ROAD PAVEMENT MAINTENANCE LIFE CYCLE ASSESSMENT – A UK CASE STUDY

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ABSTRACT

Life Cycle Assessment (LCA) of road pavements is often confined to the original pavement design life. This leads to the durability of design and materials being ignored for lack of data. Also the impacts on traffic when the pavement is rehabilitated are excluded. This paper uses a case study of a UK inter-urban road, to explore the impact of extending the system boundary of road pavement LCA to include cyclic maintenance and increased traffic emissions due to delays during maintenance. Micro-simulation traffic modelling was used to estimate emissions caused by delays at road works, for the chosen traffic management option. The emissions were compared to those created by the maintenance operation, estimated using an LCA model. In this case study, the extra traffic emissions caused by delays at road works are relatively small, compared to those from the maintenance process, except for hydrocarbon emissions. However, they are generally close to, or above, the materiality threshold recommended in PAS2050 for estimating carbon footprints. It is recommended therefore, that impact of maintenance and the emissions due to traffic disruption at road works should be included within the system boundary of road pavement LCA and carbon footprint studies and should be considered in developing guidelines for environmental product declarations of road pavement maintenance products and services.

INTRODUCTION

The life cycle assessment (LCA) of road pavements has been developing since the 1990s *(1,2)*. The life cycle inventory of pavement materials has been researched thoroughly by material associations *(3,4)*, compared to early studies of energy consumption only *(5)*. The work is strengthened by including recycled and secondary materials *(6,7)*, a growing practice in response to stakeholder calls for sustainable construction. More recent LCA research is focused on the methodological choices, for instance allocation *(8-10)*, and comparison of design options *(11,12)*.

The structural intervention (rehabilitation) in pavement life, typically after more than 20 years, is subject to design, material durability, traffic and environmental conditions. Times of rehabilitation requirements are therefore difficult to predict and this is compounded by recycling and innovation in construction techniques (e.g. warm mix asphalt, reinforcement textile), which has confined the boundary of many LCA studies to cradle-to-gate, or to the point of first construction, cradle-to-laid *(13,14)*. Besides, it has been noted in the earliest of LCA research exercises that traffic emissions in the use phase can account for the majority of emissions in the pavement life cycle *(15,16)*. The proportion has been quantified by recent European research to be in the range of 93-99% *(17)* or even higher *(18)*. Because vehicle fuel consumption is largely determined by many factors other than pavement performance *(19,20)*, traffic emissions are typically excluded from pavement LCA. This is a limitation, in that pavement maintenance and rehabilitation leads not only to additional construction activities, but queuing or diversion of traffic at road works. A few studies have investigated the additional emissions, but have been limited to simplified traffic modelling *(21)* or hypothetical scenarios *(22)*, with no validation or sensitivity check on the traffic flow or traffic management (TM) options.

These problems are related to system boundary settings. A cradle-to-gate scope can avoid the uncertainty associated with pavement use, at the expense of not taking into account any durability or recyclability. Traffic emissions under the free flow state can be estimated by multiplying the length of journey with average emission factors (e.g. kg CO_2 per vehicle kilometer), typically tied to the age, engine size and fuel type of the vehicles *(23)*, or they can be derived from commercial databases (e.g. *Ecoinvent*) *(18)* Managed traffic flows are better modelled in micro-simulation coupled with an instantaneous emissions model, because this type of tool is able to relate the emission rates to vehicle operation (e.g. driving pattern, speed profile) during a series of short time steps *(24)*, representing the restricted flow or congestion that may be caused by road works. There remains a need to explore system boundary expansion of road pavement LCA to understand the importance of this part of the pavement life cycle.

Using a case study of a UK inter-urban road, this paper investigates these two areas where boundary setting is believed to have an impact on the LCA results. This study includes pavement rehabilitation using geotextile reinforcement, and emissions from traffic disrupted during the rehabilitation. In the former, the system boundary included rehabilitation at the end of design life, in the latter, micro-simulation was used to model lane closure during the intervention. The results are discussed and recommendations on when and how to expand the boundary for road pavement LCA are made.

CASE STUDY AND LCA MODEL

The case study site is located in Lincolnshire on the A17 between Sutton Bridge and Kings Lynn, an inter-urban road in the UK East Midlands; with length 720m including 200m dual (22m width) and 520m single (11m width) carriageway. While the results of similar studies will vary widely, due to the very wide range of traffic flows on different roads, this site was chosen due to the appropriate level of construction and traffic flow data available at a location representative of many similar roads, with a variety of potential traffic management (TM) options.

The system boundary of the pavement construction and maintenance LCA is illustrated in Figure 1. Construction data on pavement layout and thickness was provided by Lincolnshire County Council. Material recipes for asphalt mixtures were based on UK asphalt material specification in compliance with BS EN 13108 *(25)*. Blast furnace slag (BFS), a by-product from the iron making process, was used as aggregates in dense bitumen macadam (DBM) base (100mm thick) and binder (60mm thick) courses, and as coarse aggregates (>2mm) in hot rolled asphalt (HRA) surface course (40mm thick). Quarry aggregates and BFS are transported for 50km, and bitumen for 200km, to the mixing plant using 20-28t truck. New asphalt and milled recycled asphalt pavement (RAP) are transported for 80km to site and stockpile, respectively, using 20-28t truck. Allocation of environmental burdens of iron making to BFS has followed the zero impact route[1] recommended by a UK industry standard tool for asphalt carbon footprinting *(14)*. The Eurobitume 2011 inventory, which is based on a mixed allocation by mass and economic value *(3)* between oil refinery products, was used for bitumen. Asphalt production followed the 'cut-off' method for end-of-life (EOL) scenario[2], in compliance with a UK public specification for measuring greenhouse gas emissions of products *(26)*. The impact of the above allocation methods on the LCA results has been reported elsewhere *(27)*.

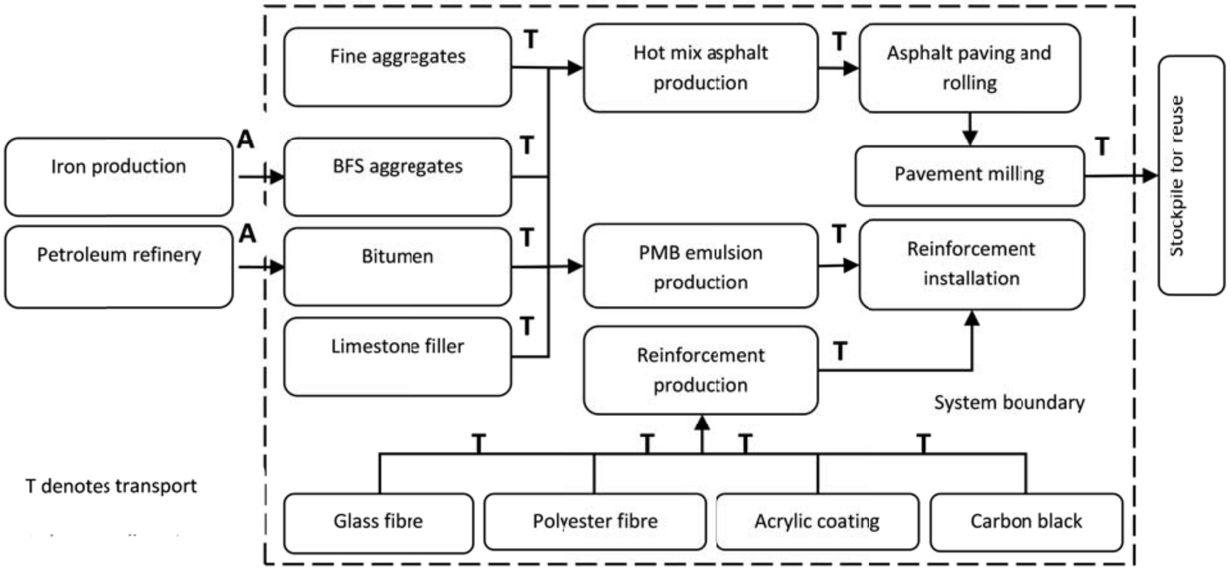

Figure 1: System boundary of A17 major rehabilitation with pavement reinforcement.

Original construction was undertaken in 1989. This case study starts in 2009, when a major rehabilitation was undertaken. Twenty years was selected as the analysis period to be consistent with the design life of the 2009 rehabilitation. This rehabilitation involves milling out of 150mm (200mm if without geotextile) of the old asphalt pavement and replacing with inlay of new asphalt mixtures. All removed materials are assumed stockpiled for reuse. The modelling was carried out in *SimaPro*, supported by data from contractors and UK specification.

During rehabilitation a reinforcement geotextile was used, which is mainly a glass fiber textile (*GlasGrid*™) overlaid by 2kg/m^2 of polymer modified bitumen (PMB) emulsion. This may have dual benefits of preventing reflection cracking, and reducing the required asphalt thickness (a 220mm inlay would otherwise have been used) and less excavation waste, at the expense of additional manufacture and installation of the reinforcement. A LCA of this reinforcement system was, therefore, required as

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[1] Alternatively, allocation can be made based on mass or economic value of the outputs.

[2] In the 'cut-off' method, each product is assigned only the burdens directly associated with it; in other words, all benefits of recycling are given downstream to using the recycled material. 'Substitution' is an alternative method of allocation; it gives all benefits of recycling to the original manufacture but requires an assumption of the EOL recovery rate.

part of this case study. The manufacture and installation of geotextiles is independent of making the asphalt layers. The modelling of pavement made with geotextiles assumed that the reinforcement (assumed to be intact) remain in place at end of the design life.

GlasGrid™ is made of 72.9% glass fiber, 2.1% polyester fiber, 25.0% acrylic coating and trace content (<0.1%) of carbon black. Raw materials are transported for an average distance of 2,000km using 32t truck to a manufacturing plant in the USA, where natural gas (0.014m^3) and electricity (0.017kWh) are consumed to produce 1m^2. The product is then shipped using ocean freighter for 5,000km to UK and 50km using 32t truck from port to site. The polymer modified bitumen emulsion was transported for 200km using 32t truck. Primary data was obtained from the manufacturer. For comparison, data in the *Ecoinvent* database was used. The unit inventory results, using CO_2e as an example, are presented in Table 1.

Table 1: Carbon Calculation of *GlasGrid*™ Cradle-to-Gate (unit: per m^2)

Production of Raw Materials	**Unit carbon ($kgCO_2e/kg$)**		**Content (g/m^2)**	**Unit carbon ($kgCO_2e/m^2$)**		**Percentage**	
Glass fiber	1.75	2.62	295.15	0.52	0.77	69%	68%
Polyester fiber	2.30	4.85	8.60	0.02	0.04	3%	4%
Acrylic coating	0.86	1.86	101.05	0.09	0.19	12%	16%
Carbon black	1.79	2.37	0.20	0.00	0.00	0%	0%
Transport of Raw Materials	**Unit carbon ($kg\ CO_2e/kg$)**		**Content (g/m^2)**	**Unit carbon ($kg\ CO_2e/m^2$)**		**Percentage**	
Road (glass fiber)	0.25		295.15	0.07	0.10	10%	9%
Road (polyester fiber)	0.12		8.60	0.00		0%	
Road (acrylic coating)	0.12		101.05	0.01		2%	
Road (carbon black)	0.12		0.20	0.00		0%	
Production of *GlasGrid*™				**Unit carbon ($kgCO_2e/m^2$)**		**Percentage**	
Natural gas consumption				0.03	0.03	3%	3%
Electricity consumption				0.01	0.01	1%	1%
TOTAL ($kg\ CO_2e/m^2$)				**0.75**	**1.19**	100%	100%

Table 1 indicated that the cradle-to-gate CO_2e of *GlasGrid*™ provided by the manufacturer is 0.75kg/m^2, in other words 37.0% less than 1.19 kg/m^2 as calculated using *Ecoinvent* default data (shaded). The *Ecoinvent* data for relevant materials was global average for year 2000; the data from materials supplier was obtained from recent literature and *TEAM*® (commercial LCA software). Interestingly, the percentages that activity groups account for were similar between the two data sources, i.e. 84-88% for materials embodied, and 9-12% for transport and about 4% for manufacture. *Ecoinvent* default data was used in the pavement LCA study, to be consistent with the other stages of the LCA.

Three scenarios were modelled that have different capital inputs and maintenance needs, to compare the cradle-to-laid inlay and future treatment:

- Actual Scenario: 200mm asphalt with geotextile in 2009, 150mm asphalt inlay at year 20 (in the actual 2009 rehabilitation,200mm old pavement replaced with new asphalt and a geotextile laid at a depth of 150mm; future rehabilitation at year 20 will leave the geotextile in place and only the 150mm asphalt above it to be replaced)
- Comparison Scenario: 200mm asphalt initially, 200mm asphalt inlay at year 20
- Alternative Scenario: 220mm asphalt initially, 220mm asphalt inlay at year 20

TRAFFIC MODELLING

Microscopic models are considered to be the most accurate and versatile analysis tools to simulate non-free flow traffic states (i.e. busy and congested). This is because micro-simulation can replicate individual vehicle movements along roads and through junctions in a network. Road maintenance, as in this A17 case study, is always carried out under TM suitable to the location and layout of the road. Off peak lane closures with traffic light control are often used in these circumstances. The micro-simulation model *AIMSUN* (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) was used in this study to evaluate the emissions generated by traffic under different TM measures.

AIMSUN was selected because of its ability to model the road network geometry, the behaviour of individual vehicles in response to traffic and signal controls (pre-timed and actuated), and its easy-to-use graphical interface. Also, a particular feature of *AIMSUN* is its ability to capture the empirical evidence of changes in driver behaviour depending on local circumstances, e.g. the acceptance of speed limits, the influence of gradients, driver interaction whilst travelling in adjacent lanes. An *AIMSUN* micro-simulation model was built for both the site located in Lincolnshire on the A17, highlighted in Figure 2, and the wider road network.

Figure 2: Site layout of A17 rehabilitation and wider road network.

Base Case Scenario

To model the base case (without road works) scenario, with no TM, weekly data extracted from the automatic traffic count (ATC) by Lincolnshire County Council were used, specifically the hourly traffic flow data for the period May and August 2010 including vehicle class and speed on a daily basis. The model was built to include road layouts, lane allocations, signal junctions, stop-lines, etc. Statistical analyses were used to produce typical flow profiles for each day of the week in order to identify the peak and inter-peak periods, thus to identify when is the best time and day to carry out the planned road works. Traffic emissions were calculated using the *AIMSUN* embedded instantaneous emissions model, four vehicle types have been simulated (i.e. car petrol, car diesel, light goods vehicle (LGV) and heavy goods vehicle (HGV)), based on the data available on fleet composition. The origin-destination (O-D) matrix of trips into, out of and within the modelled area at an hourly resolution was generated to be consistent with the traffic flows provided.

Road Works Scenario

The impact of the 2009 rehabilitation road works on traffic flow was modelled. The overnight TM simulation consisted of four shifts (phases) in three nights with temporary speed limits on site, see Figure 3. In phases 1 and 2 (night 1), work was carried out on the 400m single carriageway west of the scheme in both directions. Phase 3 (night 2) dealt with the rest of the scheme (320m) eastbound including the junction approach; Phase 4 (night 3) dealt with the rest of the scheme (320m) westbound. The simulation was conducted with two times for the start of TM from 18:00 and from 19:30. The 19:30 TM start is believed to be more practical, as at this time the traffic flows have decreased substantially. The impact of the earlier closure with a traffic flow of about 600vehicles/hour, associated with the 18:00-19:00 period, was estimated to explore the importance of this decision.

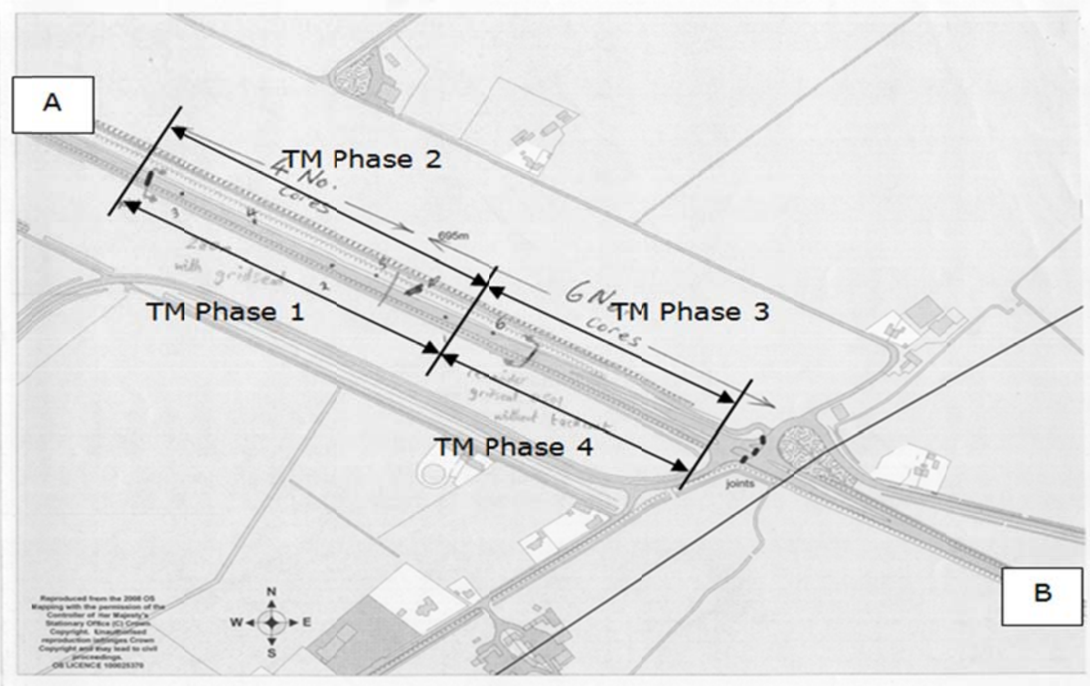

Figure 3: Phased lane closure in A17 traffic management.

RESULTS AND DISCUSSION

Results of the Pavement Construction and Maintenance LCA

Table 2 presents the LCA results of CO_2e which are presented per m^2 pavement area and multiplied by the area to give the whole case study results, i.e. a total pavement area of $10,120m^2$. Three scenarios broken down by the two stages of 2009 and 2029 represented the actual, the comparison and the alternative scenarios. The *SimaPro* results for inlay and 20-year maintenance of the A17 project are presented in Figure 4 and Figure 5.

Table 2: Influence of Using Reinforcement (rft) on Pavement CO_2e

Life Cycle Stage	Unit	Actual (with textile)	Comparison (without textile)	Alternative (without textile & 20mm thicker)
2009 Rehabilitation	kg CO_2e per m^2	42.5	40.7	44.6
2029 Rehabilitation		38.3	50.7	55.7
Total		80.8	91.4	100.3
2009 Rehabilitation	t CO_2e per case study	430.1	411.9	451.4
2029 Rehabilitation		387.6	513.1	563.7
Total		817.7	925.0	1,015.0

In Figure 4, if only the rehabilitation phase (inlay) is considered, the option with pavement reinforcement (left column) will have higher (3-21%) environmental impacts than the construction without reinforcement (right column). If not using the geotextile increases the pavement asphalt thickness by 20mm (middle column), the reinforcement option will have lower (3-6%) impacts in 8 out of 11 impact categories, and yet higher (4-13%) impacts in the other 3 categories (i.e. *Carcinogens*, *Radiation* and *Minerals*). This is because the inventory of reinforcement, predominantly glass fiber production as indicated by Table 1 (CO_2 for example), adds additional burdens on the environment. Some of these burdens (including CO_2) are offset by thinner construction, others remain higher than using 20mm thicker pavement without reinforcement.

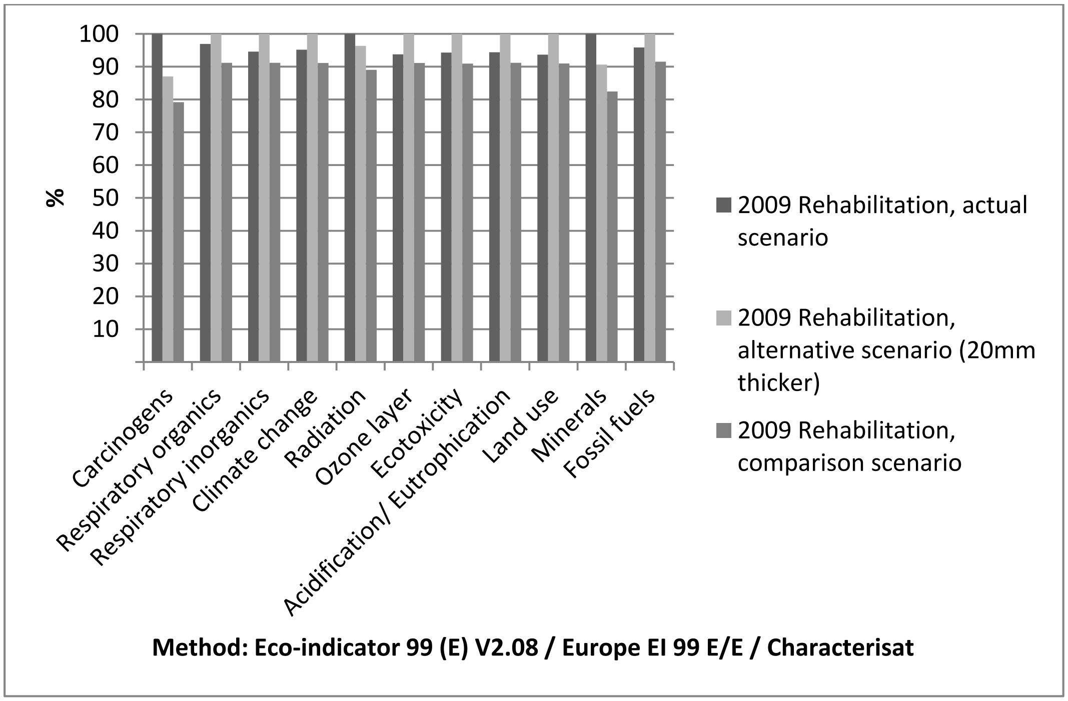

Figure 4: LCA modelling of A17 inlay.

In Figure 5, if both the 2009 rehabilitation and full depth repair at year 20 are considered, the reinforcement option (150mm inlay at year 20, left column) will have lower (2-12%) environmental impacts compared to the construction without reinforcement (200mm inlay at year 20, right column), in all impact categories. Savings in *Carcinogens*, *Radiation* and *Minerals* remain marginal (2-5%) indicating the inventory of geotextile contributes more significantly to these areas. The benefits are more (11-21%

less) when the 20mm thickness reduction (compared to middle column) is considered. Whether this pattern of results will remain if the study takes a longer analysis period (e.g. 40 years) will depend on the durability of the geotextile.

Results of CO_2e in absolute values are presented in Table 2, as per m^2 pavement area and multiplied by the quantity to give the whole case study results, i.e. a total pavement area of 10,120m^2, and new asphalt quantity of 4,857.6t (density 2.4t/m^3) or 5,343.4t for thicker pavement without reinforcement. The initial construction with reinforcement has higher (by 11%) carbon footprint than 20-year inlay, because the inputs of geotextile offset the 50mm thinner construction for inlay. Without reinforcement, the 20-year inlay will be higher (by 25%) in carbon than initial construction, because the inlay involves additional work of milling and transport the RAP (assuming 50km) to a stockpile. The reinforcement option has 4.4% higher carbon in construction than without it; but 24.5% lower in 20-year inlay. Collectively, the reinforcement reduces the carbon by 11.6%, or 19.5% if considering the reduction in thickness.

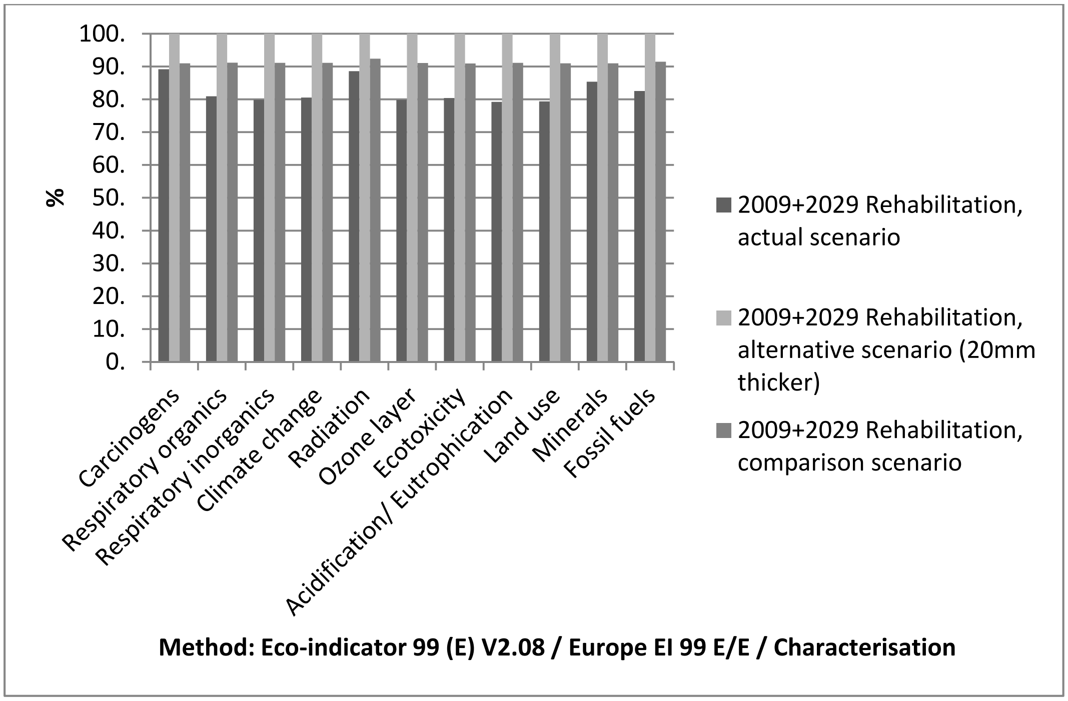

Figure 5: LCA modelling of A17 inlay and rehabilitation at Year 20.

Results of Traffic Simulation

Figure 6 shows the vehicle NO_x emissions estimated for the 2009 rehabilitation during TM. It indicates that the timing of TM could have a significant effect on emissions from disrupted traffic in all shifts (phases 1-4). The graph clearly shows that the effect would be more pronounced (from 1.5 to 8 times higher) when the road work was carried out near the junction (phases 3 & 4). Also, Figure 6 suggests that for phases 3 & 4 TM implementation after 23:00 would be best, when traffic flows fall sharply, and 21:00 for phases 1 & 2. In practice however, the start of TM is likely to be earlier because priority is given to ensure the completion of treatment and safety of the workforce within the night period.

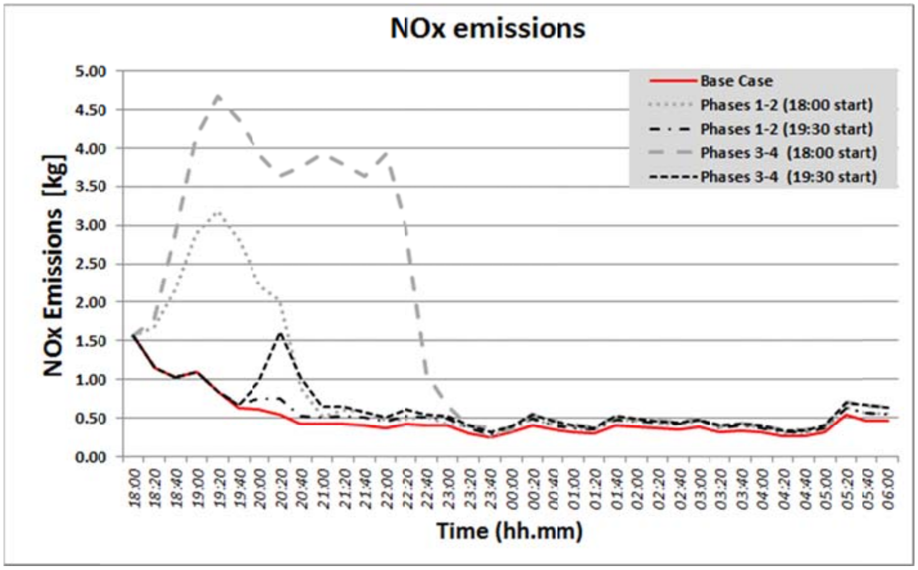

Figure 6: Vehicles NOx Emission Profiles in A17 Traffic Management

Simulation of the different scenarios described in Section 3.1-3.2 was carried out. A range of traffic and emission outputs have been generated from the *AIMSUN* model, including speed, queue length, number of stops, travel delay and emissions (CO_2, CO, NOx, HC and PM). Selected outputs are presented in Table 3.

Table 3: Additional Traffic Emissions due to Temporary Traffic-Light and Road Closure Options

Pollutants for Comparison		CO	HC	NO_x	PM	CO_2
Emissions from 2009 pavement rehabilitation (the actual practice, output from LCA)		614kg	36.4kg	1,750kg	228kg* (<10µm)	430t
Additional emissions from traffic during road works, TM by temporary traffic lights	start 19:30	7.11kg	1.33kg	13.3kg	0.35kg	1.94t
	start 18:00	59.6kg	10.4kg	98.0kg	2.69kg	16.5t
	start 19:30	1.2%	3.7%	0.8%	0.2%	0.5%
	start 18:00	9.7%	28.7%	5.6%	1.2%	3.8%

*Include 128kg (<2.5µm) and 100kg (>2.5µm and <10µm).

☐ Additional emissions from traffic disruption ▨ Relative to 2009 rehabilitation emissions

Table 3 indicates that the additional traffic emissions due to road works:

1. With start at 19:30 were low for NOx, PM and CO_2 emissions (i.e. <1%) compared to the rehabilitation emissions. Whilst carbon monoxide emission was 1.2%, hydrocarbon was more significant at 3.7%.
2. With start of road works at 18:00, the additional traffic emissions rose to more than 3% of rehabilitation emissions with the exception of PM (1.2%); hydrocarbon increased to nearly 30%. The 1% materiality threshold is recommended in PAS2050 (BSI 2011). This suggests that if a road closure is needed, the additional emissions will become significant when the traffic flow is high (e.g. 600vehicles/hour).

CONCLUSIONS AND RECOMMENDATIONS

A cradle-to-gate scope in road pavement LCA can avoid the uncertainty associated with pavement use, at the expense of not taking into account any impact of durability, maintenance or recycling etc. This case study has explored the implication of extending the system boundary of road pavement LCA, to also include the impacts of rehabilitation and traffic disruption at road works. This has been achieved by conducting LCA of pavement rehabilitation, and using micro-simulation to estimate extra traffic emissions at road works (compared to a base case of traffic emissions without road works). A benefit of using a case study is in reducing the number of assumptions required, e.g. concerning traffic levels, construction details or past rehabilitation.

The use of geotextile as pavement reinforcement has the potential of reducing pavement thickness, and reducing replacement quantities when the pavement reaches its design life. Both benefits were quantified by modelling the past rehabilitation and planned rehabilitation at year 20. In terms of CO_2, the initial construction with geotextile may have higher carbon footprint than construction without it. This is due to the embodied carbon in the manufacture and transport of the synthetics. When future rehabilitation is considered, construction with geotextile may be a better option. This is more important if this type of reinforcement can reduce thickness of the pavement (subject to analytical design and agreed industrial standards). The changes in environmental emissions when using pavement reinforcement vary. This can be attributed to the embodied inventory of textiles which differ significantly to the inventories of road building materials, such that a relatively small quantity can affect the total impacts of the pavement in certain impact areas.

Traffic modelling confirmed that the type, duration and timing of road works can significantly affect the traffic disruption and associated emissions. Comparing emissions from traffic disruption and those due to rehabilitation, for this case study, shows that those from traffic disruption are relatively small, except for hydrocarbons (HC). However, they are generally close to or above the 1% materiality threshold recommended in PAS2050 for estimates of carbon footprints. Emissions due to traffic disruption at road works should therefore, be included in road pavement LCA and carbon footprint studies. While this case study was chosen partly because its traffic levels are thought to be similar to many other inter-urban roads in England, the relationship found between traffic levels (e.g. 19:30 as opposed to 18:00 closure) and emissions during road works, means that micro-simulation of traffic flows especially for busy, strategic roads should be undertaken.

A limitation of this study, as with most road pavement LCA studies, is that the future maintenance of the case study is planned in isolation from the network of which it forms a part. In reality, road maintenance strategies are developed at a network level, and road works at an individual site may be undertaken at a time which is optimum for the network condition, traffic flows and maintenance budget. A second limitation is that only one level of traffic was modelled. It is recommended that a wider range of LCA studies, including traffic disruption at road works, be undertaken at network level and including different levels of sophistication in traffic modelling. A more complete study of this sort would provide evidence on which to base requirements for system boundary expansion of road pavement LCA studies to include traffic disruption at road works. These requirements could form part of product category rules for LCA and environmental product declarations in this sector (BSI 2012). Finally, the use of geotextile expects to improve in-service condition of the pavement, e.g. roughness. The influence in terms of difference in vehicle emissions through pavement service life is yet to be modelled and included in the system boundary.

ACKNOWLEDGEMENTS

This study was funded by an Engineering and Physical Sciences Research Council (EPSRC) Platform Grant in Pavement and Railtrack Engineering. The authors would like to thank staff at Lincolnshire County

Council and Saint-Gobain Ltd for providing data, and Virtus Ltd and Aggregate Industries Ltd for practical advice on TM.

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