Energy Conservation in Road Pavement Design, Maintenance and Utilisation

ECRPD

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Contents

1 Executive Summary

The project, 'Energy Conservation in Road Pavement Design, Maintenance and Utilisation' (ECRPD), builds on the project, 'the Integration of Energy into Road Design' (IERD), which was successfully completed in 2006.

The IERD project examined the energy requirements of the construction and operation of a road over a 20 year lifetime.

A piece of software called Joulesave was produced which operates with Bentley's MX Road design software. Joulesave automatically calculates the energy implications of an alignment as it is being designed in terms of the energy required to construct the road and also the energy which would be used on that road over a 20 year lifetime.

The Joulesave software should ideally be used at the Route Selection stage of a road design project so that the different options can be compared and the best route in terms of energy can be selected. The energy requirements of a road alignment can quickly and easily be calculated thereby enabling energy to be one of the criteria which are considered when selecting a preferred route. This would show the energy savings which are possible to achieve on a scheme. In Ireland the environmental criteria include human beings, flora and fauna, water quality, geology, hydrogeology, air quality, noise and vibration, archaeology, landscape and visual, material assets and agriculture. Energy use is not currently a specific consideration when selecting a preferred route but it is very much a contributor to air quality. Joulesave can also be used to optimise the design of an alignment in order to achieve a reduction in energy, for example the vertical alignment can be modified and Joulesave will evaluate the impact of different gradients on vehicles energy.

The Joulesave software was tested on a number of road projects during the IERD project; however, it was decided that further extensive testing should be carried out to gain reliable indications of the range of energy savings which could be made by analysing routes at the design stage.

The consortium also decided that maintenance works should be incorporated into the software as the energy used in such works is a major contribution to the overall energy use over the life of a road. The energy requirements of different materials would need to be evaluated and the results added to the Joulesave software. This was carried out in the ECRPD project and the resulting modified software is *Joulesave 2.*

The software now allows the user to choose the material types from a list of commonly used materials and new 'low energy' materials and the energy required to produce the materials and place it is evaluated. Road deterioration and rolling resistance have been incorporated into the program and their impact on vehicles' energy use is evaluated.

The Joulesave 2 software now evaluates the energy required to construct and carry out maintenance works on a road and also the energy used by vehicles over the course of the life of the road, taking into account deterioration of the road and rolling resistance as the road deteriorates.

The software has shown that the following energy savings could be achieved:

Construction Energy:	Savings of up to 47%
Operation Energy:	Savings of up to 20%
Maintenance:	Savings of up to 30%

There are twelve partners to the ECRPD project:

Waterford County Council	Ireland
National University of Ireland, Dublin	Ireland
Bentley Systems Europe	The Netherlands
Brian P. Connor & Associates Ltd.	Ireland
Statens Vag-Och Transportforskningsintitut	Sweden
Agencia Municipal de Energia do Seixal	Portugal
Engivia	Portugal
BPR Europe	France
Centrum dopravniho vyzkumu (Transport Research Centre)	Czech Republic
Ramboll	Sweden
Colas Construction Ltd.	Ireland
Technical research Centre of Finland (VTT)	Finland

The partners have expertise in the fields of road design, energy evaluation, software design, geological studies, transport research and road construction.

The project duration was three years, from 1st January 2007 to the 31st December 2010.

The project website can be visited on www.ecrpd.eu

2 Outputs from the project

2.1 Overview

The main items of work are summarised in this chapter and discussed in more detail in the following chapters.

2.2 Existing and New Road Pavement Maintenance

At the outset of the project, it was set out to compile a list of currently used pavement materials and new low energy materials and to include details of their manufacture and placement.

Data was gathered from each of the partner countries on which materials and processes are most commonly used including new low energy materials and processes. Information was gathered on the methods of manufacture and placement for each product and the following information was also gathered: the costs of the material (expensive or cheap), the road type it is used for (single carriageway/ dual carriageway), the traffic volumes it is typically used for, its freeze resistance, its moisture capabilities, the availability of the materials, the layer of road it is used for, the equipment required (existing or completely new) and whether it is used for new road construction or maintenance works.

The information gathered from this work showed which materials are most commonly used in the partners' countries and provided details on the manufacture and use of those materials.

More detail can be found in Chapter 3.

2.3 Potential Energy savings in Road Construction & Operation

In order to gain reliable indications of the type of energy savings that could be achieved by analysing routes at the design stage of a scheme, it was decided to run as many road schemes as possible through the Joulesave software. Five partners conducted this analysis for road schemes in their own countries. The analysis showed that energy savings of up to 47% could be achieved in road construction and energy savings of up to 20% could be achieved in the operation of the road over 20 years. These results were found by comparing different route options for a particular road scheme and choosing the route option with the lowest energy. An individual alignment can also be assessed in the Joulesave software to see if the design could be modified to reduce the energy costs.

More detail can be found in Chapter 4.

2.4 Energy Evaluation of Existing and New Road Materials

The work for this element of the project involved giving an energy value to the various work items carried out in road maintenance. These work items are the actions necessary to produce, i.e. manufacture, the road pavement materials and also to place them on the road. Energy values have been applied to both currently used road pavement materials and new "low energy" road pavement materials. This allows for accurate comparison between the energy used in manufacture and placement of existing road material and new "low energy" road pavement materials that are used in road maintenance.

In order to calculate and represent these energy values in the clearest manner, a spreadsheet has been produced. This spreadsheet is a result of consultation with project partners for inputs on the material types, the material mixes (both currently used and new low energy), the density of materials, the construction plant, the transport of material, the placement practices etc. Site visits were made in order to collect data. Four different carriageway types have been examined: single carriageway, wide single carriageway, dual carriageway and motorway. Energy values are calculated for each road type.

The spreadsheet produced is capable of calculating the energy values for each work item that is required for manufacture and placement of current and new road pavement materials. The spreadsheet was produced in order to calculate and represent these energy values in the clearest manner. Each layer of the road has been assigned a number of current material mixes and new material mixes. Each material mix is assigned a 'total energy to produce and place' value in the spreadsheet. By assessing the energy values for each material mix, one can evaluate which mix is most energy efficient for each layer in the carriageway.

This spreadsheet was then incorporated into Bentley's MX Road in order to predict the energy use in the maintenance of a road alignment.

More details can be found in Chapter 3.

2.5 Impact of Road Pavement on Vehicles Energy

In the IERD project, the energy used on a road alignment over a 20 year lifetime was calculated. This function of the software was carried out using VTI's VETO program which was incorporated into Joulesave. The VETO model took into consideration such factors as gradient, road surface type and traffic volumes over the course of the 20 years. However, it did not model the effect of the deterioration of the road or the impact of rolling resistance on the energy used by vehicles. These were modeled in the ECRPD project and a new version of VETO was produced, VETO ECRPD.

VETO ECRPD has been incorporated into the *Joulesave 2* software so that it now includes the impact of road deterioration on the vehicles energy over the 20 year lifetime of the road.

More details can be found in Chapter 4.

2.6 Lifecycle Analysis of Road Maintenance

It was necessary to carry out a lifecycle analysis of road maintenance to compare the environmental impacts of asphalt road construction and maintenance during the lifecycle of the road. Part of this analysis showed the process or processes that cause the greatest environmental damage during the life cycle of a product.

The computer model developed in the study can be used to compare the environmental impacts of different types of roads and their individual variations on a different composition of the road.

The aim of this part of the study was to obtain information for a transparent assessment of the system in terms of its raw material and energy intensity and environmental impact. At the same time it allows a comparison of standard and new environmental friendly technologies.

The main users are envisaged to be those who are involved in planning and solving the impact of construction on the environment. The LCA study also provides a range of information useful for other subjects and information for environmental and economic management of companies engaged in road construction.

Two maintenance processes were assessed: hot method of recycling in asphalt plant and hot in-place recycling method. It was found that when using the hot-in-place recycling method energy savings of 27.5 – 29.24 % can be achieved in the case of motorways, 27.9 – 32.7 % for dual carriageway, 27.5 – 29.3 % for wide single carriageway and 31.1 – 32.6 % for single carriageway.

More details can be found in Chapter 5.

2.7 Potential Energy Savings in Road Maintenance

The project aimed to establish what type of energy savings could be achieved by using ‘low energy’ materials. The purpose was to quantify the energy used in road maintenance on a statistically viable sample of road types, using both existing road pavement materials and new "low energy materials", and compare the energy usage between both categories of material. The new "low energy materials" correspond to current road design specifications.

The analysis shows how it is possible to achieve average energy savings of 25% to 30% using new 'low energy' materials. These savings are significant and indicate that substantial reductions in energy use are possible if consideration is given to the materials being used.

The use of 'low energy' materials is becoming increasingly popular and it is likely that more savings can be expected as newer products are developed.

Further details can be found in Chapter 6.

3 Existing and New Road Pavement Maintenance

3.1 Overview

At the outset of the project, it was set out to compile a list of currently used pavement materials and new low energy materials and to include details of their manufacture and placement.

Data was gathered from each of the partner countries on which materials and processes are most commonly used including new low energy materials and processes. Information was gathered on the methods of manufacture and placement for each product and the following information was also gathered: the costs of the material (expensive or cheap), the road type it is used for (single carriageway/ dual carriageway), the traffic volumes it is typically used for, its freeze resistance, its moisture capabilities, the availability of the materials, the layer of road it is used for, the equipment required (existing or completely new) and whether it is used for new road construction or maintenance works.

3.2 Materials

The following list summarises the currently used pavement materials (the materials in bold are the two most commonly used materials):

- Asphalt concrete (EU standard EN 13108-1 to 8 terminology)
- Very thin asphalt concrete
- Soft asphalt
- Hot rolled asphalt
- Stone mastic asphalt
- Mastic asphalt
- Porous asphalt

- Non treated gravel (EU standard EN 13285 terminology)
- Bituminous gravel- Bituminous stabilization
- Cement gravel - Cement stabilization
- Gravel treated with hydraulic binder
- Materials treated with hydraulic binder including steel slag stabilization
- Gravel treated with hydraulic binder including steel slag stabilization

3.3 Pavement Design

The following factors are taken into account when designing a road pavement:

- Economical aspects
- Materials available
- Road type
- Studded tyres (only used in Nordic countries)
- Traffic Platform (pavement support) chosen: Cumulative number of commercial vehicles
- Composition of the surface layers including subgrade, subbase and base course
- Climate conditions including freezing – thawing cycles, low temperature cracking, frost heave, moisture and high temperature conditions

3.4 Maintenance

Two main aspects of road maintenance were considered:

3.4.1 Asphalt Manufacturing

Asphalt manufacturing consists of various stages:

- Extraction of the materials
- Treatment of the materials
- Mixing
- Transport
- Spreading
- Compaction

Energy can be saved in each of these stages. The two main techniques used to decrease energy use in asphalt manufacturing are:

- the manufacturing and laying temperature (Hot-mix asphalt: >130°C, Warm or semi-warm asphalt: between 60 and 130°C, Cold asphalt: < 60°C)

- the nature of the modification process (process without major addition (other than foaming or adherence agents), the process consists of controlling the water vapour content in the final mix, sequential or multiple coating with or without bitumen foam, process with additions which modify the bitumen viscosity (specific binder, additive providing water or keeping the remaining water, paraffin or by-products), process combining two of those principles).

3.4.2 The recycling of pavement materials

Recycling began in Europe (France, Italy and Germany) in the 1980s. Energy conservation is achieved due to transport reductions (of materials from a quarry, of bitumen, of old materials) which reduce fuel consumption.

Various products can be recycled to be used in pavements:

- materials from old pavements
- surplus of excavated earth from road works
- non road materials (industrial products, demolition concrete from building, scrap tyres, glass, household refuse incineration clinker, …)

3.5 Conclusion

Table 1 summarises the findings of the study into the use of materials in each the Czech Republic, Finland, France, Ireland, Portugal and Sweden.

General use	Occasional use	Limited use	No use

Table 1: Asphalt manufacture and implementation

	Czech Republic	Finland	France	Ireland	Portugal	Sweden
Hot-mix asphalt	General use	General use	General use	General use	General use	General use
Warm or semi-warm asphalt	Limited use		Occasional use	Limited use		General use
LEA, EBE, EBT	Limited use		Occasional use			
Warm asphalt with Aspha-min	Limited use		Occasional use			
Ecoflex			Occasional use	Limited use		
WAM foam	Limited use		Occasional use			Limited use
Warm asphalt mixtures with foam	Limited use		Occasional use	Occasional use		Limited use
3E			Occasional use	Limited use		
Cold processes	Occasional use		Occasional use	Limited use		
Microsurfacing	Occasional use		Occasional use	Occasional use	Occasional use	
Ecomac			Occasional use			
Grave Emulsion / EBM				General use		
Stabilised Wetmix / SWM				General use		
Foamix				Limited use		Limited use
Ralumac				General use		
Other processes						

	Czech Republic	Finland	France	Ireland	Portugal	Sweden
Micro hot-mix asphalt (Novachip)[1]						
Flow-Mix						
Composite stabilization						
Surface dressing						
Geogrids						
New materials						
Eco-friendly binder						
Soft bitumen in bituminous mixes						
Foamed bitumen stabilization						
Foamed bitumen						
Penetration macadam[2]						
New polymer types						
Cold in-situ recycling						
Cold in plant recycling						
Hot in-situ recycling						
Hot in-plant recycling						

[1] Novachip is actually a commercial brand of micro hot-mix asphalt. For Ireland, a similar type with ULM.
[2] Penetration macadam is a very old process

4 Potential Energy Savings in Road Construction & Operation in the Partner Countries

4.1 Overview

The project 'the Integration of Energy Usage into Road Design' (IERD) was successfully completed in 2006. The project evaluated the energy used in road construction and also in the operation of a road over a 20 year lifetime. A piece of software, Joulesave, was developed which operates with Bentley's MX Road design package and calculates the energy implications of a road alignment.

As part of the ECRPD project, further analysis of road projects was conducted; several of the partners applied the Joulesave software to a number of road schemes in their countries. There were two functions of this Joulesave testing: firstly, to provide feedback to the software developer, Bentley. The partners reported any bugs or issues to Bentley and, as testing continued on a number of road schemes, suggestions for new capabilities in the software were reported. The second function of the testing was to evaluate the energy savings that can be made during the road design process. The software enables the designer to evaluate the energy requirements of a number of road design options in terms of the energy which would be required to construct the road and also the energy which would be used by vehicles on the road.

The Joulesave software should ideally be used at the Route Selection stage of a road design project so that the different options can be compared and the best route in terms of energy can be selected. This would show the energy savings which are possible to achieve on a scheme. The energy requirements of a road alignment can quickly and easily be calculated thereby enabling energy to be one of the criteria (along with ecology, archaeology etc.) which are considered when selecting a preferred route. Joulesave can also be used to optimise the design of an alignment in order to achieve a reduction in energy, for example the vertical alignment can be modified and Joulesave will evaluate the impact of different gradients on vehicles energy.

Each of the countries has analysed as many roads as possible. When selecting the routes to be evaluated, it was seen that the road planning process varies between countries. In Ireland, for example, several possible route options are proposed for a road scheme and a preferred route is chosen based on comparison of the options in terms of economic, environmental and engineering aspects. However, in some of the other partner countries, it would be unusual to have several possible route options as many of their schemes would consist of upgrading an existing road. For example, in Sweden, the roads chosen are existing roads to be upgraded as new build schemes are not under consideration at present. For this reason, there were two aspects to the testing: firstly, the software was run on a number of route options for a scheme to compare the energy usage of the different routes and, secondly, changes were made to the gradient of an alignment to establish the effect of gradient on energy.

4.2 Construction and Operational Energy

The Joulesave software calculates the energy used during construction of a road and also the energy which will be used by vehicles on the road over a 20 year lifetime. The construction energy is divided into Machinery Energy and Materials Energy, as explained in the following sections.

4.2.1 Construction Energy

Road construction was broken up into two parts: the energy used by:

i. the machinery and
ii. the materials used.

4.2.1.1 Machinery Energy

A spreadsheet entitled 'Energy Usage Operations' spreadsheet has been generated (during the IERD project) to evaluate the energy used by machinery in the construction of a road. The spreadsheet has been incorporated into the Joulesave software. A list was initially compiled of all the actions needed to construct any road. These actions were broken down into sectors of activity as follows: drainage, services, earthworks, pavement, road markings and structures. Each sector was then broken down into its constituent items. A list of typical road construction machinery was compiled for each item of activity and description of each item was defined. The fuel consumption (litres/hour) and typical output per hour were researched and calculated for each machine. For each item of activity, the smallest unit of activity was defined e.g. a kilometre for road distance, metres squared for area etc. The quantity of each unit required to complete each item of activity was calculated for each route. The fuel consumption per unit of activity and then the energy per unit were calculated. From this, the total energy per item and then the total energy per sector were calculated. This was carried out for each route option for each country. The total energy per sector for each route was added up to give the total Placement Energy. The total placement energy per kilometre was also calculated for each route.

Geotechnical reports on each of the five roads were produced and from this a list of earthworks materials for each road was drawn up. A wide variety of rock and soil types were seen to underlie the various routes. To simplify matters, a classification system was defined based on the effort required to excavate the materials. Three classifications of materials were drawn up:

i. Type A is material that can be dug up using an excavator,
ii. Type B requires ripping before excavation and
iii. Type C requires blasting before excavation.

Site visits were undertaken and the energy required to excavate soft/medium/hard rock was analysed.

4.2.1.2 Materials Energy

Data was gathered from site visits to establish the energy requirements in aggregate and bitumen production, which are the two main road-building materials. The fuel consumption of the various machines involved in aggregate and bitumen production was recorded. An evaluation of the fuel consumed by the machinery to extract, process and stockpile the aggregates was calculated as 28.38 MJ/tonne. The total added energy per tonne of bitumen produced was calculated as 4883 MJ/tonne. The quantities of aggregate and bitumen per kilometre (tonne/km) were determined and from this the Total Material Energy per kilometre was calculated.

4.2.1.3 Total Construction Energy

The total construction energy was then calculated by adding the machinery energy and the materials energy.

The Energy Usage Operations spreadsheet, as shown in the example in Table 2.1, details the amount of energy used for each sector in the construction of each road, so it can be seen where energy usage is high. Energy usage is lowest for the drainage, services and the road markings & traffic signs sectors. It can therefore be assumed that there is little potential for energy savings in these areas. The energy usage in the earthworks, pavement and structures sectors is high so these areas could be examined to see if energy savings could be made. This could be assessed at the design stage. For example, the profile of a route could be changed to optimise cut/fill volumes; different material types for the pavement could be assessed to see which is more energy efficient; quantities of basecourse etc could be examined.

:

Sector	No.	Item & Description	Units	Quantity	Plant Description	Fuel Consumption Per Hour (litres/hour)	Output per Hour	Fuel Consumption per unit	Energy per Unit	Total Energy MJ/Item	Total Energy Per Sector (TJ/Sector)
Drainage	02	Culverts incl headwalls	m	470.108	50t Crane, 36t Excavator,	49.25	30	1.641666667	63.38475	**29797.67576**	
	03	Retraining watercourses	m^3	470.108	24t exc. + 1 Truck	41	13	3.153846154	121.77	**57245.04676**	
	04	Ditches incl outfall	m	9402.159	24t exc. + 1 Truck	41	50	0.82	31.6602	**297674.2431**	
	05	Piped Drains incl manholes	m	9402.159	24t exc. + 1 Truck	41	15	2.733333333	105.534	**992247.4771**	**1.376964443**
Services	07	Install ducting for Utilities	m	37608.637	24t exc. + 1 Truck	41	25	1.64	63.3204	**2381393.945**	**2.381393945**
Earthworks	09	Strip Topsoil incl site clearance	m^2	449623.673	24t exc.,2 x A25	91.8	375	0.2448	9.451728	**4249720.662**	
	10	Tree Felling	No	0	24t exc., A25, 4 x petrol saws	64.65	11	5.877272727	226.9215	**0**	
	11	Break up any redundant pavement	m^3	0.000	36t Exc, 2 Trucks, 1 Planing Machine	121	30	4.033333333	155.727	**0**	
	12	Excavation Type C material	m^3	0.000	46t Exc, 24t Exc, Drilling Rig, Blasting Rig, 350cfm compressor, 1 Truck	171	140	1.221428571	47.15935714	**0**	
	13	Excavation of Type B material	m^3	0.000	46t Exc, Komatsu D9 or similar, 1 Truck	90.5	225	0.402222222	15.5298	**0**	
	14	Excavation of Type A material	m^3	809785.767	46t Exc, 1 Truck	50.5	275	0.183636364	7.0902	**5741543.047**	
	15	Disposal of contaminated material	m^3km	0.000	3 A40s	190.2	225	0.845333333	32.63832	**0**	
	16	Disposal of Unacceptable material	m^3km	0.000	3 A40s	190.2	225	0.845333333	32.63832	**0**	
	17	Deposition of acceptable material in embankments and other areas of Fill	m^3km	83050.750	1 Bulldozer, 1 compactor	96.5	350	0.275714286	10.64532857	**884102.5165**	
	18	Deposition of acceptable material in Landscape Areas	m^3km	3076.888	36t exc.	31	200	0.155	5.98455	**18413.79093**	
	19	Import acceptable material in and under embankments and other areas of fill	m^3km	0.000	1 Truck, 1 Shovel, Komatsu D9 or similar, 1 Bulldozer, 1 compactor	162	325	0.498461538	19.2456	**0**	
	20	Compaction in layers of acceptable material under embankments and other areas of fill, in capping areas and landscape areas	m^3	780856.375	1 Vib. Roller V5	18	175	0.102857143	3.971314286	**3101026.077**	
	21	Vertical Drains	m^3	0.000	1 46t Exc.,1 Dozer, 3 A40s	287.7	13	22.13076923	854.469	**0**	
	22	Geosynthetics	m^2	0.000	1 Truck	19.5	60	0.325	12.54825	**0**	
	23	Topsoiling	m^2	18804.319	2no. 24t excs., 2 A25s	113.3	125	0.9064	34.996104	**658077.8877**	
	24	Landscaping	m^2	0.000	2no. 24t excs., 2 A25s	113.3	250	0.4532	17.498052	**0**	**14.65288398**
Pavement	25	Sub - base in carriageway, hardshoulder and hardstrip	m^3	63019.976	1 Grader, 1 Vib Roller, 10 Trucks, 1 Loader	266	150	1.773333333	68.4684	**4314876.956**	
	26	Soil Stabilisation	m^3	0.000	1 Mixer	51	75	0.68	26.2548	**0**	
	27	Put Down Road Base	m^3	42023.580	Paver, 2 rollers, rubber-tyred exc, tractor and trailer, 8 Trucks	246.7	63	3.915873016	151.1918571	**6353623.104**	
	28	Put down Base Course	m^3	12466.030	Paver, 2 rollers, rubber-tyred exc, tractor and trailer, 8 Trucks	246.7	63	3.915873016	151.1918571	**1884762.227**	
	29	Put down Wearing Course	m^3	8273.120	Paver, 2 rollers, rubber-tyred exc, tractor and trailer, chipper, 8 Trucks	247.7	50	4.954	191.27394	**1582432.258**	
	30	Put down concrete kerbs where required	m	18804.319	Rubber-tyred exc, transit and trailer, 1 Concrete Mixer	33.125	15	2.208333333	85.26375	**1603326.716**	
	31	Put down concrete footpaths where required	m^2	0.000	Rubber-tyred exc, transit and trailer, compressor and 3 pokers, 1 Concrete Mixer	33.125	13	2.548076923	98.38125	**0**	**15.73902126**
Road Markings	32	Road Lining	m	18804.319	1 roadmarking lorry	19.5	500	0.039	1.50579	**28315.35483**	
Traffic Signs	33	Road Signing (each junction)	nr	0	Rubber-tyred exc, transit and trailer	25	0.6	41.66666667	1608.75	**0**	**0.028315355**
Structures	34	Bridges up to 10m span	m^2	0.000	50t Crane, Telescopic forklift, cherrypicker, compressor and 3 pokers, generator, 2 transits, 1 trailer, 1 Concrete Plant	105.75	0.15	705	27220.05	**0**	
	35	Bridges 10 - 50 span	m^2	0.000	50t Crane, Telescopic forklift, cherrypicker, 4 Trucks, Concrete Plant	103.75	1	103.75	4005.7875	**0**	
	36	Bridges > 50 span	m^2	0.000	50t Crane, Telescopic forklift, cherrypicker, 8 Trucks, Concrete Plant	181.75	2	90.875	3508.68375	**0**	
	37	Concrete median barriers	m	0.000	2 Extruded-concrete lorry, 1 Concrete Extrusion Machine	39	25	1.56	60.2316	**0**	
	38	Retaining Walls	m^2	0.000	Rubber-tyred Exc, Compressor and 3 pokers, generator, transit and trailer, Concrete Mixer	93.125	3	31.04166667	1198.51875	**0**	
	39	Tunnel	m traffic lanes	0.000				0	0	**0**	**0**
										34178578.99	**34.17857899**

Table 4.1

4.2.2 Operational Energy

Along with the energy used in the construction of each of the routes, the energy used by the vehicles on each route also needed to be established. A number of existing software packages for modelling traffic operation (Veto, CMEM, HDM) were initially assessed during the SAVE project and it was decided to use the Veto program, produced by VTI in Sweden. This was used to calculate the vehicle fuel consumption predictions for the various schemes.

For the purposes of this project, the traffic using the roads was split into three categories: cars, trucks and trucks with trailers. Road geometry, road surface, road surface conditions, meteorological conditions, vehicle details and driving behaviour were input into the Veto program. Each country supplied the road geometry data for its routes. Driver behaviour data, e.g. desired speed, was input for each country and for each scheme. Standard weather and road surface conditions were used for all routes. Current and predicted traffic data was known for each route.

4.3 Joulesave Software

The Joulesave software was developed by Bentley and operates with their MX Road design package. The software also incorporates the VETO program which has been developed by VTI and this evaluates the vehicles energy use on a road.

As an alignment is being designed in MX, Joulesave analyses the data and calculates the construction energy. The user is required to input details such as predicted traffic volumes, speed limits, type of surface etc. and the program calculates the energy which will be used over a 20 year life time.

Tables are then produced by the program for the construction and operational energy.

4.4 Joulesave Testing

The analysis was carried out on road projects from the Czech Republic, France, Ireland, Portugal and Sweden. Five sections of motorway, eleven sections of dual carriageways and eight sections of single carriageway roads were selected for the study.

4.5 Results & Conclusions

4.5.1 Analysis

One of the schemes in Ireland, the N25 Waterford to Glenmore scheme, will be looked at as an example.

There are 9 proposed route options for this scheme, in addition to the 'Do-Nothing' scenario which is to leave the existing road as it is. The lengths, alignments and gradients are all different but there may be some sections of route options which overlap. The alignments were run through the Joulesave software and the Construction Energy and Vehicle Energy were evaluated for a 20 year lifetime.

There are two aspects to be considered when calculating the operational (vehicles) energy. After the new scheme is constructed, there will still be a certain amount of traffic which will continue to use the existing road. The volume of traffic which uses the existing road will vary between the route options; the traffic model has shown that the proposed routes furthest from the existing road will result in a high proportion of traffic continuing to use the existing road. The road will be used for local trips as well as long journeys. The route options closer to the existing road will result in less traffic continuing to use the existing road as motorists are likely to use the new road. This must be taken into consideration in the Joulesave analysis. Therefore the existing road was also run through Joulesave.

Table 4.2 shows three columns for the Total Vehicle Energy; the 'Bypass' column shows the energy results just for traffic using the new road. The 'Existing Road' column shows the energy results just for traffic still using the existing road. The 'Bypass and Existing Road' column shows the energy results for traffic on the Bypass plus traffic on the existing road. This is the true representation of the operational energy.

The operational energy ranges from 6940 TJ for Route 4 to 8621 TJ for Route 7. These figures represent the total energy which will be used by vehicles between the years 2010 and 2029, based on traffic predictions from the traffic model for the scheme.

It can be seen that the Construction Energy ranges from 5.56 TJ for Route 9 to 9.52 TJ for Route 4. While it is worthwhile noting these values, the construction energy is small compared to the operational energy. It can be seen however that by expending more energy during the construction of a scheme, long term energy savings can be made by vehicles on the road. For example, it may be worth spending more energy on earthworks during construction to reduce a steep gradient to achieve reduced vehicle energy use over the lifetime of the road.

Table 4.2

Route Option	Type of Road	Length (km)	Total Placement Energy Per km (TJ/km)	Total Material Energy per km (TJ/km)	Road Construction Energy (TJ/km)	Total Construction Energy per Route (TJ)	Total Vehicle Energy Per Kilometre 2010-2029 (Bypass) (TJ/km)	Total Vehicle Energy for Road Project 2010-2029 (Bypass) (TJ)	Total Vehicle Energy for Road Project 2010-2029 (Existing Road) (TJ)	Total Vehicle Energy for Road Project 2010-2029 (Bypass + Existing Road) (TJ)
Route 1	Type 1 Dual Carriageway	11.79	4.89	2.59	7.48	**88.22**	378.050	**4458.722**	**3742.609**	**8201.331**
Route 2	Type 1 Dual Carriageway	9.40	3.64	2.06	5.70	**53.59**	699.829	**6579.792**	**560.537**	**7140.330**
Route 3	Type 1 Dual Carriageway	8.66	6.40	1.90	8.30	**71.88**	677.483	**5867.003**	**1145.407**	**7012.410**
Route 4	Type 1 Dual Carriageway	9.20	7.50	2.02	9.52	**87.58**	693.400	**6379.280**	**560.537**	**6939.817**
Route 5	Type 1 Dual Carriageway	9.66	3.86	2.12	5.98	**57.76**	698.706	**6748.801**	**560.537**	**7309.338**
Route 6	Type 1 Dual Carriageway	12.09	5.18	2.66	7.83	**94.70**	392.368	**4745.299**	**3742.609**	**8487.908**
Route 7	Type 1 Dual Carriageway	12.22	5.42	2.69	8.10	**99.01**	399.096	**4878.150**	**3742.609**	**8620.759**
Route 8	Type 1 Dual Carriageway	9.30	3.75	2.04	5.79	**53.83**	704.803	**6552.553**	**560.537**	**7113.090**
Route 9	Type 1 Dual Carriageway	9.39	3.49	2.06	5.56	**52.19**	759.877	**7132.205**	**-**	**7132.200**
DO-Nothing	Single Carriageway	9.49	-	-	-	**-**	-	**-**	**7485.086**	**7485.086**

4.6 Results

Table 4.3 shows a summary of the range of energy values for the construction and operation of single carriageway, dual carriageway and motorways in the Czech Republic, France, Ireland, Portugal and Sweden. These can be said to represent in a general sense the typical values for each road type but will obviously vary from scheme to scheme.

Table 4.3 Construction and Operation Energy Ranges

Road Type	Construction Energy Range (TJ/km)	Operational Energy Range (TJ/km)
Single Carriageway	3.3 → 11.7	67 → 409
Dual Carriageway	5.6 → 12.6	71 → 1291
Motorway	5.5 → 14.5	374 → 3054

There is an overlap in the construction energy values but overall there is an increase from single carriageway to motorway.

The operational energy also shows results which could be expected. A single carriageway road will generally carry less traffic per day than dual carriageway which in turn could be expected to carry less traffic than a motorway. Thus the range of values above could be said to be representative of the energy use on these road types.

4.7 Energy Savings

At the route selection stage of a project, the various route options are ranked based on environmental, economic and engineering criteria. In Ireland the environmental criteria include human beings, flora and fauna, water quality, geology, hydrogeology, air quality, noise and vibration, archaeology, landscape and visual, material assets and agriculture. Energy use is not currently a specific consideration when selecting a preferred route but it is very much a contributor to air quality.

The Joulesave program would make it very easy to evaluate the energy requirements of each route option and would allow energy to be one of the criteria to be considered when selecting a preferred route. Table 4.4 lists the construction and operation energy for each of the schemes and route options in Ireland.

Table 4.4 Construction & Operation Energy (Ireland)

Scheme	Route option	Construction Energy (TJ)	Operational Energy Bypass + Existing (TJ)
N25 Waterford to Glenmore	1	88.22	8201
	2	53.59	7140
	3	71.88	7012
	4	87.58	6940
	5	57.76	7309
	6	94.7	8488
	7	99.01	8621
	8	53.83	7113
	9	52.19	7132
N25 Dungarvan Bypass	1	155.46	9790
	2	108.71	10123
	3	156.07	10157
	4	179.08	10151
	6	123.05	10641
	6_1	113.72	9871
	7	146.9	10939
	9	131.45	10490
	10	178.62	10550
M20 Cork to Limerick	Red	638.39	36000
	Blue	677.38	36899
	Yellow	660.13	36496
	Brown	659.45	36739
N11 Enniscorthy Bypass	Cyan	270.3	23391
	Orange	431.92	25889
N11 Gorey Bypass	East	192.59	20503
	West	207.81	18824
N24 Tipperary Bypass	Southern	433.99	11697
	Northern	260.44	10466

4.7.1 Operational Energy Savings

In the case of the N25 Waterford to Glenmore scheme, vehicles on Route 4 would use the least amount of energy with the energy over a 20 year lifetime predicted to be 6940 TJ. The predicted operational energy of Route 7 is 8621 TJ. It can be said that selecting Route 4 over Route 7 would lead to savings of 1681 TJ, or 20%, over the life of the road.

Likewise, in the case of the N25 Dungarvan Bypass, energy savings of 11% are possible if Route 1 is selected as the preferred route.

Table 4.5 summarises the energy savings which could be achieved.

Table 4.5 Operational Energy savings

Scheme	Possible savings (TJ)	Possible savings %
N25 Waterford to Glenmore	1681	20%
N25 Dungarvan Bypass	1149	11%
M20 Cork to Limerick	899	2%
N11 Enniscorthy Bypass	2498	10%
N11 Gorey Bypass	1679	8%
N24 Tipperary Bypass	1231	11%

It can be see that savings of up to 20% can be achieved and on average savings of approximately 10% could be possible by evaluating the energy requirements of each route option.

4.7.2 Construction Energy Savings

The energy used in construction is much less than that used in operation but it is worth examining nonetheless. Looking at the Irish schemes again, Table 4.6 shows the savings which could be made during construction.

Table 4.6 Construction energy savings

Scheme	Possible savings (TJ)	Possible savings %
N25 Waterford to Glenmore	46.8	47%
N25 Dungarvan Bypass	70.4	39%
M20 Cork to Limerick	39	6%
N11 Enniscorthy Bypass	161.6	37%
N11 Gorey Bypass	15.22	7%
N24 Tipperary Bypass	173.6	40%

4.8 Optimisation of Routes

Changes can be made to the design of the alignments to establish if further savings can be made. For example, a steeper gradient would require vehicles to use more energy. The gradients along a route can be changed to see if it would be worthwhile expending more energy during construction to reduce the gradient in order to make long-term operational energy savings.

One of the schemes in Ireland, the N25 Dungarvan Bypass, will be looked at as an example. A steep gradient is required over a section of the scheme. Table 4.7 shows the results for gradients of 3%, 4%, 5% and 6% along this section of road. To achieve a 3% grade would require significant earthworks and this is shown by the relatively high construction energy, 179 TJ. The construction energy for the 4% gradient is also relatively high while the construction energy for gradients of 5% and 6% are much the same.

The vehicles energy does increase with increasing gradient but not significantly. In this case, it would not be worth the extra energy required to construct the 3% gradient as the savings over 20 years are so small (87TJ).

Table 4.7 Effect of gradient on energy

Route Option	Type of Road	Length (km)	Total Placement Energy Per km (TJ/km)	Total Material Energy per km (TJ/km)	Road Construction Energy (TJ/km)	Total Construction Energy per Route (TJ)	Total Vehicle Energy Per Kilometre 2010-2029 (Bypass) (TJ/km)	Total Vehicle Energy for Road Project 2010-2029 (Bypass) (TJ)
3% grade	Type 2 Dual Carriageway	15.877	8.66	2.62	11.28	**179.09**	258.456	**4103.513**
4% grade	Type 2 Dual Carriageway	15.877	6.30	2.62	8.92	**141.62**	258.937	**4111.145**
5% grade	Type 2 Dual Carriageway	15.877	4.35	2.62	6.97	**110.66**	263.483	**4183.313**
6% grade	Type 2 Dual Carriageway	15.877	4.71	2.62	7.33	**116.38**	263.980	**4191.212**

4.9 Conclusion

It can be seen that considerable energy savings could be made in the operation of a road and, to a lesser extent, in the construction of a road. Evaluation of the energy implications of a scheme during the design stages could lead to significant savings over the life of a road.

In Ireland, the National Roads Authority plan to include the monetisation of construction issues in the planning stages of major road schemes. Interest has been expressed in the Joulesave tool as a means of quantifying the energy costs of construction which can then be expressed in financial terms. This will fulfil departmental requirements for monetisation of environmental impacts of road schemes. Discussions are ongoing at present.

5 Potential Energy Savings in Road Pavement Design in the Partner Countries

5.1 Overview

The work for this element of the project involved giving an energy value to the various work items carried out in road pavement maintenance. These work items are the actions necessary to produce the road pavement materials and also to place them on the road. Energy values have been applied to both currently used road pavement materials and new “low energy” road pavement materials. This allows for accurate comparison between the energy used in production and placement of existing road material and new “low energy” road pavement materials that are used in road maintenance.

In order to calculate and represent these energy values in the clearest manner, a spreadsheet has been produced. This spreadsheet is a result of consultation with project partners for inputs on the material types, the material mixes (both currently used and new low energy), the density of materials, the construction plant, the transport of material, the placement practices etc. Site visits were made in order to collect data. Four different carriageway types have been examined: single carriageway, wide single carriageway, dual carriageway and motorway. Energy values are calculated for each road type.

This spreadsheet has been incorporated via Joulesave into Bentley’s MX Road in order to predict the energy use in the maintenance of a road alignment.

The main equation used to evaluate the total energy to produce the material mix for the road maintenance (both currently used and low energy) is:

Total Energy to Produce a Material Mix = Total Placement Energy per Layer + Total Material Manufacturing Energy per Layer + Total Mixture Production Energy per Layer

Each material mix that has been assigned to each layer (Base/regulating, Binder, Surface, and Tack Coat layer) has a Total Energy value assigned to it. By assessing the energy values for each material mix, one can evaluate which mix is most energy efficient for each layer of each carriageway. If the user then sums together the Total Energy value for each most energy efficient mix chosen in each layer, they can determine the Total Energy required to produce and place the Most Energy Efficient Carriageway to Construct from a pavement maintenance viewpoint. It does not reflect any future energy efficiency of the road from use of the road by vehicles.

5.2 Methodology

A spreadsheet was developed which evaluates the energy requirements of conducting maintenance works on a road. The user can select the road type: single carriageway, wide single carriageway, dual carriageway or motorway. A list of materials is provided for each layer of the road: base/regulating, binder, surface and tack coat. The user can select the materials for each layer from a list which includes existing commonly used materials and also new low energy materials.

The user must also input the quantities of material, aggregates, bitumen and filler required per mix per kilometre. See table 1.

On the 'Transport' worksheet, the user must input the following:

- Quantity of Material Carried at Full Load (m^3)
- Fuel Consumption at Empty Load (litre/hr) and Full load (litre/hr)
- Average Speed Vehicle will travel at to and from Road Building Site (km/hr)
- Distance from Bitumen Depot - One Way Only (km)
- Distance from Material Mixture Production Point e.g. Quarry - One Way Only (km).

The output of this spreadsheet is the Total Energy Used on Round Trip per Unit of Material Carried (MJ/m^3). See Table 2

Table 3 shows the combinations of plant that would be used for each layer for each road type. This has been incorporated into the software so the user does not have to select anything. The energy used to construct or place each layer of the road for different materials for each road type is calculated in the spreadsheet.

Table 5.1

Material Quantities for Single Carriageway

Description of Road Layer	Description of Material Mix	Units of Measurement	Total Material ENTER Total Number of Cubic Metres of Material Required Per Mix Per Kilometre (m^3/km)	Aggregates ENTER Total Number of Cubic Metres of Aggregates Required Per Mix Per Kilometre (tonne/km)	Bitumen ENTER Total Number of Cubic Metres of Bitumen Required Per Mix Per Kilometre (tonne/km)	Filler ENTER Total Number of Cubic Metres of Filler Required Per Mix Per Kilometre (tonne/km)
Base/regulating	Dense Macadam Base Cl. 903	m^3	1230	1180.8	49.2	n/a
	Heavy Duty Macadam Base Cl. 930	m^3	922.5	885.6	36.9	n/a
	Grave Emulsion	m^3	1537.5	1476	61.5	n/a
Binder	Dense Macadam Binder Cl. 906	m^3	738	703.314	34.686	n/a
	Heavy Duty Macadam Binder Cl. 933	m^3	615	586.095	28.905	n/a
Surface	Dense Macadam surface Cl. 909	m^3	492	461.004	30.996	n/a
	Close graded Macadam Surface Cl. 912	m^3	492	466.908	25.092	n/a
	Open Graded Macadam Surface Cl. 916	m^3	492	465.924	26.076	n/a
	Thin Surface Cl. 942	m^3	492	462.48	29.52	n/a
	Porous Asphalt Surface Cl. 938	m^3	492	460.02	31.98	n/a
	HRA Surface Course (Recipe Mix) Cl. 910	m^3	553.5	511.9875	41.5125	n/a
	HRA Surface Course (Design Mix) Cl. 911	m^3	553.5	517.5225	35.9775	n/a
Surface	Thin Surface Course, 20mm thick (emulsion + aggregates)	m^3	492	462.48	29.52	
	Semi-Granular Bituminous Concrete	m^3	492	462.48	29.52	
			Total Number of Units of Material Required Per Layer Per Kilometre	Total Number of Units of Aggregates Required Per Layer Per Kilometre	Total Number of tonnes of Bitumen Required Per Layer Per Kilometre	Total Number of Units of Filler Required Per Layer Per Kilometre
Tack Coat	Bituminous spray tack coat to Clause 920	m^2	24600	n/a	12.3	n/a
Cold milling/planing	Milling off existing carriageway and hard shoulders to tie into existing (i.e. 60mm for binder and 40mm for surface)	m^3	250	n/a	n/a	n/a

Table 5.2

Transport Calculations

Single Carriageway

Vehicle	Vehicle Description	Vehicle Make and Model	Amount of Material Carried @ Full Load (Tonnes of bitumen and m^3 of material mixture)	User Enter Average Speed Vehicle will Travel at to and from Road Building Site (km/hr)	Fuel Consumption @ Empty Load (litre/100km)	Fuel Consumption @ Full Load (litre/100km)	User Enter Distance from Bitumen Depot One Way Only (km)	User Enter Distance from Material Mixture Production Point e.g. Quarry - One Way Only (km)	Total Fuel Used @ Full Load (litres)	Total Fuel Used @ Empty Load (litres)	Total Fuel Used on Round Trip (litres)	Total Energy Used on Round Trip (MJ)	Total Energy Used on Round Trip Per Unit of Material Carried (MJ/Tonne for bitumen and MJ/m^3 for the material mixtures)
Truck 1	Bitumen Delivery Truck	Cab: Mercedes 46/25 to ADR spec. Tanks: Crossland/Clayton/Lag etc.	28		35	47	150	n/a	70.5	52.5	123	4749.03	169.6082143
Truck 2	Material Mixture Delivery Truck		12.5		35	47	n/a	50	23.5	17.5	41	1583.01	126.6408

Table 5.3 Placement Plant Total

Total Plant List and Description for Placement	Total Fuel Consumption (Litre/hour)
Single Carriageway	
Paver, 2 rollers, rubber tyred excavator, small truck, compressor + jack hammer	97.75
Paver, vibrating roller, pneumatic tyred roller, compressor+jack hammer	72.75
Paver, 2 rollers, rubber tyred excavator, small truck, compressor	97.75
Paver, 2 rollers, water bowser, compressor, jack hammer	82.75
Paver, 2 rollers, gritter, mini excavator, water bowser, compressor, jack hammer, bobcat/small excavator (for	135.25
Roller, 3 x 25 tonne trucks, 1 roller	82
Paver, Roller, rubber--tyred exc, tractor and trailer, 1 x 25 tonne truck	87.75
Sprayer	19.5
Planing machine, small excavator	64
Rigid tipper truck	18
Wide Single Carriageway	
2 Pavers, 2 rollers, rubber-tyred exc, tractor and trailer, 1 x 25 tonne truck	130.5
Dual Carriageway	
2 Pavers, 4 rollers, rubber tyred excavator, small truck, compressor, jack hammer	154.5
2 Pavers, 2 vibrating rollers, 2 pneumatic tyred rollers, compressor, jack hammer	131.5
2 Pavers, 4 rollers, rubber tyred excavator, small truck, compressor	154.5
2 Pavers, 4 rollers, water bowser, compressor, jack hammer	139.5
2 Pavers, 4 rollers, 2 gritters, mini excavator, water bowser, compressor, jack hammer, bobcat/small	211.5
2 Pavers, 2 rollers, rubber-tyred exc, tractor and trailer, 2 x 25 tonne trucks	148.5
Articulated Truck	19.5
Motorway	
1 Paver, 1 loader, 25 tonne truck, 2 compactors, 2 vibratory rollers, mobile feeder, 24t excavator	166.25
1 loader, 2 x 25 tonne trucks, 2 pavers, 4 vibratory rollers, mobile feeder, 5 x 24t excavators	295

In calculations on energy with regards to construction equipment, Caterpillar machinery is used as it is an international brand, used in many European countries, and fuel consumption values were easily assessable.

For each carriageway, both currently used and new low energy material mixes are examined for each different road layer. There are three road layers examined: base/regulating, binder, and surface. Each road layer is assigned associated material mixes as detailed below in table 5.4. Once energy calculations are completed, one can establish which material mix is most efficient. Comparing each material mix within each road layer allows the spreadsheet user to evaluate which material mix (new or old) is most energy efficient for that road layer. By summing together the energy of the most energy efficient mix for each of the road layers, the total energy to maintain the road in the most energy efficient way can be established.

Table 5.4
Description of road layers and their associated material mixes

Description of Road Layer	Description of Material Mix
Base/regulating	Dense Macadam Base Cl. 903
	Heavy Duty Macadam Base Cl. 930
	Grave Emulsion
Binder	Dense Macadam Binder Cl. 906
	Heavy Duty Macadam Binder Cl. 933
Surface	Dense Macadam surface Cl. 909
	Close graded Macadam Surface Cl. 912
	Open Graded Macadam Surface Cl. 916
	Thin Surface Cl. 942
	Porous Asphalt Surface Cl. 938
	HRA Surface Course (Recipe Mix) Cl. 910
	HRA Surface Course (Design Mix) Cl. 911
Surface	Thin Surface Course, 20mm thick (emulsion + aggregates)
	Semi-Granular Bituminous Concrete
Tack Coat	Bituminous spray tack coat to Clause 920

6 Impact of Road Pavement on Energy

6.1 Overview

In order to assess the impact of road pavement on vehicles' energy, a model was developed which took road deterioration and rolling resistance into consideration. This model was developed by VTI and incorporated into their VETO program.

The VETO model was then incorporated into the *Joulesave 2* software thereby including the effect of road deterioration on vehicles' energy.

Sections 6.2 and 6.3 describe the methods used to evaluate the effects of rolling resistance and road deterioration on vehicles' energy.

6.2 Rolling Resistance

The main objective of the ECPRD project is to develop models and methods to minimise the sum of energy use for road construction, for road maintenance and for road traffic. In order to estimate energy use for road traffic the influence of road surface conditions on driving resistance and energy use is of major importance. This part of driving resistance effects has been categorised as rolling resistance.

The existing literature shows the effects of road surface conditions on rolling resistance in a wide range of values. The reasons for this wide range could be:

- different methods used: fuel consumption; coast down; laboratory methods etc.
- a measuring problem in general isolating small additional forces
- use of different measures for characterising a specific road condition
- a lack of control of variables other than the road surface
- high correlations in the group of road surface variables
- high correlations between road surface and other variables depending on study design

When adding a new study of road surface rolling resistance effects to the long list of other studies it should be of major importance to prove that the accuracy is high. It is difficult to judge the level of accuracy in different studies. A possible criterion in such comparisons could depend on which variables are under control. Another criterion could be if these variables are/are not included in the analysis. If they have not been included, effects will still be there but may appear disguised in other variables like road roughness and macrotexture.

In this study the coastdown method is used to estimate driving resistance. The reasons for selecting this method are:

- the acceleration level gives a true measure of the driving resistance under real conditions
- the costs for equipment is comparatively low
- to avoid uncertainties caused by the engine and used fuel if compared to fuel consumption measurements
- there is a good potential for recording of all explanatory variables of importance.

Explanatory variables which were used in the analysis:
- speed and acceleration
- gradient
- curvature
- crossfall
- roughness
- macrotexture
- ruts
- ambient temperature
- wind speed
- air pressure.

In total, 34 road strips have been used for the measurements. These strips have been selected in order to cover the main variation in roughness and macrotexture for Swedish roads with the extra requirement that there should be a low correlation between explanatory variables.

Road surface conditions have been recorded with a Road Surface Tester (RST). The RST system reports roughness and macrotexture by several different measures. In total three test vehicles have been used: a car; a van (RST) and a truck (RDT). The operating weights were approximately 1700, 3300 and 14500 kg. The literature points out that it should be possible to detect even small effects on rolling resistance. This raises a high demand in registration of conditions with high accuracy or controlled conditions. One very important condition is to use the same tyre pressure before measurements on each test strip.

Estimated effects per unit change of IRI and MPD for the car depend on speed level:
- at 50 km/h:
  - IRI: increase in rolling resistance by 1.8%
  - MPD: increase in rolling resistance by 17 %
- at 90 km/h:
  - IRI: increase in rolling resistance by 6.0 %

- MPD: increase in rolling resistance by 30 %

In the function used for regression an ambient temperature correction term is included. The presented effects then represent 25 °C. If the air temperature in the estimated model decreases the relative IRI and MPD effects will decrease. The average coast down temperature for the car was 8 °C.

The IRI and MPD results for the other two test vehicles are not proven to be speed dependent.

For the RST the road surface effects are not proven to be different from zero. The RDT results in some cases have a wrong sign and these are deemed as being unreliable.

Compared to the literature, IRI effects are in the middle of the survey interval and MPD effects are in the upper part of the survey interval.

The analyses include tests with different road surface measures for roughness and macrotexture. Even if differences are small, IRI and MPD give the best fit of measured coastdown data to the model function compared to other alternative measures. The dynamic behaviour of a road vehicle on an uneven road is, in principle, possible to simulate. The additional driving resistance from road roughness is then estimated based on damping losses in tyres and shock absorbers. The coastdown measurements were used to validate such a simulation routine:

- the simulated additional resistances were far less than those estimated by measurements
- the correlation between simulated and measured values was very good.

Simulations should at least be possible to use after calibration.

In ECRPD there is a need for a general model representative of all types of vehicles and all models of tyres per vehicle type. Such a general model has been expressed based on the coastdown results and on literature.

The results of this ECRPD study represent an important contribution to road surface rolling resistance effects both for methodology and for presented effects. Still there are several shortcomings:

- the quality in described road conditions, especially the gradient
- the varying results for different aggregation levels
- the lack of data for vehicle types other than cars
- the lack of data for different tyre models

- the lack of data for different load conditions
- the lack of data for different load levels
- the discrepancy between simulations and measurements etc.

It is important to reduce these shortcomings in the future.

The total resistance that the engine has to overcome can be categorised in the following components:

- air resistance
- rolling resistance
- inertial resistance
- gradient resistance
- side force resistance
- transmission losses
- losses from the use of auxiliaries
- engine friction.

When discussing driving resistance and rolling resistance, the varying definitions in use can be a confusing matter. They are usually related to the measurement method that is applied. If, for instance, fuel consumption is measured, then driving resistance will probably include all the resistances in the list above. If, on the other hand, coastdown measurements are applied, then engine friction, auxiliaries and part of the transmission losses will not be included in "total driving resistance". If comparisons between different measurement methods are to be done then results must be properly translated.

There are similar problems for the rolling resistance. Depending on the method used for estimation, the rolling resistance will include a different set of resistance components. Rolling resistance in the literature could include a large number of different components:

- influence from the tyre construction when driving on a smooth surface
- influence from different tyre dimensions
- influence from the macrotexture on the tyre
- influence from road roughness on the tyre, on the suspension system and on total air resistance
- influence from wheel bearings
- influence from parts of the transmission
- influence from wheel brakes if not controlled
- influence from air resistance on the wheel

- influence from road deflection
- influence from micro-slip
- influence from the side force
- influence from a bogie in horizontal curves
- influence from selected tyre pressure
- influence from ambient air temperature or air pressure on tyre pressure
- influence from driving conditions on tyre pressure.

The total driving resistance for a road vehicle is a function of many variable groups:

- vehicle parameters
- road surface properties
- road alignment
- weather conditions
- speed pattern also including:
    - the gear position
    - the use of wheel brakes
    - the use of auxiliaries.

When conducting outdoor measurements of driving resistance with the focus on rolling resistance the following conditions are of special interest:

- ambient temperature
- wind speed and direction
- aerodynamic effects from surrounding road traffic
- air pressure
- road gradient
- road horizontal curvature and cross fall
- road surface conditions
- vehicle mass and other vehicle parameters.

The ambient air temperature and pressure will influence both air and rolling resistance. Air temperature also influences transmission losses. In the ECRPD study, the focus is on additional resistance from road surface conditions for fully warmed up vehicles.

The wind speed and direction have more than minor importance on driving resistance. These variables then have to be measured for data adjustment, if possible, or for selection of measured data with the wind speed below a “low” limit value. To measure a representative wind speed and direction is not an easy task since there will be variations along the road strip as well as between the road area and a position where wind speed is suitable to measure. Surrounding traffic will also cause aerodynamic effects on the test vehicle. In principle there should be no opposing traffic or vehicles behind or in front of the test vehicle (Hammarström, 2000a).

The air pressure influences both air resistance and rolling resistance. Since the air pressure can vary during a day the tyre pressure needs to be controlled several times during a measuring day. Rolling resistance measurements in general are done on “horizontal” road segments. One should then notice that the additional resistance from a gradient equal to 1% is approximately equal to the rolling resistance of a car. The road condition effects on rolling resistance of interest are from some percents and upwards i.e. corresponding to a gradient smaller than 1/1000.

Both horizontal curvature and crossfall generate side forces, which affect the driving resistance. The vehicle mass will change with the amount of fuel in the tank. If the vehicle mass decreases by one percent the rolling resistance will also decrease by approximately one percent.

6.2.1 Feasible methods for determining rolling resistance

In the literature, a number of different methods have been applied to estimate how driving resistance is influenced by the road surface. These can be summarised in the following main categories:

- coastdown measurements including different methods in order to measure acceleration force or torque measurements in the wheel suspension or in special designed trailers
- torque measurement in the transmission
- fuel consumption measurements
- test bench measurements of shock absorbers
- test bench measurements of vertical pulsating force on tyre
- laboratory measurements inside or outside a drum with a smooth or a rough surface
- mechanistic simulation of roughness and side forces based on properties for the tyre and the suspension. In this case one needs measured data including spring and damping parameters for the tyres and for the vehicle suspension. Of course validation measurements are also needed.
- detailed numeric simulation of tyre dynamics by solving partial differential equations.

There are also other types of laboratory measurements, but they are not used that often for road surface effects.

There is an ISO standard for rolling resistance measurements at laboratory conditions; this standardised method includes adjustment functions for temperature and the radius of the roller for laboratory measurements.

6.3 Road Deterioration

The deterioration of a road depends on the strength of the road. The strength of a road construction for each type of sub grade should be a function of the thickness of, in particular, the bound layers in the road. The materials used in the construction are also of importance for the strength. When the thickness of these layers increases the strength of the road is supposed to increase and also the energy use for road construction.

The deciding factors for providing a new road surface include the following road surface measures:

- Cracks
- Road roughness (*IRI*)
- Ruts
- Cross fall

The energy use of road traffic will increase when these measures increase. Also important for the road traffic energy is the macro texture of the surface (*MPD*). This measure will initially decrease by time. When *MPD* decreases rolling resistance and fuel consumption will be reduced.

Road deterioration models are necessary in order to find the optimal strength of a road construction while also minimising energy use for construction, maintenance and for traffic. To some extent existing models have been used and in other cases new models have been developed. One important existing model is the HDM-4 model. In this model one can see that there are local calibration factors in most sub models. This must also be the case for the ECRPD model.

One important variable in the models is the number of passing axles on heavy vehicles. These axles are translated into 100 kilo Newton axles (*N100*).

The presented models have been calibrated based on the Swedish LTPP data base. In this database over 600 selected road sections have been observed from 1985 until today.

The strength of the road is the key variable for describing deterioration of the road surface. Unfortunately a representative model for strength seems to be difficult to develop based on statistical data. The estimated strength functions, based on LTPP statistics, of layer thickness have low degrees of explanation. Based on statistics, several cases indicate reduced strength with increasing thickness. The proposed model is based on recommended values for road construction. The recommended strength information on the contrary has strong connections to layer thickness. This contradiction is not satisfactory.

Models used for crack estimation are split into initiation and propagation. Existing models have been recalibrated and to some extent modified. Cracks are of importance both for *IRI* and *MPD*.

Ruts are caused by deformation from heavy traffic and from studded tyre wear.

The *MPD* value decreases with time until the crack propagation starts.

The change of *IRI* with time is expressed based on the type of sub grade, strength (*SCI300)*[3] and the crack index. The average increase in *IRI* per year for a time period of 20 years is 0.018 and 0.030 when *SCI300* is equal to 100 and 200 respectively and *N100* is equal to 100000 per year. For a new pavement, in LTPP, *IRI* is approximately equal to 1.

The structure of the model for road deterioration is year by year and lane by lane.
For motorways different deterioration is expected in different lanes in the same direction.

The strength of a road construction for each type of sub grade should be a function of the thickness of the unbound and the bound layers in the road. When the thickness of these layers increases, the strength of the road increases but the energy use for road construction also increases. The deciding factors for a new road surface are based on road surface measures including:

- cracks
- road roughness
- ruts
- ravelling
- potholes
- cross fall

[3] When the strength increases *SCI300* decreases.

The road user has criteria for each measure to decide if a new road surface needs to be constructed. When the criteria are reached for any of the measures a decision will be made to carry out resurfacing works. There will also be a time gap from the time the criteria are reached until the resurfacing is actually carried out.

Another factor to consider is the length of road along which the criteria for resurfacing have been met. For road planning purposes in Sweden the normal length for road surface data sections is 20 m.[4] The question then would be how many such 20 m sections have to meet the criteria in order to make a decision about resurfacing.

There also could be different categories of actions:

- just repairs of the surface
- recycling and use of the material in the existing pavement
- a new pavement above the old
- a total new construction.

The model described below represents the last two alternatives.

The more time that passes before adding a new road surface the more energy will be used both for the resurfacing and by the traffic on the road. The increased energy use for the traffic is a function of increased driving resistance as the road surface deteriorates. The question of interest is to find the resurfacing periods and layer thickness that minimise the total sum of energy used for the total lifetime of the road. If the total lifetime was a function of these variables as well the complexity of the analysis would increase.

The objective for this study was:

- to make use of existing knowledge in the ECRPD project about road deterioration
- to develop a model describing road strength as a function of the unbound and bound road layers
- to put together existing models for the change of cracks, roughness, ruts and macro texture by time
- to develop new deterioration models when there are no acceptable existing models.

6.4 Final model

The final model includes:

- strength, *SCI300*
- cracking, initiation and propagation

[4] In Sweden the road surface on the main road network is measured on a yearly basis. For these measurements so called RST vehicles are used. The measurement equipment among other things includes laser equipment.

- ruts
- macrotexture, *MPD*
- roughness, *IRI*

Road surface conditions need to be described **year by year** from the year of new pavement. The conditions are per lane. A normal situation should be a systematic change in traffic per year and because of that a systematic change in road surface conditions year by year.

Road surface data have been used as input to VETO (Hammarström and Karlsson, 1987). In the last VETO version *IRI* and *MPD* are described per road object. Cross fall is described "meter by meter". The resulting output from the deterioration model is then average *IRI* and *MPD* per road object and year.

6.4.1 Strength, *SCI300*

Input data:

- subgrade
- unbound layer thickness, mm
- bound layer thickness, mm
- calibration factor

An alternative is that the user gives *SCI300* directly as input.

Output data: *SCI300* for a new pavement.

6.4.2 Cracking

Initiation. Input data:

- *N100* per year and lane
- *SCI300* for a new pavement
- Calibration factor

Just for initiation the selected *SCI300* might be replaced if the value is below the limit curve value. N100 is an average value for the initiation time interval. One problem then is how to estimate this value since the time period is not available at this stage.
Output data:

- limit curve for the validity of the initiation model

- accumulated number of *N100* until the start of propagation, sum(*N100*(init))

Propagation. Input data:

- *Sum(N100 (init))*
- *N100* per year and direction. The same problem as for initiation.

Output data: *Si* at each year. This value is the sum of *Si(init)* and additional *Si* during propagation.

6.4.3 Ruts

Input data:

- *SCI300*
- *sum(N100(j))*, sum of *N100* year by year from new pavement until year (j)
- *sum(light(j))*
- number of months per year with studded tyres
- percentage of light vehicles with studded tyres during months with studded tyres

Output data: rut depth year by year and lane by lane after the pavement was new.

6.4.4 Macrotexture, *MPD*

Input data:

- surface type
- *sum(N100(j))*, sum of *N100* year by year from new pavement until year (j)
- crack index year by year
- calibration factor

Output data: *MPD* year by year and lane by lane from the new pavement.

6.4.5 Roughness, *IRI*

Input data:

- sub grade
- *SCI300*
- crack index year by year from the last resurfacing

- calibration factor

Output data: *IRI* year by year and lane by lane.

7 Lifecycle Analysis of Road Maintenance

7.1 Overview

The main goal of this part of the study was to compare the environmental impacts of asphalt road construction and maintenance during its life cycle. Another goal was to determine in which process or group of processes during the life cycle of a product is the greatest environmental damage. The computer model developed in the study can be used to compare the environmental impacts of different types of roads and their individual variations on a different composition of the road.

The purpose of the study was to obtain information for a transparent assessment of the system in terms of its raw material and energy intensity and environmental impact. At the same time it allows a comparison of standard and new environmental friendly technologies.

The main users are envisaged to be those who are involved in planning and solving the impact of construction on the environment. The LCA study also provides a range of information useful for other subjects and information for environmental and economic management of companies engaged in road construction.

7.2 Scope of the study

7.2.1 Product system

The study covers construction and maintenance of the asphalt pavement for four typical road types. Initial phases of road construction, for example land preparation and foundation construction, are not included. Selected types of road are motorway, dual carriageway, wide single carriageway and single carriageway. Figure 7.1 illustrates in detail which part of the road is covered in this study. Figure 7.2 illustrates which processes in the course of the life time period of the asphalt pavements are covered in this study. Traffic is not included.

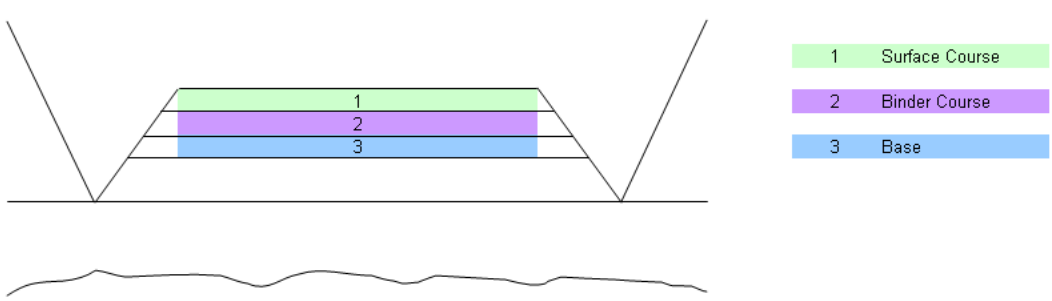

Figure 7.1. Cross-section of the road, coloured asphalt layers are covered in this study

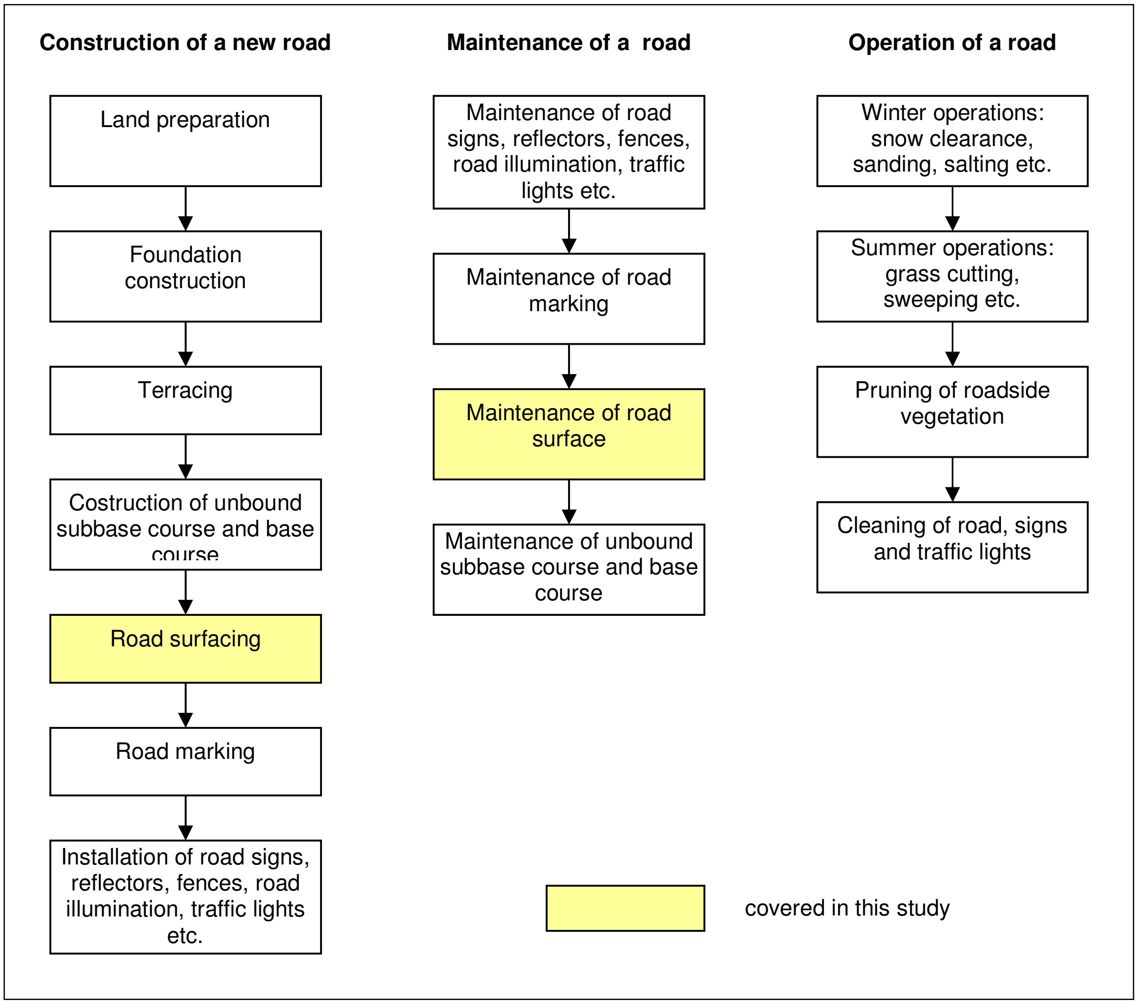

Figure 7.2. Processes in course of road life time period

In the list below the intended road construction and maintenance processes are shown.

Initial construction of the pavement

- Asphalt laying and rolling, hot method, road base
- Asphalt laying and rolling, hot method, binder course
- Asphalt laying and rolling, hot method, surface course
- Application of adhesion layer (tack coat)

Maintenance of the pavement

Scenario A:

- Milling of asphalt surface
- Asphalt laying and rolling in maintenance, hot method, surface course
- Adhesion layer (tack coat) application between asphalt layers

Scenario B:

- Remix in maintenance, hot method in situ, surface course

Due to the local nature of the effects of road construction, primarily local data was used. Use was also made of general Czech knowledge, which was supplemented by international sources of data where necessary.

7.2.1.1 Production of fuels and energy

Data from production of electricity, diesel fuel, liquified petroleum gas and natural gas comes from The Boustead model database. Data for diesel contains extraction of crude oil, transport to refinery, refining, storage and transport to user. Data for LPG contains extraction of crude oil, transport to refinery, production of gas, storage and transport to user. Data for NG contains extraction, imports and delivery to user. Data for electricity comes from electricity generation mix in each country (including import and export). It includes production in power plants and distribution in electric grid (including extraction and transport sources for electricity production).

7.2.1.2 Production of materials

In the case of raw materials production the Gemis database was used (aggregates, sand, lime), data from producer (bitumen, emulsion, asphalt mixture) and data from international study (emulsifier). The emissions from fuels production and electricity generation, included in the production of materials, were specified above.

7.2.1.3 Transportation

It was assumed that the materials used in road construction would be transported by lorry. The quantities to be transported were calculated on the basis parameters of roads and composition of mixtures. Emissions of transportation were assessed in accordance with the Emission Inventory Guidebook. The emissions from fuel production were specified above.

7.2.1.4 Road construction and reconstruction

The masses, volumes and weights per unit volume of road paving materials during storage and transportation were calculated based on information provided by Transport research centrum, material suppliers and TP standards. The operating times and energy consumption of work machines were calculated based on data cards from machine producers. The emissions of machines were calculated based on the emission factors from the Emission Inventory Guidebook. The emissions from fuels production were specified above.

7.2.1.5 *Data deficiencies and uncertainties*

Establishment of inventory data for working operation is complicated and the data depends on many factors such as climatic conditions, the human factor and others. During the calculations of working operations, the average efficiency of machines and optimal summer climatic conditions are considered. An effective working time of machines of 50 min./hour is used in most cases, where accurate data from long-term measurement of the machine manufacturer is not known.

Another problem is the determination of emissions of dust particles released from the materials used in their handling during the various stages of processing, especially during transportation. Even greater health risks are small dust particles $PM_{1,0}$ and $PM_{2,5}$, which remain a long time in the atmosphere and are transported over long distances. More accurate data on emissions $PM_{1,0}$ and $PM_{2,5}$ are not known and are part of the total emissions of dust particles.

Parameters of different production technologies of products may vary. Emissions depend greatly on the type of fuel used. In the study, primarily environmentally friendly technologies are used, which use mainly electricity and natural gas in the operation. In the case of the refineries fuel oil is used, which is generated during the processing of crude oil.

7.3 *Comparsion from point of view of life cycle*

A comparison was made of all defined types of roads and maintenance of the two scenarios for these types of roads. In the list below the intended road construction and maintenance processes are shown.

Initial construction of the pavement and maintenance of the pavement:

Scenario A: hot method of recycling in asphalt plant

Scenario B: hot-in-place method of recycling.

The lowest energy consumption is achieved for wide single carriageway - construction and scenario A of maintenance and for motorway - construction and scenario B of maintenance.
The lowest CO, SO_x, NO_x, CO_2, CH_4 emissions are achieved in the case of single carriageway - construction and scenario B of maintenance and in the case of motorway - construction and scenario B of maintenance.
The lowest HC emissions are achieved in the case of single carriageway - construction and scenario A of maintenance and in the case of motorway - construction and scenario B of maintenance.

The lowest PM emissions are achieved in the case of wide single carriageway - construction and scenario B of maintenance and in the case of dual carriageway - construction and scenario B of maintenance.
The lowest N_2O emissions are achieved in the case of single carriageway - construction and scenario A and B of maintenance and in the case of motorway - construction and scenario B of maintenance.
The lowest global warming potential is achieved in the case of single carriageway - construction and scenario B of maintenance and in the case of motorway - construction and scenario B of maintenance.

7.4 Results

The construction of a new road is a very energy-consuming process. Production of asphalt mixtures and their application consumes approximately 9384,7 – 9986,3 GJ/km for motorways, 9374,5 – 9979,9 GJ/km for dual carriageway, 3166,2 – 3357,0 GJ/km for wide single carriageway and 3132,8 – 3343,2 GJ/km for single carriageway. The most energy intensive process is the production of asphalt mixtures, which consumes about 92,4 – 92,9 % of energy. Transport of materials and mixtures consumes about 5,7 – 6,3 % of energy and processes of pavement laying consumes 1,0 – 1,8 % of energy.

Maintenance of asphalt surfaces, as described in scenario A (hot method of recycling in asphalt plant), consumes approximately 2096,0 – 2221,7 GJ/km for motorways, 1977,5 – 2141,9 GJ/km for dual carriageway, 872,9 – 927,0 GJ/km for wide single carriageway and 898,5 – 954,6 GJ/km for single carriageway. It accounts for 90,4 – 90,8 % of the production process of new mixture, 5,3 – 5,8 % to transport materials and asphalt mixtures and 3,3 – 4,1 % for the operations.

Maintenance of asphalt surfaces, as described in scenario B (hot-in-place recycling method), consumes approximately 1519,8 – 1584,6 GJ/km for motorways, 1425,2 – 1489,0 GJ/km for dual carriageway, 632,6 – 660,4 GJ/km for wide single carriageway and 618,8 – 648,1 GJ/km for single carriageway. It accounts for 68,5 – 71,2 % of the production process of new mixture, 3,0 – 3,4 % to transport materials and asphalt mixtures and 25,3 – 28,4 % for the remixing and other operations.

When using the hot-in-place recycling method energy savings of 27,5 – 29,24 % can be achieved in the case of motorways, 27,9 – 32,7 % for dual carriageway, 27,5 – 29,3 % for wide single carriageway and 31,1 – 32,6 % for single carriageway.

8 Potential Energy Savings In Road Maintenance

8.1 Overview

The project aimed to establish what type of energy savings could be achieved by using ‘low energy’ materials. The purpose is to quantify the energy used in road maintenance on a statistically viable sample of road type, using both existing road pavement materials and new “low energy materials”, and compare the energy usage between both categories of material. The new “low energy materials” correspond to current road design specifications.

Routes were selected in Ireland and Portugal for the analysis. The final results will give a statistically reliable picture on EU25 scale of potential energy savings and facilitate regulatory authorities (National Governments and EU) to decide if low energy materials should be promoted for use in road pavement maintenance.

Table 8.1 – Road Routes Selected

PORTUGAL

Road Name	A29 Stretch : Estarreja / Ovar	IC6 Stretch : Catraia dos Poços / Venda de Galizes
Road Type	2 x 2 Lines	1 x 2 Lines
Length	8,4 km	17,0 km
Traffic Volumes - TMDA	*T.M.by Day - 2 Directions*	*T.M.by Day - 2 Directions*
	2010 - Ligth:40.300 Heavy:7.900	2010 - Ligth:4.892 Heavy:643
	2020 - Ligth:46.200 Heavy:9.500	2020 - Ligth:5.805 Heavy:853
	2030 - Ligth:49.700 Heavy:10.500	2030 - Ligth:6.400 Heavy:950
Speed Limits	120 km/h	100 km/h
Obs.	Motorway recently constrcted - 1years	Advanced planning satge - Final design

IRELAND

Road Name	N25 Stretch : Carroll's X Overlay	M11 Stretch : Gorey Bypass	M9 Stretch : Waterford/ Knocktopher	N11 Stretch : Scarawalsh	R708 Stretch : SE Airport Road
Road Type	Single Carriageway	Motorway	Motorway	Single Carriageway	Single Carriageway
Length	1,6 km	22,0 km	23,6 km	5,52 km	5,10 km
Traffic Volumes - TMDA		*40MSA*	*35MSA*		*10MSA*
Speed Limits	100km/h	120km/h	120km/h	100km/h	80km/h
Obs.	Maintenance overlay 2008	Recently Constructed 2008	Recently Constructed 2009	Maintenance overlay 2007	Recently Constructed 2008

Tables 8.2.1 and 8.2.2 show the data for existing road pavement materials and for new “low energy materials”, concerning the quantities of aggregate and bitumen per km.

Table 8.2.1 – Quantities of aggregate and bitumen per km. Existing pavement

--- PORTUGAL ---

A29 - Estarreja / Ovar

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	GNT (non treated gravel)	8,400	41 160,000	1,000	---	2,350	---	96 726,000	---
Roadbase	GB3 (gravel bitumen mixture)		41 160,000	0,960	0,040	2,350	1,020	92 856,960	1 679,328
Binder course	BBSG (semi-granular bituminous concr		10 290,000	0,945	0,055	2,350	1,020	22 851,518	577,269
Wearing course	BBTM (very thin bituminous concrete)		8 232,000	0,944	0,056	2,350	1,020	18 261,869	470,212
							Total	230 696,346	2 726,809
							tonnes / km	**27 463,851**	**324,620**

IC 6 - Catraia dos Poços / Venda de Galizes

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	GNT (non treated gravel)	17,096	64 110,000	1,000	---	2,350	---	150 658,500	---
Roadbase	GB3 (gravel bitumen mixture)		17 096,000	0,960	0,040	2,350	1,020	38 568,576	697,517
Binder course	BBSG (semi-granular bituminous concr		17 096,000	0,945	0,055	2,350	1,020	37 965,942	959,086
Wearing course	BBTM (very thin bituminous concrete)		10 685,000	0,944	0,056	2,350	1,020	23 703,604	610,327
							Total	250 896,622	2 266,930
							tonnes / km	**14 675,750**	**132,600**

-- IRELAND --

N25 Carroll's X

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	N/A	1,600	---	1,000	---	2,350	---	---	---
Roadbase	Dense Macadam Base		2 104,000	0,960	0,040	2,350	1,020	4 746,624	85,843
Binder course	Dense Macadam Binder Course		1 157,200	0,953	0,047	2,350	1,020	2 591,607	55,476
Wearing course	Hot Rolled Asphalt		946,800	0,926	0,074	2,350	1,020	2 060,331	71,464

	Aggregate	Bitumen
Total	9 398,563	212,784
tonnes / km	**5 874,102**	**132,990**

M11 Gorey Bypass

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	Clause 804	22,000	69 300,000	1,000	---	2,350	---	162 855,000	---
Roadbase	HDM 50		87 780,000	0,960	0,040	2,350	1,020	198 031,680	3 581,424
Binder course	HDM50		27 720,000	0,953	0,047	2,350	1,020	62 080,326	1 328,897
Wearing course	Thin Wearing Course		16 170,000	0,940	0,060	2,350	1,020	35 719,530	989,604

	Aggregate	Bitumen
Total	458 686,536	5 899,925
tonnes / km	**20 849,388**	**268,178**

M9 Waterford/Knocktopher

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	Clause 804	23,600	74 340,000	1,000	---	2,350	---	174 699,000	---
Roadbase	HDM/DBM 50		118 944,000	0,960	0,040	2,350	1,020	268 337,664	4 852,915
Binder course	HDM50/DBM50		27 258,000	0,953	0,047	2,350	1,020	61 045,654	1 306,749
Wearing course	Thin Wearing Course		17 346,000	0,940	0,060	2,350	1,020	38 317,314	1 061,575

	Aggregate	Bitumen
Total	542 399,632	7 221,239
tonnes / km	**22 983,035**	**305,985**

N11 Scarawalsh

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	N/A	5,520	---	1,000	---	2,350	---	---	---
Roadbase	Dense Macadam Base		5 520,000	0,960	0,040	2,350	1,020	12 453,120	225,216
Binder course	Dense Macadam Binder Course		3 795,000	0,953	0,047	2,350	1,020	8 499,092	181,932
Wearing course	Hot Rolled Asphalt		3 055,320	0,926	0,074	2,350	1,020	6 648,682	230,616

	Aggregate	Bitumen
Total	27 600,894	637,764
tonnes / km	**5 000,162**	**115,537**

R708 SE Airport Road

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	Clause 804	5,100	6 120,000	1,000	---	2,350	---	14 382,000	---
Roadbase	Dense Macadam Base		5 712,000	0,960	0,040	2,350	1,020	12 886,272	233,050
Binder course	Dense Macadam Binder Course		2 244,000	0,953	0,047	2,350	1,020	5 025,550	107,577
Wearing course	Hot Rolled Asphalt		1 836,000	0,926	0,074	2,350	1,020	3 995,320	138,581

	Aggregate	Bitumen
Total	36 289,142	479,208
tonnes / km	**7 115,518**	**93,962**

Table 8.2.2 – Quantities of aggregate and bitumen per km. New "low energy materials"

--- PORTUGAL ---

A29 - Estarreja / Ovar

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	GNT (non treated gravel)	8,400	41 160,000	1,000	---	2,350	---	96 726,000	---
Roadbase	CBM		30 870,000	0,960	0,040	2,350	1,500	69 642,720	1 852,200
Binder course	BBSG (semi-granular bituminous concr		16 464,000	0,945	0,055	2,350	1,020	36 562,428	923,630
Wearing course	BBTM (very thin bituminous concrete)		8 232,000	0,944	0,056	2,350	1,020	18 261,869	470,212

	Aggregate	Bitumen
Total	221 193,017	3 246,042
tonnes / km	**26 332,502**	**386,434**

IC 6 - Catraia dos Poços / Venda de Galizes

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	GNT (non treated gravel)	17,096	64 110,000	1,000	---	2,350	---	150 658,500	---
Roadbase	GB3 (gravel bitumen mixture)		3 205,500	0,960	0,040	2,350	1,500	7 231,608	192,330
Binder course	BBSG (semi-granular bituminous concr		10 685,000	0,945	0,055	2,350	1,020	23 728,714	599,429
Wearing course	BBTM (very thin bituminous concrete)		10 685,000	0,944	0,056	2,350	1,020	23 703,604	610,327

	Aggregate	Bitumen
Total	205 322,426	1 402,086
tonnes / km	**12 009,969**	**82,013**

IRELAND

N25 Carroll's X

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	N/A	1,600	0,000	1,000	---	2,350	---	0,000	---
Roadbase	Dense Macadam Base		2 104,000	0,930	0,070	2,350	1,020	4 598,292	150,226
Binder course	Dense Macadam Binder Course		1 157,200	0,953	0,047	2,350	1,020	2 591,607	55,476
Wearing course	Hot Rolled Asphalt		946,800	0,926	0,074	2,350	1,020	2 060,331	71,464

	Aggregate	Bitumen
Total	9 250,231	277,166
tonnes / km	**5 781,394**	**173,229**

M11 Gorey Bypass

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	Clause 804	22,000	69 300,000	1,000	---	2,350	---	162 855,000	---
Roadbase	HDM 50		85 470,000	0,960	0,040	2,350	1,020	192 820,320	3 487,176
Binder course	HDM50		66 990,000	0,953	0,047	2,350	1,020	150 027,455	3 211,501
Wearing course	Thin Wearing Course		16 170,000	0,940	0,060	2,350	1,020	35 719,530	989,604

	Aggregate	Bitumen
Total	541 422,305	7 688,281
tonnes / km	**24 610,105**	**349,467**

M9 Waterford/Knocktopher

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	Clause 804	23,600	74 340,000	1,000	---	2,350	---	174 699,000	---
Roadbase	HDM/DBM 50		89 208,000	0,960	0,040	2,350	1,020	201 253,248	3 639,686
Binder course	HDM50/DBM50		76 818,000	0,953	0,047	2,350	1,020	172 037,752	3 682,655
Wearing course	Thin Wearing Course		17 346,000	0,940	0,060	2,350	1,020	38 317,314	1 061,575

	Aggregate	Bitumen
Total	586 307,314	8 383,917
tonnes / km	**24 843,530**	**355,251**

N11 Scarawalsh

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	N/A	5,520	0,000	1,000	---	2,350	---	0,000	---
Roadbase	Dense Macadam Base		5 520,000	0,930	0,070	2,350	1,020	12 063,960	394,128
Binder course	Dense Macadam Binder Course		3 795,000	0,953	0,047	2,350	1,020	8 499,092	181,932
Wearing course	Hot Rolled Asphalt		3 055,320	0,926	0,074	2,350	1,020	6 648,682	230,616

	Aggregate	Bitumen
Total	27 211,734	806,676
tonnes / km	**4 929,662**	**146,137**

R708 SE Airport Road

layer	Material	lenght (km)	Paved area x thickness (m³)	% Aggregate	% Bitumen	Aggregate Density (t/m³)	Bitumen density (t/m³)	Aggregate (tonnes)	Bitumen (tonnes)
Sub-base	Clause 804	5,100	6 120,000	1,000	---	2,350	---	14 382,000	---
Roadbase	Dense Macadam Base		6 120,000	0,960	0,040	2,350	1,020	13 806,720	249,696
Binder course	Dense Macadam Binder Course		4 080,000	0,953	0,047	2,350	1,020	9 137,364	195,595
Wearing course	Hot Rolled Asphalt		1 836,000	0,926	0,074	2,350	1,020	3 995,320	138,581

	Aggregate	Bitumen
Total	41 321,404	583,872
tonnes / km	**8 102,236**	**114,485**

Tables 8.3.1 and 8.3.1 show the results of the energy used per km in order to manufacture and place both pavement solutions.

Table 8.3.1 – Energy used per km in order to manufacture and place. Existing pavement

----------------------------- PORTUGAL -----------------------------

A29 - Estarreja / Ovar

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	27 463,851	324,620	0,78	1,59	4,56	6,92

IC 6 - Catraia dos Poços / Venda de Galizes

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	14 675,750	132,600	0,42	0,65	1,68	2,74

----------------------------- IRELAND -----------------------------

N25 Carroll's X

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	5 874,102	132,990	0,17	0,65	1,68	2,50

M11 Gorey Bypass

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	20 849,388	268,178	0,59	1,31	3,84	5,74

M9 Waterford/Knocktopher

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	22 983,035	305,985	0,65	1,49	4,45	6,59

N11 Scarawalsh

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	5 000,162	115,537	0,14	0,56	1,43	2,14

R708 SE Airport Road

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	7 115,518	93,962	0,20	0,46	1,23	1,89

Total added energy per unit:

- Aggregates 28,38 MJ / tonne
- Bitumen 4 883 MJ / tonne
- Production Hot Mix 280 MJ / tonne
- Production Cold Mix 15 MJ / tonne

Table 8.3.2 – Energy used per km in order to manufacture and place. New "low energy" materials

----------------------------- PORTUGAL -----------------------------

A29 - Estarreja / Ovar

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	26 332,502	386,434	0,75	1,89	2,00	4,64

IC 6 - Catraia dos Poços / Venda de Galizes

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	12 009,969	82,013	0,34	0,40	0,80	1,54

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N25 Carroll's X

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	5 781,394	173,229	0,16	0,85	0,88	1,89

M11 Gorey Bypass

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	24 610,105	349,467	0,70	1,71	2,55	4,96

M9 Waterford/Knocktopher

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	24 843,530	355,251	0,71	1,73	2,68	5,12

N11 Scarawalsh

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	4 929,662	146,137	0,14	0,71	0,82	1,68

R708 SE Airport Road

Road & Route Option	Quantity of Aggregate (tonnes/km)	Quantity of Bitumen (tonnes/km)	Energy Aggregate (TJ/km)	Energy Bitumen (TJ/km)	Energy Production (TJ/km)	Total Material Energy Per km (TJ/km)
General Country	8 102,236	114,485	0,23	0,56	0,78	1,57

Table 8.4 shows the results of the energy savings in manufacture and placement with new "low energy materials".

Table 8.4 – Energy saving with the new "low energy materials"

------------------------------ **PORTUGAL** ------------------------------

A29 - Estarreja / Ovar

Road & Route Option	Total Material Energy Per km Hot Mix (TJ/km)	Total Material Energy Per km Low Energy (TJ/km)	Saving %
General Country	6,92	4,64	33,0%

IC 6 - Catraia dos Poços / Venda de Galizes

Road & Route Option	Total Material Energy Per km Hot Mix (TJ/km)	Total Material Energy Per km Low Energy (TJ/km)	Saving %
General Country	2,74	1,54	43,7%

------------------------------ **IRELAND** ------------------------------

N25 Carroll's X

Road & Route Option	Total Material Energy Per km Hot Mix (TJ/km)	Total Material Energy Per km Low Energy (TJ/km)	Saving %
General Country	2,50	1,89	24,3%

M11 Gorey Bypass

Road & Route Option	Total Material Energy Per km Hot Mix (TJ/km)	Total Material Energy Per km Low Energy (TJ/km)	Saving %
General Country	5,74	4,96	13,7%

M9 Waterford/Knocktopher

Road & Route Option	Total Material Energy Per km Hot Mix (TJ/km)	Total Material Energy Per km Low Energy (TJ/km)	Saving %
General Country	6,59	5,12	22,3%

N11 Scarawalsh

Road & Route Option	Total Material Energy Per km Hot Mix (TJ/km)	Total Material Energy Per km Low Energy (TJ/km)	Saving %
General Country	2,14	1,68	21,6%

R708 SE Airport Road

Road & Route Option	Total Material Energy Per km Hot Mix (TJ/km)	Total Material Energy Per km Low Energy (TJ/km)	Saving %
General Country	1,89	1,57	16,9%

8.2 Conclusion

One of the aims of this project was to show the energy savings which could be made by using new 'low energy' materials instead of the more commonly used materials. The analysis described above shows how it is possible to achieve average energy savings of 25% to 30% using new 'low energy' materials. These savings are significant and indicate that substantial reductions in energy use are possible if consideration is given to the materials being used.

The use of 'low energy' materials is becoming increasingly popular and it is likely that more savings can be expected as newer products are developed.