methods are the focus of this directive. The directive requires strategic noise mapping (large-scale maps of the noise pollution expressed in terms of the noise indicators L_{den} and L_{night}) and action planning based on the strategic noise maps to manage and, where necessary, actively reduce the levels of environmental noise. The directive also provides the common basic definitions and imposes the use of common indicators and equivalent computation methods to ensure for the first time the comparability of noise pollution statistics across the entire EU. In this way, the first harmonized legal EU-wide legislation on environmental noise has been provided to complement existing national legislation and to ensure that the countries that do not yet have their own national regulations start finally to address the problem of environmental noise.

The ability to apply these methods of integrated risk assessment, however, does not come without difficulty. It requires the relevant data and skills within the organization and also an institutional culture geared towards collaboration, consultation and evidence-based policy. Each of these needs to be developed and fostered. Data limitations, for example, have constrained the application of the HEARTS approach in the case study cities – though these were selected in part because of their favourable data situation. Even greater problems might be expected to occur elsewhere. The technical skills to apply the models – and, equally important, to interpret the results – are also clearly limited, with the result that many cities (including the case study cities) often outsource activities such as pollution modelling or detailed pollution surveys. Capacity-building is thus an important requirement if integrated risk assessments are actually to be used for city-level transport planning.

The issues of culture and governance go deeper. Several problems of this nature were encountered in HEARTS – often because of a lack of established collaboration between departments, in some cases perhaps because of limited interdepartmental communication. These problems are not unusual.

Resolving these problems, thus, requires both technical and structural action. Technical solutions include the development and adoption of agreed and consistent data standards for integrated health risk assessment, like those being developed for environmental applications under the Global Monitoring for Environment and Security initiative and the Infrastructure for Spatial Information in Europe (INSPIRE) initiative. These standards need to govern not only data collection activities (such as the reporting of health outcomes or environmental monitoring) but also the choice of models and definition of indicators for risk assessment. At the same time, the need for diversity (to reflect different local conditions, issues, data situations and capacity) needs to be recognized. Integrated health risk assessment is therefore unlikely to be implemented quickly; it requires concerted action to establish both the infrastructure and the institutional commitment and capability to make it work. This will take time. It also requires learning from existing good practice – such as the institutional round-tables used to generate the local transport plan in the case study city of Leicester.

The concept of integrated health risk assessment emphasizes health promotion and disease prevention through the active participation of individuals and policy-makers. In such a context, the role of policy-makers is important: promoting awareness campaigns informing people in an easy and understandable way about multiple health risks of transport activities and how to cope with them.

From a policy-making viewpoint, the estimations provided through the HEARTS modelling tools can be seen as an ex-ante evaluation of the proposed policy initiatives at urban level. According to this approach, the HEARTS transport scenarios could provide to policy-makers and local government managers an estimation of the effects, in a quantitative way, that can be expected from the implementation of a determined set of policies or measures.

Moreover, if policy-makers have already implemented the policies or measures to be simulated, the simulation from HEARTS modelling could be used for ex-post evaluation, useful for carrying out sensitivity analysis about the policy effects that could be expected under different conditions.

The ability to evaluate and compare various transport scenarios to provide an integrated evaluation of health effects, addressing air pollution, noise and road crashes, is one of the fundamental motivations of HEARTS.

The value of the HEARTS approach to municipal authorities in Europe should be further explored. Indeed, the integration of models into decision-making would form an interesting study itself. Many questions remain open to discussion and political negotiation, such as who implements the integrated approach: the policy-makers or project proponent? Who carries it out: institutional agencies and/or independent bodies? Within the process, who does what, such as collecting data, preparing the report, monitoring the results and communicating the output? Who pays: the proponent, the public sector or others? The response from city case studies involved in the project was encouraging, but the effective relevance and use of the information on the health dimension of transport for cities interested in applying the methods developed in HEARTS cannot be fully assessed based on the project's experience.

Finally, the health implications of transport policies should preferably be addressed at different levels and geopolitical scales. An approach such as the one developed in HEARTS is focused on the local, city-level scale. It is important that this be complemented, and mutually supported, by efforts at the regional, national and supranational levels. For example, at the pan-European level (including the 52 Member States of the WHO European Region), the Transport, Health and Environment Pan-European Programme (2002) provides a policy framework that brings together transport, health and environment ministries from the pan-European region and facilitates the integration of environmental concerns into transport policies with a special emphasis on urban areas.

4.5 Future developments

The HEARTS approach represents a step forward in the development of an integrated approach to assess the health effects of urban transport policy. The feasibility of an integrated approach was demonstrated, but some issues remain open.

- Validation: different models can be validated to different degrees. Means of carrying out "fair" comparisons should be further identified.

- Data access and integration: methodological reflection and the development of models and tools for implementation are the main objective of projects like HEARTS. However, experience shows that difficulty in obtaining data, assessing its completeness and quality, ensuring consistency between different sources, answering questions of property and rights, cleaning, formatting, transferring and so on, absorb a large proportion of the efforts. This depends heavily on the circumstances and is difficult to be reliably predicted at the stage of project planning.

- Training for implementation: systems for integrated analysis are complex and cannot be used "off the shelf". Simplified methods could be made available to planners for preliminary assessments such as screening exercises.

- The applications require a good level of knowledge, normally to be found in established teams. It is not clear yet how a satisfactory balance between level of complexity on one hand and affordable investment in capacity-building (required to build adequate expertise) on the other can be pursued.

- Construction of an automated decision-support system: while in principle such a system is conceivable, this is not the direction followed and suggested by HEARTS. It is uncertain whether algorithms and software to accomplish this are realistic feasible, and above all the utility of such a system is dubious.

- Combined exposure: exposure to two or more stressors is an important field of research that has to be addressed in the next few years.

- How can HEARTS be applied to other modes of transport such as railways and aircraft?

- Further health benefits and risks of transport policies in urban areas can be included, notably physical activity through cycling and walking and psychosocial effects.

- Extension of the modelling to include a regional scale: by design, HEARTS did not cover all possible areas of interest in transport and health. One of the biggest challenges for the future is to identify what additional areas of research and implementation would be most beneficial and useful to support policy-making.

4.6 Final considerations

The HEARTS project emphasizes the need to make human health and safety an integral part of the impact assessment of transport policies, plans, scenarios and planning. Within the process of integration, it has to recognize the presence of different levels: the vertical integration among different models originated and developed in different disciplines with different purposes and horizontal integration, which is particularly important within the health side. Vertical integration means a common reference architecture, interconnected data collection and collaborative tools. The horizontal dimension means taking care of the different nature of the outcomes within precise analysis. For example, in health this means being able to use dose-response curves for different effects, apply a common method of measurement and acknowledge the fact that there are several unknown issues regarding mixed exposure and double-counting.

In HEARTS we demonstrated the possibilities and difficulty of implementing an integrated approach to traffic and transport effects. We have identified and characterized a complex set of steps and selection of models that together constitute a decision-support tool to test different urban policy scenarios. The HEARTS integration takes place through using existing methods (such as in noise modelling) and developing new models (such as in road crashes and pedestrian modelling). This approach, exploiting different methods, can be defined as multimodal because the integration does not mean a unique tool and an entire method but a connection among different approaches.

The ability to access and use data, the difficulty of obtaining some specific information and the complexity of work coordination constitute a challenge that has to be undertaken to improve current policy-making and to contribute to a health-promoting approach to transport. Several open issues on integration were successfully addressed, but the full development of integrated methods requires continuing and further strengthening the collaboration among different partners and testing several modelling solutions. This will require:

- analysing different data sources and comparing exposure and health assessment results;

- bringing together different risk assessment models and health analysis models through a GIS; and

- developing better means to communicate results, not only to decision-makers but also to broader audiences.

As a result of the development and validation of the model, an operational system has been developed for integrated assessment of exposure from road transport that can be used as a basis for health risk assessment. The system (STEMS-2) provides estimates of exposure to traffic-related air pollution, noise and road crashes in the form of individual-level exposure profiles for time periods of the user's choice. A graphical user interface has been developed to run the system and to design individual studies. The system also generates indicative time–activity profiles that can be used as a basis for estimating population-level exposure distributions or to compare exposure under different policy scenarios. Key components of the system have been validated as part of HEARTS, but further validation and refinement of the system is planned.

The other modelling approach, the probabilistic EXPOLIS air pollution exposure simulation framework, does not yet lend itself to integrating air pollution, noise (could be developed) and road crashes (likely more difficult). Its results are probability density distributions of exposure in the target population over time. On the other hand, general transport and traffic policies focus on the population level, citywide and long-term results, and consequently this is not a limitation. Probabilistic simulation techniques require fewer data in aggregated form (averages and distribution parameters); their results can be validated and are robust and realistic. Field exposure data, attributed to the relevant sources, and respective ambient pollution and the target population time–activity data need to be collected for both model development and validation. This was done for urban PM exposure in the Florence case study and in a more focused and detailed way concerning exposure to different particle size fractions in traffic in the Leicester case study. PM is a chemically nonspecific pollutant and may originate from different emission sources. Thus, PM toxicity may vary depending on its chemical composition. PM is used as the most significant predictor of health outcomes among air pollutants. HEARTS made a specific effort to characterize the production of and exposure to different particle size fractions resulting from road traffic. If the PM toxicity could be determined based on source types, PM might be controlled more successfully (Ito et al., 2004).

Despite the still intermediate stage of integration of traffic risk models, each case study does produce a clear differentiation between the compared and modelled alternatives in a form that is relevant for decision-making. As innovative studies often do, the results were sometimes surprising and indicate the need to redefine the original question and to search for solutions to problems that were not on the original agenda. We refer, for example, to the conflicting interests of individual and population benefits emerging when considering exposure in vehicles. The HEARTS findings indicate the need to significantly reduce traffic pollution exposure from private cars and in – and not just from – public transport, in order to consolidate the individual and population level interests. Nevertheless, even a scenario of zero-emission vehicles will still have crashes, noise and restricted physical activity.

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