Road Transport Infrastructure

HIGHLIGHTS

■ **TECHNOLOGY STATUS -** Road transport infrastructure enables movements of people and goods within and between countries. It is also a sector within the construction industry that has demonstrated significant developments over time and ongoing growth, particularly in the emerging economies. This brief highlights the different impacts of the road transport infrastructure, including those from construction, maintenance and operation (use). The operation (use) phase of a road transport infrastructure has the most significance in terms of environmental and economic impact. While the focus in this phase is usually on the dominant role of tail-pipe GHG emissions from vehicles, the operation of the physical infrastructure should also accounted for. In total, the road transport infrastructure is thought to account for between 8% and 18% of the full life cycle energy requirements and GHG emissions from road transport.

■ **PERFORMANCE AND COSTS -** Energy consumption, GHG emissions and costs of road transport infrastructure fall broadly into the three phases: (i) construction, (ii) maintenance, and (iii) operation (decommissioning is not included in this brief). The construction and maintenance costs of a road transport infrastructure vary according to location and availability of raw materials (in general, signage and lighting systems are not included in the construction costs). GHG emissions resulting from road construction have been estimated to be between 0.37 and 1.07 ktCO_2/km for a 13m wide road – depending on construction methods. Maintenance over the road lifetime (typically 40 years) can also be significant in terms of costs, energy consumption and GHG emissions. GHG emissions are estimated at between 26% and 67% of the total emissions from the construction phase, depending on materials and conditions of the maintenance regime. During operation, costs, energy consumption and GHG emissions result primarily from electricity use for lighting, signals and signage and so vary significantly depending on local conditions (e.g. lighting requirements, electricity generation mix). Significant reductions in costs and environmental impacts can be achieved during road operation using specific materials and design methods to improve energy efficiency. For example, a 50-70% energy savings in street lighting are deemed possible through the combination of LEDs paired with intelligent smart controls. Additional savings in cost, energy use and GHG emissions can be obtained from measures and technologies to mitigate/avoid congestion and from the use of appropriate coating with low surface rolling resistances. In some cases, these have been estimated to be significantly larger than savings from construction and maintenance activity.

■ **POTENTIAL AND BARRIERS -** The performance of road transport infrastructure has a long-term impact on future patterns of consumption and many national governments have already outlined an intention to improve or increase road transport infrastructure in the coming years. New materials and construction techniques, alternative maintenance regimes and new power sources are all options to help reduce the future costs of road transport infrastructure. Intelligent transport systems (ITS) are deemed to significantly reduce on-road emissions at relatively low cost and infrastructure impact, although there is little or no quantitative information available on this. Numerous new technologies and their utilisation for cost reduction are currently being investigated. However, long-term planning and the demand-driven nature of transport infrastructure may represent a barrier to using new, environmentally friendly techniques. Higher initial costs have often been a hindrance to implementation. Also, some novel technologies require significant development before they can be considered suitable for widespread use.

TECHNOLOGY STATUS

Road transport infrastructure forms physical links between regions and nations and is a key facilitator for the exchange of goods, services and people, and countries' economic growth [1]. The United Nations Economic Commission for Europe has provided UN countries with legal frameworks and agreements to facilitate a coherent international development of transport networks. Recently, road transport infrastructure has been recognised to have a significant impact on the overall greenhouse gas (GHG) emissions [2]. For the purposes of this brief, road transport infrastructure is defined as the road network and associated physical infrastructure such as signage, lighting and vehicle refuelling service. Energy consumption, environmental impacts and costs of a road transport infrastructure refer to three distinct but interlinked areas including (i) the construction of the physical infrastructure and the associated construction materials; (ii) the road maintenance over time; and (iii) the road operation (use), the latter being strongly related to the energy supply to vehicles that use the infrastructure and the energy needed for infrastructure operation (e.g. lighting, signage). Each such area has associated energy use, emissions and costs that are discussed in the text, with typical figures provided in the summary Tables 1 and 5. This brief primarily focuses on energy use, emissions and costs associated to these areas, and on future solutions to alleviate the negative impacts. Decommissioning and disposal phases [3] are beyond the scope of the brief.

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■ **The Road Transport Life Cycle -** The impact of road transport infrastructure from the energy and environmental perspective is initially linked to the construction including associated materials and services, but the importance of whole life-cycle of a road transport infrastructure - including the use by vehicles and their own life cycle - is increasingly acknowledged in design, planning and decision processes. For example, proponents of road building may highlight the congestion relieving advantages of building additional lanes for busy routes (and the consequent theoretical reduction in energy consumption and emissions). However, considering the increased demand induced by a larger capacity, this approach may not be the most efficient option to address road transport issues due to increased GHG emissions over the life cycle of additional lanes [23]. Figure 1 shows a simplified life-cycle energy model for a road infrastructure and includes vehicles and associated maintenance. The life cycle analysis includes the energy consumption and GHG emissions at each phase.

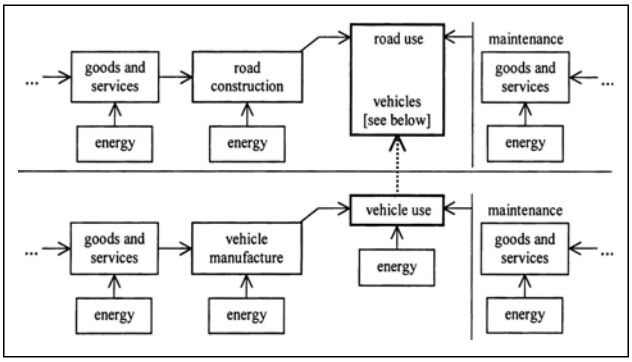

Figure 1 – Life-cycle energy model for road transport infrastructure [7]

Some key figures available in the literature may help put this matter in a quantitative perspective. For example, emissions from vehicle exhausts were estimated to account for 17% of the global GHG emissions in 2005 [4]; lifecycle emissions from road infrastructure construction, maintenance and operation have been estimated to account for between 8% and 18% of total lifecycle energy requirements for a road vehicle [5]; according to [6], infrastructure may account for up to 15% of the total GHG emissions per passenger-km from car transport in the US (i.e. including lifecycle emissions from the fuels, vehicles and infrastructure); Differing materials or surface types can have an impact on the energy embodied in road infrastructure which ranges from 8.4 TJ/km for granular road type, to 39 TJ/km for full depth asphalt [7]. The following sections focus on the energy consumption and GHG emissions from design, construction and maintenance of a road transport infrastructure (including bridges and tunnels) as well as on the energy supply (e.g. signage and lighting) that enables infrastructure use.

■ **Road Construction, Maintenance and Operation -** Construction of new roads is essential in developing countries to ensure economic development and growth whereas in developed countries, rehabilitation and maintenance of the existing roads may be preferable. Research for road construction technologies focuses primarily on more durable materials and low energy-consuming rolling surfaces [15]. The environmental sustainability of the infrastructure construction is gaining increasing importance. In the United Kingdom. the CEEQUAL scheme, established in 2003, has been designed to develop the sustainability of civil engineering projects, through improving project specification, design and construction [10]. More broadly, the CEEQUAL scheme is applicable to international projects within the framework of a collaboration with the Australian Green Infrastructure Council (AGIC) [21] and the American Society of Civil Engineers (ASCE) [22]. In the United States, federal highway departments provide funding and support to universities (e.g. University of Washington) to develop a scheme solely devoted to roads. 'Greenroads' [9] is a sustainability rating system for roads and any road infrastructure related project (including fixed links) that includes ratings against criteria that consider all aspects of construction and refurbishment project, including planning. A significant research effort is devoted to materials for road construction, maintenance and repair. The dominant materials for the construction and maintenance of a road infrastructure are currently cement and asphalt. Cement (and concrete) is one of the most energy-intensive materials and is estimated to account for 2.4% of global CO_2 emissions from industrial and energy sources [12]; concrete is estimated to be the second most consumed material after water [13]. However, today's technical solutions enable the use of recycled materials (either asphalt, cement and concrete) to reduce the use of *virgin* materials for construction and maintenance [8], [9], [10]. Waste and recycled materials can be re-processed on site to form the raw materials, with benefits in terms of mass balance and economics. Concrete can be crushed and re-used in the form of aggregate in all construction sectors, or can be recycled (in controlled amounts) in cement manufacturing processes. Though no quantitative information is available from the literature, on-site material re-use for road construction and maintenance offers well recognised benefits, not least the reduced cost of transportation of the raw materials. Using by-products from other industrial sectors can be another option. However, test campaigns are needed to avoid the use of hazardous by-products. The SAMARIS project [11] establishes a methodology for assessing the suitability of materials to be reused. A number of technologies and initiatives provide designers and decision-makers with tools to reduce energy use and GHG emissions from road infrastructure based on detailed databases on materials, type and location of road infrastructure (e.g.

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International Road Federation, IRF) [8]. Important savings can also be achieved during road operation as a result of careful consideration of the overall design, construction, maintenance and operation needs, and the whole lifetime cost. For example, road surfaces that reduce rolling resistance can significantly increase the fuel efficiency of vehicles over the road lifetime. The MIRIAM project is a global study established by a group of European and US based partners to investigate the potential to reduce GHG emissions through low rolling resistance surfaces [14].

■ **Lighting and Refuelling Infrastructure -** Road maintenance and operation also involve auxiliary systems, primarily lighting and refuelling infrastructure. In the UK the economic and environmental costs of maintaining street lighting represents a significant proportion of energy costs for local authorities [17] and a study on Swedish road infrastructure has estimated that 95% of the energy consumption for operation of road transport infrastructure (excluding the fuel for vehicles) is due to electricity use for lighting [18]. Actual energy needs for lighting vary significantly by country (e.g. lower lighting is needed in countries with longer daylight hours) and road type (urban roads, highways, motorways, etc.). Refuelling stations for vehicles are key components of the road infrastructure. Traditional fuels such as gasoline and diesel have well established infrastructure, service stations and supply systems which enable users to power their vehicles. However, the increasing use of alternative fuels (LPG, CNG, biofuels, electricity, hydrogen) and powertrain technologies (hybrids, plug-in electric, and fuel cell vehicles) poses new technology and investment challenges.

PERFORMANCE AND COSTS

■ **Road Construction, Maintenance and Operation -** It is widely recognised that road transport infrastructure decisions have a significant environmental, economic, and social impact in the short term, but they also have a long-term impact through patterns of operation and use [3]. Road transport infrastructure studies address both direct and indirect energy use and emissions from road transport infrastructure. Direct energy use and emissions are those associated to vehicles use and vehicle exhaust emissions, while indirect emissions are those associated to manufacturing of basic road materials, road construction and maintenance, and - in some cases - to vehicle manufacture as well. A study based in the United States found that indirect emissions (per passenger-km travelled) can account for up to 30% of the total emissions from road transport – this includes infrastructure provision and the vehicle and fuel lifecycle emissions [3]. Other studies have estimated that the total contribution of the infrastructure alone is between 8% and 18% [6]. In Sweden, indirect energy consumption from road transport has been estimated to be up to 45% of total energy consumption. This breaks down to 22% for infrastructure construction and servicing, 9% for fuel production and distribution, and the remaining 14% for vehicle manufacture and maintenance [3]. Typical energy consumption and emissions during infrastructure construction, maintenance and operation are illustrated in **Figure 2** [18], based on estimates for roads with street lighting in Sweden over 40-year use. According to this analysis, energy consumption and GHG emissions associated with construction and maintenance of concrete roads can double those of asphalt roads. Another source has estimated the CO_2 emissions from construction and maintenance of one additional lane on the US highway can be as high as about 2.2 $ktCO_2$/km over a 50 year life span [19]. Corresponding figures for unpaved roads are significantly lower; according to [4], the total energy consumption for construction and maintenance of granular road types over 40 years has been estimated at around 8.4 TJ/km, compared to 39 TJ/km for full depth asphalt road. Figures for different regions are not readily identifiable, but significant variation is to be expected depending on local conditions, road specifications, sourced materials and basic energy sources. Studies also suggest that the energy use for lifetime maintenance may be significant compared with initial construction – for example one study estimates road infrastructure emissions at around 10% of the total, comprising of 6% for construction and 4% maintenance over 40 years [7].

The importance of surface material selection, surface rolling resistance and the increased surface roughness due to wearing over time (along with impact of congestion due to construction and maintenance) has also been highlighted in a recent US study [16]. This study found that material consumption, traffic congestion caused by construction/maintenance activities, and roughness effects caused by overlay deterioration are three dominant factors that influence the environmental impacts and costs of overlay systems. The study also found that over a 40 year period the engineered cementitious composite (ECC) overlay can reduce total life-cycle energy by 15% and GHG emissions by 32% compared to the concrete overlay system (**Figure 3**). These advantages were attributed to the enhanced material properties of ECC, which prevent cracking failures.

Principles of best practise can be applied to the design and construction of durable roads. Examples of best practise road design include perpetual pavements, which are built in thin layers to promote durability and prevent surface stresses from penetrating through to lower layers, enabling top layer repairs/maintenance only [38]. Specific design requirements may also lead to different construction techniques such as the use of porous draining asphalt paving that allows water to filter through the road surface and prevents vehicle sliding in raining conditions. Best practices also include considering existing road infrastructure and materials as an alternative to virgin materials. In the United States, about 18 billion tons of asphalt pavement is estimated to be already in situ and potentially used as Reclaimed Asphalt Pavement (RAP). Using a 25% RAP in new road construction can reduce lifetime greenhouse gas emissions of road infrastructure by 10% [38]. Redundant roads could be crushed for use as aggregate onsite or RAP, and generate an estimated capital cost savings in road construction of $2.40 per metric ton if a 40% RAP is used in building road infrastructure. Other best practice examples include sourcing materials locally and/or procuring materials that have been manufactured using best practise techniques (e.g. energy efficient manufacturing or energy sourced from alternatives to fossil fuels). Design and engineering considerations still have an important role to play in reducing GHG emissions from the road transport infrastructure [39]. Design considerations also involve road operational emissions and costs. For example, a Canadian study found that heavy trucks running on concrete (rather than asphalt) is more efficient in terms of fuel use. It was discovered that for a high volume roadway, asphalt generates 738 tCO_2e/km compared to 674 tCO_2e/km generated by concrete over a lifetime cycle, which would have a significant impact over the whole lifecycle of the road [40]. Similar results have also been presented in a recent US study [16].

The capital costs of road transport infrastructure construction and maintenance is usually funded by governments through public agencies, with a possible participation of private investors, and balanced by taxation and user charges (tolls). In the United States, the federal expenditure on highways and streets in 2009 totalled more than $977 billion [24] for about 6.5 million km of road (2008 data). This equates to about $148,600 per km of road and includes both construction of new roads (at a significantly higher cost per km) and the maintenance of existing infrastructure. As far as the construction cost is concerned, a World Bank study completed from 1995 and 1999 for 40 countries [25] provided an average construction cost of new paved roads or road widening of $0.87 million per km, with a range of $0.14 million/km to 1.83 million/km. The corresponding cost for unpaved roads ranged from $0.06 million/km to $0.61 million/km, with an average figure of $ 0.25 million/km. These costs - as well as emissions during construction - can be significantly reduced with the use of alternative materials; for example the use of High Modulus Asphalt Materials (HMAM) can reduce construction costs by 18% and energy consumption and GHG emissions by 21% compared to traditional road based on asphalt [29]. In the United States, it has been estimated [16] that the overall lifetime costs of the alternative engineered cementitious composite (ECC) overlay system is about 40% lower (**Figure 4**) than the cost of concrete and much lower than the cost of hot mixed asphalt (HMA) alternatives. In spite of the higher initial construction

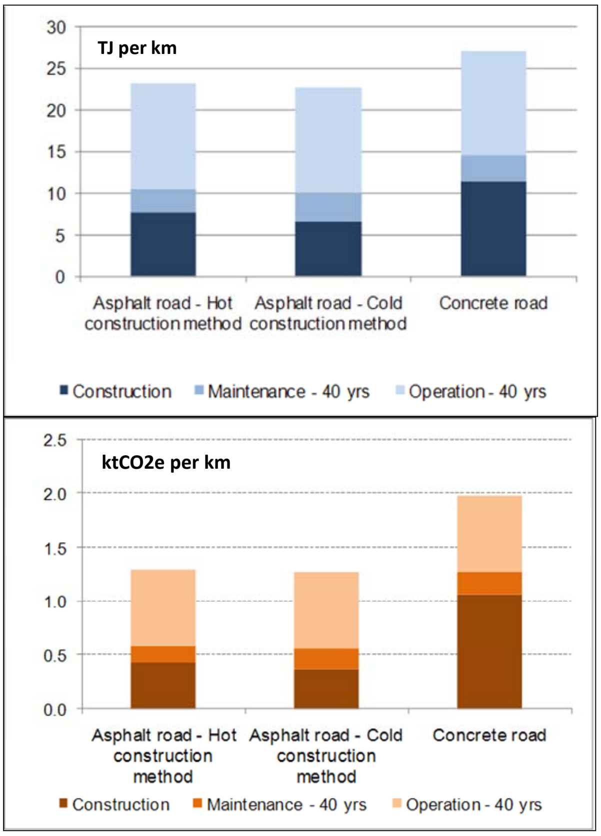

Figure 2– Estimated energy and GHG emissions from of road infrastructure construction, operation and maintenance for 13m width road (excluding the embodied energy of the asphalt material itself) [18].

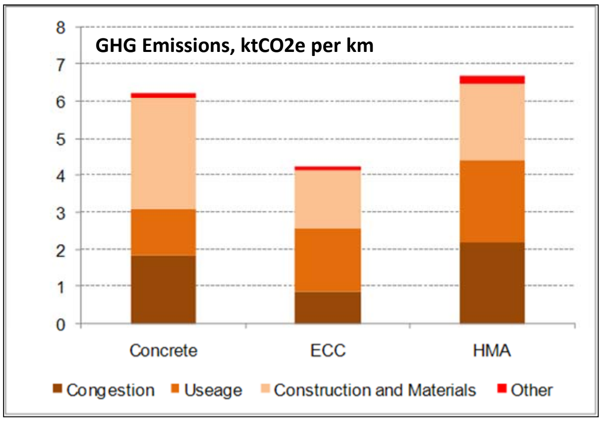

Figure 3- Variations in GHG emissions for alternative road surface materials for a 22m width highway [16].

cost, lifetime costs are lower due to the reduced need and frequency of maintenance resulting from the improved ECC material properties. The study makes also available estimates of costs, energy consumption and emissions due to congestion resulting from road maintenance (e.g. managed detours/ queuing traffic) and from factors such as vehicles consumption due to road surface roughness during normal operation. These kinds of costs may account for up to 80% of total life cycle costs in each overlay system. They are paid by

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users and usually are not included in the analyses. Maintenance regimes can have a significant impact in terms of cost and emission savings. Conventional road surfaces (concrete and asphalt) typically require several instances of remedial maintenance (RM) and one reconstruction (RC) over the 40-year road lifetime [16]. Alternative regimes based on a combination of preventative maintenance (PM) and corrective maintenance (RM) have been demonstrated to save energy, GHG emissions and costs (Table 6) [30].

■ The Role of Intelligent Transport Systems - Intelligent Transport Systems (ITS) have the potential to help manage traffic flows, reduce congestion and tailpipe emissions, and improve road transport safety. ITS are based on information and communication technologies applied to road transport infrastructure through dynamic message signage and intelligent vehicles [37]. For example; ITS may feature highway and motorway signage, which can have congestion and accident monitoring, reporting equipment and messaging updated remotely or automatically, as well as electronically managed road toll stations. However, ITS currently poses significant costs to implement; a 2004 study by the UK Department of Transport estimated set-up costs of at least $16 billion with further operating costs of $3-8 billion for a 6.4 million km road network. The US Department of Transportation (USDOT) has also investigated the use of ITS to reduce congestions and wasted fuel [24]. They estimated that up to 2.8 billion gallons of fuel are wasted annually due motorists stuck in traffic queues [37] and that this figure can be drastically reduced along with associated GHG emissions.

■ Lighting and Refuelling Infrastructure

The energy consumption and emissions from road infrastructure operation is dominated by the electricity consumption for street and traffic lights (up to 95% in Sweden for illuminated roads) [18]. This proportion is likely to be lower in countries with greater daylight hours and will also depend on the proportion of road illumination on different parts of the road network (e.g. close to 100% for urban roads and lower values for highways/motorways). The relative importance of lighting in the overall infrastructure impact in terms of GHG emissions is also highly dependent on the local electricity generation mix. A study carried out in the United Kingdom [17] makes available information on the capital costs of providing new street lighting infrastructure, with variable lighting regime, and energy savings of between 20% and 58% (depending on road type and the regime applied). The payback period versus maintaining the existing lighting schemes already in use was estimated to be around 30 years for residential routes, 4.6 years for traffic routes and 6 years for motorways (see Table 2). Additional savings

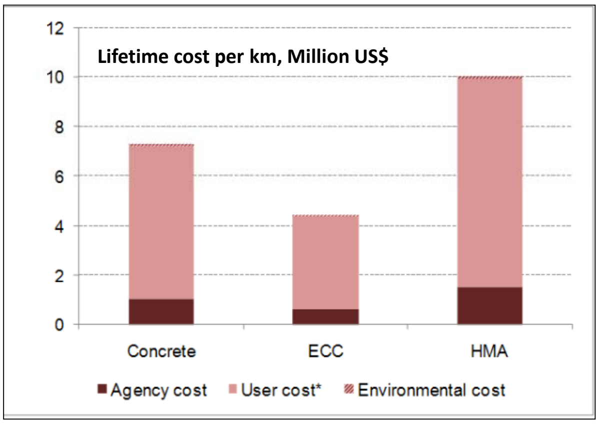

Figure 4 – Variation and breakdown in lifetime construction and maintenance costs for different road surface materials [16]

may be obtained from the use of low-energy lighting such as LEDs. A trial announced in March 2011 in Sydney (Australia) is expected to provide energy savings in the order of 50-70% through the combination of LEDs paired with intelligent smart controls [31].

The impact of energy consumption on GHG emissions attributable to maintaining and operating road transport infrastructure has prompted the publication of a guidance in the United Kingdom to aid decision making on street lighting and road maintenance [37]. This guidance encourages decision makers to implement technology advances that require lower power inputs or provide brighter lighting with reduced energy consumption, and introduce consideration of carbon emissions in any decision making process. An assessment has been carried out to investigate lighting schemes along different routes, and the patterns of use [17]. The study finds that significant capital and emissions savings can be achieved by adjusting the hours in which lighting is used. Three different scenarios are considered:

1. Do nothing – Maintain existing patterns of use (E).

2. Implement variable lighting (e.g. periods and intensity) according to need) (VL).

3. Light streets for only part of the time (e.g. switching off lighting at a certain time of night) (PN).

The study also took into consideration 'blanket lighting' conditions (Option 1), and a scenario where requirements dictate lighting and where lighting meets national minimum standards (Option 2A). In each case, savings are obtained from adjusting patterns of use, as demonstrated in Figure 5. Other lighting solutions include 'white light' which is more energy efficient, motion sensors to switch off lights when they are not needed, and dimming lights. Studies have found that a 50% dimming street lights can reduce costs by 40% and are imperceptible to the human eye (**Figure 5**) [41].

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Vehicle refuelling throughout the road network relies mainly on traditional petrol and diesel refuelling stations which performance, costs and implications are well established. Supply and storage of alternative fuels and power sources (e.g. electricity, and potentially hydrogen in the longer term) present new challenges in terms of technology, investment and environmental implications, which deserve careful assessments. For example, one study assesses the implications of developing a hydrogen infrastructure in Europe by analysing two different scenarios [32], and estimates number and capacity of re-fuelling stations required in Europe, and level of investment. The total investment costs range from $14.7 billion (assuming a 5% hydrogen share in energy consumption by 2030) to $30.2 billion (20% share by 2030). This corresponds to approximately 20,900 and 53,700 hydrogen refueling stations, equivalent (on average) to a station every 16.3 km and 6.4 km respectively, assuming about 341,000 km of major European roads at the end of 2007 (out of a total 4.6 million km) [33]. Similar studies exist for electricity supply to electrical vehicles (EV). They focus mainly on costs and capacity of charging infrastructure, batteries and range performance of the vehicles. However, very little information is available with regards to the embedded emissions resulting from EV recharging infrastructure. Nansai [34] in 2001 estimated a figure of around 1.8 tCO_2 per vehicle, that is around 5% of total lifecycle emissions for a current gasoline vehicle. The costs of an EV charging infrastructure have been assessed in a 2011 modeling study [47], which estimates that if construction and maintenance costs of a charging infrastructure are coupled with market incentives to encourage the EV use, they would outweigh any cost benefits until at least 80% of the vehicle market was comprised of electric vehicles. As a consequence, significant private investment is unlikely to take place while demand for alternative transport fuels and power trains is low [35] and the financial risk is high.

Potential and Barriers

Many National Governments plan to improve or increase road transport infrastructure in the coming years. For example, India intends to add more than 50,000 km of roads to the existing 3 million km of road network infrastructure by 2015 [26]. Investment in road infrastructure is estimated to require a total of over $40 billion equating to over $800,000 of investment per km of road. Similarly, the Mexican government has also committed to invest $26 billion in road transport infrastructure, to either building new roads or improving the condition of the 17,598 km of highways (equivalent to over $1.48 million per km) [27]. In comparison, recent estimates for motorway construction cost in the UK provide figure of around £1.5 million ($2.4 million) per lane-km [28]. More efficient and less polluting materials and technologies for road transport infrastructure

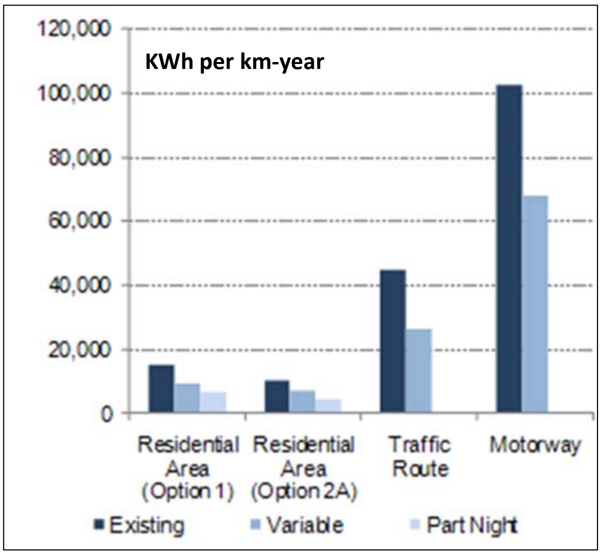

Figure 5 - Variations in energy consumption for alternative lighting schemes [17].

are being developed, but their use is hindered by the high capital costs, the long lifespan of existing road infrastructure (typically, 40 years) [18], and the urgency for new infrastructure to ease congestion and facilitate economic development. As a consequence, novel techniques and materials will take time to enter the market and provide benefits. In addition, many national policies currently aim to move from road transport of passenger or goods to other, less emission-intensive transport modes (e.g. rail), or to support a more efficient use of existing infrastructure. Therefore, novel technology options to reduce emissions from road transport infrastructure appear to be risky, with also little incentive for private investors [42].

Innovative road transport technologies not only include materials and construction technologies but also new LED-based lighting embedded within the road surfaces to pass safety and warning messages to road users, and motion sensors to activate lighting only when it is needed. More advanced technology approaches to future road transport infrastructure include Solar Roadways [44] (US-DOE) and SolaRoad (the Netherlands) which generate solar energy from solar cells embedded in road surfaces. Given the early stages of these technologies, cost assessments and potential deployment are highly uncertain. Based on broad assumptions, SolaRoad predicts that the electricity generation could be between 0.35 and 0.65 GWh per $km^{2,}$ depending on the road width and type (Table 7), but further research is needed to confirm these estimates.

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Table 1 – Summary Table – Key data and Figures for road transport infrastructure [18]

Energy Consumption, MJ/m²	Asphalt road - Hot construction method	Asphalt road - Cold construction method	Concrete road
Construction	589	505	885
Maintenance - 40 yrs	221	266	230
Operation - 40 yrs	969	969	969
TOTAL	1,779	1,740	2,084
CO_2 Emissions, $kgCO_2/m^2$	Asphalt road - Hot construction method	Asphalt road - Cold construction method	Concrete road
Construction	30.9	26.5	77.0
Maintenance - 40 yrs	11.6	13.9	14.7
Operation - 40 yrs	50.8	50.8	50.8
TOTAL	93.3	91.2	142.5
All GHG Emissions, $kgCO_2e/m^2$	Asphalt road - Hot construction method	Asphalt road - Cold construction method	Concrete road
Construction	32.80	28.20	81.94
Maintenance - 40 yrs	12.30	14.80	15.65
Operation - 40 yrs	54.00	54.00	54.00
TOTAL	99.1	97.0	151.6
Energy Consumption,TJ/km (13m wide, single carriageway)	Asphalt road - Hot construction method	Asphalt road - Cold construction method	Concrete road
Construction	7.66	6.57	11.51
Maintenance - 40 yrs	2.87	3.46	2.99
Operation - 40 yrs	12.60	12.60	12.60
TOTAL	23.13	22.62	27.09
CO_2 Emissions, $ktCO_2$/km (13m wide, single carriageway)	Asphalt road - Hot construction method	Asphalt road - Cold construction method	Concrete road
Construction	0.40	0.34	1.00
Maintenance - 40 yrs	0.15	0.18	0.19
Operation - 40 yrs	0.66	0.66	0.66
TOTAL	1.21	1.19	1.85
All GHG Emissions, $ktCO_2$/km (13m wide, single carriageway)	Asphalt road - Hot construction method	Asphalt road - Cold construction method	Concrete road
Construction	0.43	0.37	1.07
Maintenance - 40 yrs	0.16	0.19	0.20
Operation - 40 yrs	0.70	0.70	0.70
Total	1.29	1.26	1.97

Table 2 – Energy consumption, GHG Emissions and Costs of Alternative Street Lighting in the UK [17]

Type of road	Lighting Scheme	Energy		GHG, tCO_2/yr		Energy Cost[1], £/yr	Capital Cost (re-lighting), £	Operational Cost, £/yr
		kWh/yr	% Saving	Short term[2]	Long term[3]			
Residential Area S2 (Option 1[4])	Existing	15,058	-	8.09	6.47	1,280	N/A	1,165
	Variable	9,283	38%	4.98	3.99	789	41,220	594
	Part Night	6,367	58%	3.42	2.74	541	41,220	594
Residential Area to BS 5489-1:2003 (S4&S5) (Option 1)	Existing	15,031	-	8.07	6.46	1,278	N/A	1,165
	Variable	12,054	20%	6.47	5.18	1,025	41,220	594
	Part Night	7,814	48%	4.20	3.36	664	41,220	594
Residential Area to BS 5489-1:2003 (S4&S5) (Option 2A[5])	Existing	10,148	-	5.45	4.36	863	N/A	1,165
	Variable	6,914	32%	3.71	2.97	588	37,020	583
	Part Night	4,482	56%	2.41	1.93	381	37,020	583
Traffic Route	Existing	44,724	-	24.02	19.23	3,802	104,230	not available
	Variable	26,413	41%	14.18	11.36	2,245	111,380	not available
Motorway	Existing	102,380	-	54.98	44.02	8,702	N/A	not available
	Variable	67,950	34%	36.49	29.22	5,776	20,622	not available

[1] 0.43 $kgCO_2$/kWh
[2] at 8.5 p/kWh
[3] 0.537 $kgCO_2$/kWh
[4] Option 1: all roads lit to S2 with 6m mounting height 70W son luminaires
[5] Option 2°: Main estate road lit to S4 with 6m mounting height 50W son luminaires and other estate road main estate lit to S5 with 6m mounting height 50W son luminaires

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Table 3 – Transport Statistics for Europe and North America, 2009 (/2004*) [48], [20]

Country	Population	Area (km^2)	Inhabitants (per km^2)	Total consumption of energy in transport sector (all modes)in TJ	Consumption of energy by road transport sector in % of total transport sector consumption	Consumption of energy by road transport sector (in TJ)	km of Road transport infrastructure	Consumption of energy by road transport sector per km of road network (TJ/km)	Consumption of energy by road transport sector per 1000 population (TJ/1000 population)
Austria	8,355,260	82,433	101	361,242	86%	311,359	111,902	2.8	37
Belgium	10,753,080	30,328	355	466,017	79%	370,224	153,872	2.4	34
Bulgaria	7,606,551	110,910	69	122,529	87%	106,796	19,435	5.5	14
Czech Rep.	10,467,542	77,272	135	276,963	89%	246,904	130,638	1.9	24
Denmark	5,511,451	42,393	130	217,461	77%	168,337	73,331	2.3	31
Finland	5,326,314	304,594	17	201,261	81%	162,188	106,479	1.5	30
France	64,369,147	541,412	119	2,110,139	83%	1,758,220	1,041,173	1.7	27
Germany	82,002,356	348,946	235	2,584,759	82%	2,127,309	N/A	N/A	26
Greece	11,260,402	131,957	85	385,925	77%	299,080	N/A	N/A	27
Hungary	10,030,975	91,733	109	200,328	92%	183,661	197,518	0.9	18
Ireland	4,450,030	68,891	65	196,480	86%	169,137	96,695	1.7	38
Italy	60,045,068	301,333	199	1,770,562	86%	1,525,925	249,198	6.1	25
Netherlands	16,485,787	33,873	487	632,390	74%	470,691	130,316	3.6	29
Norway	4,799,252	306,252	16	210,236	68%	142,806	93,691	1.5	30
Poland	38,135,876	304,349	125	693,714	93%	644,836	384,953	1.7	17
Portugal	10,627,250	88,796	120	307,328	83%	256,236	N/A	N/A	24
Romania	21,498,616	229,713	94	224,549	89%	199,842	82,034	2.4	9
Slovakia	5,412,254	48,104	113	99,599	79%	78,457	43,879	1.8	14
Slovenia	2,032,362	20,141	101	73,890	97%	71,641	38,925	1.8	35
Spain	45,828,172	499,110	92	1,584,160	81%	1,278,022	165,093	7.7	28
Sweden	9,256,347	411,000	23	357,302	86%	307,255	141,322	2.2	33
Switzerland	7,701,856	41,263	187	309,381	77%	238,970	71,454	3.3	31
Turkey	71,517,100	783,562	91	685,132	81%	555,639	362,660	1.5	8
Canada*	31,974,000	9,970,610	3	2,328,372	76.1%	1,771,891	N/A	N/A	55.4
Russia*	143,474,000	17,075,400	8	3,976,588	42.1%	1,674,144	546,353	3.06	11.7
USA*	293,655,000	9,363,520	31	26,757,063	82.6%	22,101,334	6,433,291	3.44	75.3

* Data for Canada, Russian Federation and the United States are from [20], for 2004. Data for all other countries are for 2009.

Table 4 – Scenarios for the introduction of hydrogen road transport refuelling infrastructure [32]

Scenario decription	Capacity (MWH2)	Investment, per station (€)	Investment (converted to USD6)	Lifetime (years)	Required number	Total cost of refuelling infrastructure scenario (million USD)
1. Early introduction of hydrogen which will contribute 20% stationary and transport energy consumption by 2030	15 GWh/a	400,000	563,440	20	53,710	$30,262
2. Longer term penetration with hydrogen providing a share of 5% in stationary and transport energy consumption by 2030	10 GWh/a	500,000	704,300	20	20,887	$14,711

Table 5 – Summary Table: Cost, Energy Use and Emissions for Different Road Surfaces [16]

Cost, US$ million per km	Concrete	ECC	HMA
Agency cost	1.01	0.62	1.48
User cost[7]	6.19	3.74	8.42
Environmental cost	0.09	0.07	0.11
Total cost	7.29	4.43	10.00
Primary energy, TJ per km	Concrete	ECC	HMA
Congestion	26.6	13.9	31.3
Usage	16.2	19.7	27.8
Construction and Materials	23.1	23.1	142.4
Other	3.5	2.3	4.6
TOTAL	69.4	59.0	206.0
GHG emissions, ktCO_2e per km	Concrete	ECC	HMA
Congestion	1.83	0.85	2.17
Usage	1.28	1.70	2.26
Construction and Materials	2.98	1.57	2.04
Other	0.13	0.13	0.21
TOTAL	6.21	4.26	6.68

[6] Exchange rate obtained from http://www.economist.com/markets/currency/ and accessed on 25th March 2011
[7] congestion and rolling resistance

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Table 6 – Summary Results for LCA Road Maintenance Processes [30]

Treatment		20-year maintenance plan			40-yrs	
		$ per lane-mile	tonne CO_2e per lane-mile	GHG / $	$ per lane-km	tCO_2e per lane-km
Do nothing	DN	0	0	n/a	0	0.0
Preventative maintenance	PM	33,396	19	5.64E-04	41,503	23.6
Corrective maintenance	CM	71,818	63	8.74E-04	89,251	78.3
Restorative maintenance	RM	180,632	107	5.90E-04	224,479	133.0
Reconstruction	RC	507,958	238	4.68E-04	631,261	295.8

Table 7 – SolaRoad Energy Production [20], [45], [46]

Road width (metres) [46]	SolaRoad energy potential (Netherlands)
7	0.35 GWh/km^2
9	0.45 GWh/km^2
10	0.5 GWh/km^2
13	0.65 GWh/km^2

Notes: Calculations are based on energy generation of 50 kWh per m^2 [45]

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